Mathew Kurian
Reza Ardakanian *Editors*

Governing the Nexus

Water, Soil and Waste Resources Considering Global Change

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Institute for Integrated Management
of Material Fluxes and of Resources

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Abbreviations and Acronyms

ABES	Associação Brasileira de Engenharia Sanitária e Ambiental
AMC	Advanced Market Commitment
ANA	Agência Nacional de Águas
ASIS	(FAO) Agriculture Stress Index System
BOO	Build Own Operate
BOT	Build Own Operate Transfer
C	Carbon
CapExHrd	Capital Expenditure on Hardware
CapExSoft	Capital Expenditure on Software
CapManEx	Capital Maintenance Expenditure
CCEMO	Canada Centre for Mapping and Earth Observation
CCT	Conditional Cash Transfer
CELSS	Controlled Ecological Life-Support System
CESS	The Centre for Economic and Social Studies
CF	Carbon Finance
CH_4	Methane
CIRRA	Centro Internacional de Referência em Reúso de Água
CO_2	Carbon dioxide
CoC	Cost of Capital
COD	Cash on Delivery
CPCB	Central Pollution Control Board, in India
CPIA	Country Policy and Institutional Assessment
CVS	Centro de Vigilância Sanitária
DCF	Discounted Cash Flow
dS/m	Decisiemens per metre
DWA	Deutsche Verinigung für Wasserwirtschaft, Abwasser und Abfall—German Association of Water Management, Waste Water and Waste
EC	Electrical Conductivity
EC	European Council
EEA	European Environmental Agency
EMI	Electromagnetic Induction

EP	European Parliament
EU	European Union
ExDS	Expenditure Direct Support Costs
ExIDS	Expenditure Indirect Support Costs
FAO	Food and Agriculture Organization
GHG	Greenhouse Gases
GIS	Geoinformation Systems
GPOBA	Global Partnership on Output Based Aid (World Bank)
GPR	Ground Penetrating Radar
GWP	Global Warming Potential
HYV	High Yielding Varieties
ICT	Information and Communication Technology
IDA	International Development Agency
IEC	Information, Education and Communication
IPM	Integrated Pest Management
IRC	International Water and Sanitation Centre
ISO	International Organisation of Standards
IVA	Independent Verification Agent
IWRM	Integrated Water Resources Management
LAWA	Länderarbeitsgemeinschaft Wasser—German Working Group on Water Issues
LCA	Life Cycle Analysis
LCC	Life-Cycle Cost or Life-Cycle Costing
LCCA	Life-Cycle Cost Approach
LiDAR	LIght Detection And Ranging
LNRMI	Livelihoods and Natural Resources Management Institute
MPA	Movimento dos Pequenos Agricultores
MTEF	Medium-Term Expenditure Frameworks
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
N_2O	Nitrous oxide
NH_3	Ammonia
NIR visible	Near-infrared
NPV	Net Present Value
O&M	Operation and Maintenance
OBA	Output-Based Aid
OBD	Output-Based Disbursement
OECD	Organisation for Economic Co-operation and Development
OPCPR	Procurement Policy and Services Department (World Bank)
OpEx	Annual Operation and Maintenance Costs
PAHO	Pan American Health Organization
P-E	Poverty-Environment
PES	Payment for Environmental Services
PPP	Public–Private Partnerships
PV	Present Value

R&D	Research and Development
RADAR	RAdio Detection And Ranging
RBF	Results-Based Financing
SABESP	Companhia de Saneamento Básico do Estado de São Paulo S.A
SAR	Sodium Adsorbtion Ratio
SDG	Sustainable Development Goals
SRI	Systems of Rice Intensification
TDS	Total Dissolved Solids
ToP	Take or Pay
TRMM	Tropical Rain Measurement Missio
UA	Urban Agriculture
UNEP	United Nations Environment Programme
UNW-AIS	UN-Water Activity Information System
USEPA	United States Environmental Protection Agency
USP	University of Sao Paulo
UWWTP	Urban Waste Water Treatment Plant
VGE	Virtual Geographic Environments
vis-MIR	Visible Mid-infrared
vis-NIR	Visible-near
WASH	WAter, Sanitation and Hygiene
WASSAN	Watershed Support Services and Activities Network
WCT	Water Conservation Technology
WF	Water Footprint
WFD	European Water Framework Directive
WGI	World Governance Indicators
WLC	Whole-Life Costs
WP	Water Points
WPM	Water Point Mapping
WSW	Water–Soil–Waste

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Part I
Global Change and the Nexus Approach to Management of Environmental Resources

Chapter 1
The Nexus Approach to Governance of Environmental Resources Considering Global Change

Mathew Kurian and Reza Ardakanian

1 Introduction

Global trends such as urbanization, demographic and climate change that are currently underway pose serious challenges to sustainable development and integrated resources management. The International Panel on Climate Change noted in 2007 that one key feature of these changes is an acceleration of the global hydro-cycle. This is manifested in the increasing frequency or severity of extreme events such as floods and droughts. Since water is a potent dissolver and transport agent of soils, nutrients, other chemicals and materials and wastes may ‘migrate’ with water and could be ‘lost’ in unwanted places such as oceans, which may make recycling unfeasible with technologies that are available today. The ‘volatility’ of water resources needs to be accounted for given an increasing demand for food production. At the same time, there is a growing concern about soil degradation and the decline in soil quality, while the demand for food is going to increase. In this context, environmental quality can be satisfied only if soil, waste and water resources are managed in a sustainable and integrated manner. Given the limitations of the conventional technology transfer model in terms of addressing environmental challenges it is now acknowledged that capacity development approaches that aim to facilitate technology *adaptation* may offer a better chance of success.

The complex relations between demands, resource availability and quality and, financial and physical constraints can be addressed by knowledge-based policies and reform of professional practice. The nexus approach recognizes the urgent need for this knowledge and its interpretation in a policy-relevant setting guided by the

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understanding that there is a lack of blueprints for development based on integrated management of water, soil and waste resources in the Member States. Generation and application of knowledge is a priority for individuals, as well as institutional capacity development. It is against this background that the UNU-FLORES Institute for Integrated Management of Material Fluxes and of Resources was established in Dresden, Germany. UNU-FLORES is supposed to extend and upscale the concept of integrated resource management through adopting a truly integrative perspective by considering inter-related resources (water, soil, waste) and emphasizing fluxes of resources between phases and compartments. Thus, instead of traditional input–output models, UNU-FLORES focused on whether the consistent tracing (follow-up) and management of resources as fluxes (passage, flow, transport, transfer) would result in sustainable management outcomes. UNU-FLORES will pursue the achievement of sustainable environmental outcomes by serving as a think tank that promotes integrated resources management.

2 Evidence-Based Decision-Making

Over half a century of development research has led us to two fundamental questions: First, why does good science not always result in good policy? Two, will improved management of natural resources mitigate livelihood risks?[1] Conversely, will mitigation of livelihood risks result in improved management of natural resources? Some have referred to this conundrum as the Poverty-Environment (P-E) nexus. P-E causality can be attributed to the effects of scale of interventions. For example, a government programme to restore soil fertility may succeed at plot or farm scale but increasing spatial and temporal scale may increase uncertainty due to introduction of exogenous factors such as seasonal differences in farming practices, fluctuations in prices in factor and product markets and divergence in strategies of extension agencies.

The role of government in managing the P-E nexus is crucial since a large proportion of degradable natural resources (forests, river systems, groundwater aquifers) that are prone to degradation are not under private ownership. Furthermore, solid waste management is also not far from government influence since worldwide landfill sites are usually under government control. On the other hand, land under private title is not averse to the effects of government action. For example, changes in subsidy regime for agricultural inputs such as seeds or inputs such as fuel can lead to more intensive cultivation practices with impacts on natural resources. Examples could include water pollution, overdraft of groundwater aquifers or decreasing soil fertility.

---

[1] Livelihood risks could relate to access to income, employment, food and services (eg. water supply, ecosystem services).

Privatization experiments that were undertaken the world over concluded that optimum results may not be forthcoming since individuals may harvest forests or over pump aquifers with an eye on short-term profit at the cost of longer term benefit. Attempts at decentralization which followed, resulted in delegation of a number of tasks from higher to lower tiers of government but with little autonomy granted to local governments in terms of local taxes and tariffs. Decentralization in many respects heightened competition among local governments for central fiscal transfers and in some respects limited scope for cooperation for management of shared resources such as rivers.

UNU-FLORES acknowledges the role of government as a key player in management of environmental resources. Moreover, it also acknowledges that the role of government has changed because of the forces that have been unleashed by the following trends: (a) privatization, (b) decentralization and (c) emergence of information and communication technologies (ICT). ICTs have been supported by vast improvements in processing power that now makes it possible to collect, aggregate and display information based on analysed data from individual consumers and/or physical data points (example: water points) (Schonberger and Cuker 2013). This trend has the power to transform how we perceive the role of sampling, confidence levels and causality in research.

Evidence-based decision-making is founded on assumptions arising from these trends.

- Decision-makers are guided by correlations and not simply by certainty offered by results of controlled experiments/field trials (example: slash and burn agriculture reduces soil fertility).
- Data visualization is likely to encourage decision-makers to pose questions that require policy-relevant research (example: Why do certain geographies have higher incidence of water pollution?).
- Data visualization is likely to enable decision-makers to compare performance on a wide variety of indicators (example: efficiency, equity, integration).
- Data visualization is likely to promote transparent discussion of trade-offs (example: increased efficiency of water use may be at the cost of equity).
- Data visualization is likely to prompt collective action that involves political negotiation (example: What contributions of financial and human resources can authorities at multiple levels commit to achieve a commonly agreed goal?).

3 Divides in Environmental Governance

Environmental governance in developing and emerging economies suffers from fragmented approaches to planning and policy implementation. Fragmented approaches arise from competition among urban and rural local governments for central fiscal transfers, overlapping jurisdictional boundaries and inadequate management coordination among line departments and ministries. In many instances, fragmentary approaches are supported by a poor evidence base on the relationship between infrastructure construction and environmental outcomes. For example, absence of disaggregate, reliable and more frequent information at appropriate scales makes it difficult to predict the environmental outcomes of constructing dams, tube wells or storm drains in terms of sediment capture, aquifer recharge and wastewater reuse respectively. Institutional fragmentation is also supported by weak feedback loops between legal and policy formulation, spatial and temporal variation in biophysical environment and socioeconomic change within communities of environmental resource users. As a result decision-makers cannot design programme and project interventions with precision and may be unable to respond effectively to feedback from consumers on changes in service delivery parameters (affordability, reliability or quality) or to the effects of increased variability in frequency, intensity and duration of environmental shocks (droughts or floods).

The intellectual basis for fragmentary approaches to planning is supported in large measure by divides in approaches to environmental governance. Five divides in environmental governance are evident in emerging and developing countries as described below.

1. *Infrastructure versus services*: Many developing countries have invested heavily in infrastructure including hydropower dams, water and wastewater treatment and irrigation. While much of this expansion has been justified to increase food productivity and promote human security, there have been others that have questioned how this may have been achieved at the expense of investments in maintaining infrastructure. Further, the benefits of infrastructure construction in several cases may have bypassed those segments of society that needed public support the most. An explicit focus on service parameters such as affordability, reliability and quality has until recently been overlooked by conventional planning processes and structures (Kurian 2010b).
2. *Centralized versus decentralized government*: A focus on infrastructure construction in many cases led to expensive technologies being selected. Big dams and sophisticated treatment technologies were the order of the day following the Lewisian model of economic growth. As a result, central fiscal transfers were perpetuated and there was little incentive for local governments to rely on local revenue sources to match their expenditure plans. Accountability was compromised, service charges skyrocketed and poor consumers who were unable to pay suffered from lack of public services. Decision-making power remained concentrated with higher tiers of government and donors. Local initiative and autonomy suffered as a result and prospects for adaptive environmental management were compromised. As a result, political decentralization began to gain importance in academic and policy discussions.
3. *Public versus private management models*: In response to growing disenchantment with centralized management, due to their inability to protect environmental resources, there was a phase of utility privatizations notably in South America. During the 1990s, the political mood also favoured community-based natural resources management that emphasized themes of co-production and

participation. Based on lessons emerging from the earlier wave of utility privatizations public–private partnerships gained ground. Deregulation involved retaining asset ownership with public agencies, but engaging with the private sector through a variety of institutional contractual arrangements ranging from Build Own Operate Transfer (BOT) to divestures and concessions. One of the outcomes of such experiments with public–private partnerships has been institutional innovations ranging from budget support to Output Based Aid (OBA).

4. *Short-term versus reliance on long-term planning perspectives*: Centralized government structures and processes have placed great emphasis on budgets as a mechanism for allocation of public finances. Conventional budget preparation involves consolidation and aggregation of expenditure plans of several ministries and line departments. The process of appropriation usually can take a year and in developing countries, the links between disbursements and achievement of public policy outcomes are seldom clear. As a result, there has been a disproportionate emphasis on capital costs of infrastructure with little discussion of costs related to operation and maintenance. In recent years, some have even questioned the methods employed to compute capital costs and have argued forcefully to take a longer term view of the life cycle of infrastructure projects to ascertain the possible revenue streams that may be possible to finance infrastructure operation and maintenance.
5. *Efficiency versus equity*: The emphasis on infrastructure construction led to a focus on utility and system efficiency. The subsequent interest in community-based natural resources management led to an interest in issues such as equity in benefit distribution along lines of gender, age or ethnicity. In the case of water, for example, both approaches generated their own set of metrics and methods ranging from measurements of Non-revenue/Unaccounted for Water to perspectives on multiple uses of water services. While non-revenue water and monitoring of physical systems emphasized quantitative data and measurements, multiple use perspectives often highlighted qualitative data and participatory data collection techniques.

3.1 The Nexus: Overarching Research Questions on Governance and Institutional Structures

Based on the above discussion, we can identify three broad overarching questions that can guide thinking on institutional arrangements and governance structures that advance the nexus approach to management of environmental resources: water, waste and soil.

(a) **The question of intersectionality:** What are the critical mass of factors at the intersection of material fluxes, public financing and heterogeneity and changes in institutional and biophysical environment that can define the scope and relevance of the nexus approach to environmental management? (b) **The question of interactionality:** How are feedback loops structured to capture both vertical and horizontal interactions between (1) legal and policy reform, (2) structural changes in economy and society and (3) variability in the biophysical environment? (c) **The question of hybridity:** What role can trans-disciplinary approaches play in building capacity through support for innovative planning instruments and monitoring and assessment methods, advances in pedagogic and didactic techniques, formative and summative assessments and accreditation and certification of blended learning curriculum for achievement of nexus competencies?

4 Science-Policy Interface and Integrated Management of Water, Waste and Soil Resources

The ongoing debate on IWRM that was spurred by a presentation by IWMI has challenged many development practitioners to re-think paradigms of sustainable development and integrated resources management. Similarly, in development circles there are policy questions with regard to the usefulness of large-scale underground drainage systems compared to condominial sewers for decentralized waste management. In the area of solid waste management there are policy challenges related to the need to balance requirements for waste incineration plants and landfills with the fact that the local economy in many developing countries benefit in terms of employment from informal waste collection and disposal. In the area of soil management there are important trade-offs that decision-makers have to make based on the impact that improved techniques can have on soil run-off while at the same time considering the benefits that sediment transport offers over time for populations further downstream of large water catchments. How large the impacts of soil erosion are at plot, farm or watershed scales requires good scientific understanding. Three basic principles can guide the process of developing management options that respond to the challenges posed by soil degradation and decline in soil quality (Lal 2013): (1) replace what is removed, (2) respond to what is changed and (3) predict what will happen from anthropogenic and natural perturbations. Following these basic principles helps to develop site- and region-specific management options. Further, good science is also required to distinguish between findings at varying scales and their generalizability in terms of policy advice in a regional context. With respect to monitoring of groundwater levels and quality, there is an acute need for better scientific understanding of aquifer characteristics and their behaviour in the event of special stresses such as changes in temperature and rainfall or human induced economic activity such as large-scale mining operations. From a governance perspective, good science is required to understand the comparative benefits of employing centralized versus decentralized technologies and public versus private management models for infrastructure construction and Operation and Maintenance (O&M). Furthermore, there is an established need to inform and convince decision-makers of equity effects (disaggregated by gender, age or ethnicity) of the impact that scientific experiments to reverse soil erosion, water scarcity and water quality will have on local populations.

4.1 Data Gaps Identified by the Bonn Conference

The Bonn conference held in November 2011 pointed out ‘integrated planning across the nexus, involving also city and spatial planning, environmental protection and forestry, can unlock significant efficiency gains’. The subsequent Rio+20 Conference emphasized the importance of adopting a nexus approach to land, water and waste management. The background paper prepared for the Bonn conference reviewed a number of case studies to conclude that while there are no blueprints or panaceas there are some underlying principles that can guide implementation of the nexus approach (Hoff 2011). For instance, cross-sectoral management can minimize trade-offs, build synergies and increase resource use efficiency. In particular, in multi-use systems, wastes, residues and by-products can be turned into a resource for other products and services and co-benefits can be produced. Productive sanitation in combination with wastewater reuse is an example of recycling and closing loops of water, nutrients and other resources. Other examples include multifunctional and green agriculture, natural or constructed wetlands, agro-forestry, crop-livestock systems, land rehabilitation with biofuel crops such as jatropha, and wastewater-energy integration. Reusing waste products instead of discharging them into the environment can also reduce clean-up costs. The background paper prepared in the run-up to the Bonn Conference highlighted the following knowledge gaps of relevance to the work programme of UNU-FLORES (Kurian and Ardakanian 2014).

1. There is a lack of consistent and agreed upon water quality standards for different crops and production systems, which would standardize and promote wastewater reuse and hence increase water use efficiency.
2. More data are needed on sustainably available water resources, in particular on safe aquifer yields and for so-called ‘economically water scarce’ regions, such as sub-Saharan Africa.
3. There are scarce data on consumptive water use in the energy sector, compared to withdrawal data.
4. The effects of increasing energy or water scarcity on food and water or energy security, as well as potential synergies between land, water and energy management, are not well understood. Questions include to what extent can higher availability of one resource sustainably reduce scarcity of another, and how might this work at different spatial scales?
5. New nexus indicators/metrics, which address sustainable resource use, human well-being and equity as well as integrated assessments of water, energy and food sectors, are required for future quantitative trade-off analyses. System thinking, robust analytical tools, including life cycle analysis and consistent data

sets across the water, energy and food sectors are essential for building synergies, avoiding tensions, and to monitor and inform policies and regulations across the nexus.

4.2 Key Questions Posed by the International Kick-off Workshop, November 11–12, Dresden

1. What are the advantages of a centralized versus a decentralized approach to implementation of integrated management approaches?
2. Which institutional structures and mechanisms have proven helpful for implementing integrated and cross-sectoral management strategies?
3. How effective are inter-institutional/ministerial/organizational mechanisms in implementing integrative approaches?
4. Are these structures and mechanisms similar or what are the differences at various scales (from local to global) and in various regions?
5. Which type of economic incentives will be required/helpful to foster nexus approaches?
6. Is there/what is a common approach to institutional capacity development?

5 Key Research Questions of Relevance to Capacity Development

5.1 Why Does Good Science not Always Equate with Good Policy?

Efficiency metrics can rely on quantitative analysis of large data sets while equity metrics demand greater engagement with qualitative perspectives to support and validate arguments. An important point that needs to be made here is that environmental decision-making involves *trade-offs* at multiple scales (across space, vertically and horizontally, and over time). Some of the most important trade-offs are not guided by the supremacy of quantitative data sets alone. Where the stakes are not as high, rigorous data analysis may help clinch the argument. However, in situations where the stakes are extremely high the trade-offs made can be influenced by political rather than statistical significance. One opportunity is to focus on identifying data gaps and devising methodologies for data collection that combine quantitative and qualitative perspectives with the potential to influence decision-making at strategic nodes of the governance framework.

5.2 Why Does Statistical Significance not Always Equate with What Is Politically Expedient?

Once data have been collected, one needs to be creative about analysis. The emphasis could be on identifying messages and strategies for engagement and presentation that enable us to use evidence to influence decision-making. The focus should be on identifying and conveying information that is politically nuanced and where required backed up with rigorous data analysis. Information is key and data and data analysis is a means to help us define the message for decision-makers who in many situations have to make political choices. For example, what strategies can we employ to highlight the public health impacts of inadequate water and waste management? What strategies can we employ to engage with decision-makers at multiple levels (catchment- regional, watershed-district, village-farm, household-plot) on choices related to allocation of financial resources, soil conservation practices or water/waste management strategies?

5.3 Institutional Arrangements and Governance Structures: Preliminary Hypothesis

Based on the examination of trends relating to evolution of the nexus concept and subsequent discussions held as part of the international kick-off workshop in Dresden, the following hypotheses have been identified, They can serve to guide UNU-FLORES in articulating key elements of a research and education programme that advances the nexus approach to management of water, soil and waste resources (Kurian and Ardakanian 2014).

1. Management of water, waste and soil resources could be guided by principles of efficiency, equity and environmental sustainability.
2. The nexus approach to management of environmental resources will be advanced by employing approaches, strategies and methodologies that pursue the effective management of trade-offs, promotion of synergies and identification of opportunities for resource optimisation.
3. The nexus approach can enhance the possibility of integrated management of environmental resources by identifying through trial and error factors that influence governance of water, soil and waste resources that lie at the intersection of: (a) spatial dynamics of material fluxes, (b) socio-ecological differences in resource use and (c) rules that guide allocation of public finances.
4. The nexus approach to management of water, waste and soil resources is premised on the fact that there are no blueprint solutions to complex socio-ecological challenges. Instead, solutions have to be crafted at the appropriate scale: IWRM, decentralization and participation may prove to be selectively useful strategies in different environmental and socio-political contexts.

5. IWRM may necessitate working at different spatial scales and a basin may present itself as one of several possible options as an appropriate unit of analysis for water, soil and waste resources.
6. Decentralization necessitates engaging with issues of accountability in allocations of financial and human resources within the public sector, notably intergovernmental fiscal transfers to agriculture, water and public health departments.
7. Participation necessitates engaging with consumers to ascertain their views on reliability, affordability and adequacy of environmental services; for example by ascertaining the cost of infrastructure investments in fields of water, waste and soil management.
8. Results-based financing has proven useful in enhancing accountability of public sector decision-making with regard to social infrastructure (schools and health).
9. Economic incentives such as budget support, cash conditional transfers, cash on demand and output-based aid will result in improvements in service delivery outcomes.
10. The development of capacity for trans-disciplinary approaches to planning and environmental management may enhance prospects for successful design, implementation and evaluation of results-based financing strategies in development programmes and projects.

5.4 The Logic and Structure of This Volume

This volume is focused on elaborating upon key themes of the nexus approach to management of environmental resources—water, soil and waste. The book is based on papers and discussions surrounding the international kick-off workshop of the UNU-FLORES institute that was held in Dresden, Germany in November, 2013. The antecedents of the current interest in the nexus approach can be traced back to a workshop held in 1986 in New Delhi, the focus of which was on the nexus of water, energy and food. This book places that discussion in the context of current challenges surrounding global change: demographic change, urbanization and climate change.

Governance approaches and perspectives have received very little attention in relation to the nexus of water, energy and food or the nexus of water, soil and waste. This is a serious shortcoming that this volume attempts to address by providing a framework for discussion of key science-policy challenges confronting decision-makers globally. From an institutional point of view the nexus approach to environmental governance can be examined from the perspective of: (a) Global change and nexus approach to environmental governance, (b) Financing of infrastructure projects and (c) Strategies for implementation.

Chapters 1, 2 and 3 will address issues of global change and the nexus approach to environmental governance. Concepts of P-E nexus, adaptive management, intersectionality, interactionality and hybridity will be discussed in outlining the challenges of implementing the nexus approach to management of environmental resources—water, soil and waste. Chapters 4, 5 and 6 will elaborate upon issues relating to financing of infrastructure projects. Questions of accountability and autonomy will be discussed in the context of discourses of decentralization and deregulation. Concepts relating to central transfers, taxes and tariffs and potential applications of results-based financing approaches in supporting sustainable service delivery will be examined. Chapters 7, 8 and 9 will discuss strategies for implementation by focusing on European experience with application of life-cycle cost analysis in water and wastewater projects, use of an agroecology framework to support wastewater reuse in agriculture and applications of data visualization techniques for evidence-based decision-making.

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Chapter 2
The Water-Energy-Food Nexus: Enhancing Adaptive Capacity to Complex Global Challenges

Christopher A. Scott, Mathew Kurian and James L. Wescoat Jr.

1 Introduction: Global Change, Grand Challenges

Multiple intersecting factors place pressure on planetary systems on which society and ecosystems depend. Climate change and variability, resource use patterns, globalization viewed in terms of economic enterprise and environmental change, poverty and inequitable access to social services, as well as the international development enterprise itself, have led to a rethinking of development that solely addresses economic growth. Fulfilling the essential human aspirations for quality of life, meaningful education, productive and rewarding work, harmonious relations, and sustainable natural resource use requires ingenuity, foresight and adaptability. Societal and environmental conditions are changing rapidly in ways that increase uncertainty for decision-making over a range of scales. The intimate links between social and ecological processes are strengthened (made more fundamental than perhaps previously believed) in the age of profound human manipulation of planetary processes characterized as the Anthropocene (Steffen et al. 2011). The shift in global thinking towards sustainable futures is underscored by the global community subscribing to the Sustainable Development Goals (SDGs), which in 2015 will supplant

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the more target-oriented Millennium Development Goals (MDGs) (Sachs 2012). We are confronted by a series of challenges to the resilience of the global social-ecological system. At the same time, we are developing and refining an expanding array of capabilities to understand and influence the complex dynamics of coupled systems. This places society at a crossroads: Follow the past decades' path of resource exploitation and social inequality, or usher in a new world order premised on planetary resilience (Rockström et al. 2009; National Research Council 1999).

A global transition of such sweeping importance has been extremely difficult to initiate for reasons of path dependence in political systems; economic models that permit accumulation at the expense of depletion; degradation and dispossession (largely outside the remit of regulation); and the precarious condition of ecosystems in a range of contexts globally that provide fewer and more riskier survival options for billions of the world's poor, thus allowing little flexibility to innovate and adapt. Yet the transition has begun, founded on a series of understandings that are rooted in holistic systems thinking, driven by new conceptions and lifestyle choices of a growing number of the world's youth fatigued by status quo arrangements, and crucially, aided by an emerging set of tools that permit citizens, community groups, organizations and policymakers to actuate adaptive responses to the drivers of global change. Among these tools are integrated approaches to resource use that emphasize longer-term social and ecological sustainability while offering operational means to internalize externalities, foresee and mitigate unintended consequences, and above all, strengthen resilience through outcome-oriented open learning and institutional change. This is a tall order, and while specific transition pathways that often emerge gradually must be seized rapidly, the conceptual development and tools application processes have benefitted from a decade or more of innovation and experimentation.

Enter the 'nexus' of multiple resources, linked in turn to management and policy frameworks, and embedded in broader political processes. The nexus conceptually links multiple resource-use practices and serves paradigmatically to understand interrelations among such practices that were previously considered in isolation. Here we will demonstrate that resource recovery is at the core of operationalizing the nexus. This is fundamentally different from efficiency and productivity, although nexus practices can be seen in terms of deriving increased output from limited resources.

1.1 The Nexus Approach: The Antecedents

It is instructive here to provide a historical review of the resource nexus. When, where and how did it emerge? Who supports and who opposes nexus frameworks and for what reasons? Indeed, how are multiple nexus[1] construed, interlinked or

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[1] Etymologically and linguistically, nexus is both the singular and the plural form.

divergent? What implications do the past decades of conceptual development around the 'nexus approach' have for future resource use paradigms? How can the nexus be used to address global-change challenges?

Early references in the published literature to the term 'nexus' as cited in Google Scholar arise in philosophy to refer to overlapping experience and physical objects (Whitehead 1929), in the institutional literature to trace contractual relationships among multiple, tiered firms (Wigmore 1943), in cell biology to describe complex electro-chemical interlinkages required for organ and tissue function (Dewey and Barr 1962), in economics to characterize mutual dependencies of wages, prices and labour productivity (Bodkin 1962), and subsequently in numerous additional disciplines. With specific reference to interlinked natural resource use practices, nexus terminology appears to have begun in 1983 with the Food-Energy Nexus Programme of the United Nations University (UNU), which sought to better understand coupled food and energy challenges in developing countries paying particular attention to technical and policy solutions (Sachs and Silk 1990). Food and energy as crucial determinants of development (Batliwala 1982) were considered in their broader environmental context; thus, at least two international conferences were organized to develop and illustrate further the interlinkages among food (agriculture, nutrition), energy (biomass, post-harvest residues, animal traction, fuel, electricity) and ecosystems (land, forests, water). The first of these conferences on Food, Energy, and Ecosystems, was held in Brasilia, Brazil in 1984 (Alam 1988). The Second International Symposium on the Food-Energy Nexus and Ecosystems was held in New Delhi, India, February 12–14, 1986 (Parikh 1986). Modelling approaches to address the food-energy nexus were also developed and published for the UNU (Pimentel 1985).

In parallel fashion and approximately concurrently in the mid-1980s, but apparently dissociated from the UNU-initiated programmes in developing countries, there was emerging recognition in the Western United States of the implicit water-resource dimension of the nexus between energy (hydropower, thermoelectric generation) and agriculture (food production, groundwater pumping). Solomon (1987) identified land and water constraints to electrical power generation, while Durant and Holmes (1985) recognized that water management in the Western U.S. would increasingly have to account for energy and environmental needs for water, in addition to the prevailing agricultural-irrigation and urban-industrial demands. Although Ingram et al. (1984) did not undertake detailed analysis of resource coupling that we currently understand as the basic plane of the nexus, their analysis presented in *Water Resources Research,* intended to reach both technical and managerial audiences, was prescient of the institutional dimensions of water resource management in the Western U.S. Gleick (1994) provided an important overview of water and energy linkages.

Explicit reference to the 'water-energy nexus' so prevalent today appears to have begun in the mid-to-late 1990s and early 2000s. Thus, Sant and Dixit (1996) addressed energy supply for groundwater pumping as part of a Water-Energy Nexus project funded by International Energy Initiatives (in Bangalore, India), while Padmanaban and Sarkar (2001) and Malik (2002) identified the groundwater-electricity nexus analytical and policy approach, which was developed and consolidated in India by Shah et al. (2003, 2007a, b), who emphasized the need for knowledge transfer between the farming and electricity sectors, and by Kumar (2005). The electricity-for-water nexus was applied to Jordan by Scott et al. (2003) and extended to Mexico by Scott and Shah (2004) and Scott et al. (2004a, b) with particular attention to policy and legal dimensions that expanded the physical-resource conception of the nexus.

Simultaneously, but once again in relative isolation from groundwater-electricity linkages, the converse resource dependence of water demands for energy generation were emerging under the nexus banner in the Western U.S. (Lofman et al. 2002; Government Accountability Office 2009; Sovacool and Sovacool 2009 to cite a few), promoted by Sandia National Laboratory (Hightower and Pierce 2008), universities in water-scarce states (Scott and Pasqualetti 2010; Kenney and Wilkinson 2011), the Electric Power Research Institute (2002), Natural Resources Defense Council and Pacific Institute (Wolff et al. 2004), the Stockholm Environment Institute (Fisher and Ackerman 2011), and others (Griffiths-Sattenspiel and Wilson 2009; Carter 2010). Similar studies were also published in Europe (Bailey 2011; Floerke et al. 2011; Hardy et al. 2012) and for the Middle East (Siddiqi and Anadon 2011). Later studies cited here increasingly recognized bidirectional water-energy nexus links, accounting for the energy needed to produce energy as well as the energy requirements of water management.

1.2 Emergence of the Water-Energy-Food Nexus

Use of any two terms suggests specific subsectors or issues, while three inter-linkages are considerably more multivalent. For example, the water and energy linkage may suggest hydropower, power plant cooling or groundwater pumping. The water and food linkage usually evokes irrigation and perhaps rainwater harvesting. The energy and food linkage most commonly raises concerns about biofuels versus crops trade-offs. However, the three sectors considered jointly include and transcend these specific sectoral linkages. They imply integrated, almost comprehensive, natural resource systems.

However, formal published recognition of the three-way mutual interactions among water, energy and food; branded as the WEF Nexus that is of principal concern in this chapter did not appear until 2008 (Hellegers et al. 2008; Siegfried et al. 2008). Again, the WEF Nexus had a significant focus on India, in part because the Hellegers et al. piece emanated from a workshop held in 2006 in Hyderabad, India, which itself built on groundwater irrigation (electricity nexus work cited above). This was followed in short order by Lopez-Gunn (2009) placing the WEF Nexus in an adaptation context, Lazarus (2010), Hoff (2011) as further elaborated below, Scott (2011) with emphasis on climate change drivers, Wescoat and

Halvorson (2012), Bogardi et al. (2012), Granit et al. (2013), and Siddiqi and Wescoat (2013) to cite a few of the burgeoning set of publications on the WEF Nexus. In parallel fashion, and again approximately co-terminously with research developments in the mid-2000s, institutional support for the WEF Nexus gained significant momentum via the Bonn Freshwater Conference, the Bonn 2011 Nexus Conference, the Stockholm World Water Week, the United Nations Economic Commission for Europe, and the now well established Water, Energy, and Food Security Nexus Resource Platform Nexus.[2]

A series of broader international initiatives to develop a coherent and comprehensive analytical framework for WEF Nexus, particularly as related to sustainable development, have emerged. This includes 'The Nexus between Energy, Food, Land Use, and Water: Application of a Multi-Scale Integrated Approach',[3] which applies the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to case studies such as sugarcane biofuel in Mauritius, groundwater irrigation in Punjab, India, and alternative electrical generation in South Africa. The metabolism approach of MuSIASEM represents a social-ecological system of understanding linked to resource use (Madrid et al. 2013).

The November 16–18, 2011 'Water, Energy and Food Security Nexus—Solutions for the Green Economy' Bonn 2011 conference, in particular, provided an institutional platform and continuity to WEF Nexus initiatives. Follow up to Bonn 2011 includes a series of regional dialogues, private-sector participation including a focus on infrastructure and investment, practical tools (analytical models, best practices, etc.), and knowledge-based assessments of the nexus. These contributed to the Rio 2012 United Nations Conference on Sustainable Development and a subsequent series of international meetings focusing on the nexus, including those held in Stockholm and Dresden. UNU-FLORES in Dresden was established to advance the nexus approach to integrated management of environmental resources: water, waste and soil (UNU-FLORES 2013). UNU-FLORES will extend and upscale the nexus concept through adopting an integrative framework by considering inter-related resources (water, soil, waste) and emphasizing fluxes of resources between phases and compartments (Lall 2013). Given the limitations of the conventional technology-transfer model, it is acknowledged that capacity development approaches that aim to facilitate technology adaptation offer a better chance of achieving integrated management of environmental resources. Continued institutional development for the nexus includes the 2014 World Water Week in Stockholm on the theme, 'Water and Energy—Making the Link,' and the UNU-FLORES 2015 Nexus Conference.

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[2] See http://www.water-energy-food.org/ for more information.

[3] UN Food and Agriculture Organisation—FAO with support from the Deutsche Gesellschaft für Internationale Zusammenarbeit—GIZ. See also http://nexus-assessment.info/ for more information.

1.3 Characterizing the WEF Nexus

The central role played by water and energy resource use and governance in assuring food sufficiency and security required, even forced, the systematic synthesis of siloed resource management regimes. Yet this is not synthesis for its own sake, a question of intellectual or conceptual elegance. The nexus approach requires that interrelating factors be brought together, those that previously had been considered separated, indeed even isolated. As we will demonstrate, the nexus is fundamentally about resource recovery, closing the loop and capturing true efficiency gains instead of simply displacing or masking increased resource use (Lankford 2013; Scott et al. 2014). Understanding and acting upon this core of the nexus is central to diminishing the human footprint on planetary boundaries. Thus, resource recovery is the fundamental biophysical expression of the nexus approach.

Figure 1 indicates the interlinkages of water, energy and food on three planes: biophysical resources, institutions and security. Linkages between any two of the

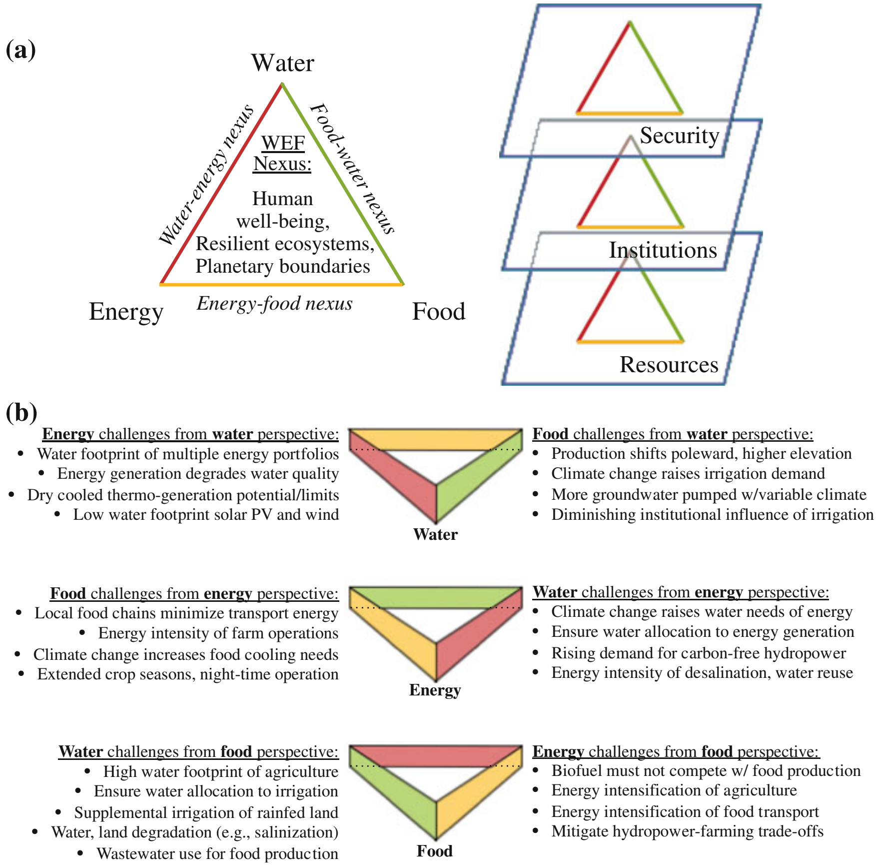

Fig. 1 **a** Water-energy-food nexus interlinkages at multiple levels. **b** Water-energy-food nexus tri-opticon challenge perspectives

nodes are expressed as the water-energy nexus, the food-water nexus, etc. The nexus is simultaneously about resource recovery through efficiency improvements and the recovery of saved resources in the process of efficiency conversions.

Below, we will demonstrate, via a series of thought exercises, how use of the other two resources is viewed from the position of each node of the nexus (see Fig. 1a, b). In other words, from a water resource perspective, how do food (production, distribution and security) and energy (generation, supply, dependence within the water sector) appear in terms of resource recovery and operational efficiency gains? In order to represent these challenges as seen from multiple nexus perspectives, in Fig. 1b we characterize processes and management distinctly from materials and resources.

2 Resource Use and Policy Integration

Integration of resource-use practices and comparative views across distinct disciplinary domains had gained traction before the mid-2000s advent of the WEF Nexus. Early thinking on irrigation management linked to integrated pest management (IPM) arose out of serious environmental and agronomic challenges presented by the Green Revolution in the 1960s and 1970s. But these were local, and occasionally regional, management problems even though globalization trends during that period raised evidence of their recurring nature. Systems thinking, integrated approaches and interdisciplinarity were making headway. Irrigation, for example, was in vogue as a socio-technical domain of study and practice. Natural resources in a watershed context were increasingly linked to food production, while water and food access was recognized to be strongly mediated by social and institutional dynamics, especially via diverse forms of collective action around common-pool resources (Kurian and Dietz 2012). This became a development imperative, a moral and ethical challenge. In line with the quality of life view that we espoused in the introductory paragraphs, above, there is heightening awareness of the ethical and moral dimensions of water, energy and food (López-Gunn et al. 2012).

Parallel trends in thinking were emerging for energy resources, in which end-users' behaviours and choices strongly influenced energy sufficiency and unleashed the development potential of economic opportunity and quality of life at local, regional, national and indeed global scales. Energy self-provisioning in many developing country settings was transitioning over to utility-based or cooperative forms of energy supply. The links of the energy sector with food production and supply were recognized and consolidated programmatically (e.g. via UNU initiatives cited above). But it was the same Green Revolution set of challenges necessitating coordination between irrigation and pest management that ultimately raised the need for water-energy-food linkages, which a generation later is expressed as the WEF Nexus. Thus, India with chronic water, energy and food insecurity undergirded by poverty and development challenges, was centre stage for emergence of the nexus concept. India also became, and in some respects remains, the hub of WEF experimentation due to innovation and polycentric governance (with an active and informed civil society constellation of NGOs and social movements, often in collaboration, occasionally in conflict with formal state institutions that themselves were not impervious to change and new ways of thinking).

Water for food production has required significant investments in infrastructure (dams, canals, conveyance systems) that, with the advent of pumping technology, has been developed to the detriment of landscapes re-plumbed as a result. Food production was not necessarily the ultimate imperative; it was also the settlement of lands as in the western United States, the domination of territory and subjugation of local populations as in British famine relief initiatives in colonial India. Much of this goes back to the Wittfogel hydraulic society hypothesis whereupon the ability to control water allowed for the control of food supply, population, settlements, society and the environment (for reviews, see Wescoat 2000; and Wescoat and Halvorson 2000).

Indeed in some cases, water requirements for energy production compete with water requirements for food production. Recently in the United States, the diversions of freshwater for electrical power plant cooling exceeded the diversions of fresh water for irrigation. Is energy the ‘wild card’ driving the WEF Nexus? Energy resource extraction has rising environmental and social costs, with commercial interests driving voracious resource extraction and depletion. The private sector feigns ‘ungovernability’; the allure of mobile and often fugitive foreign direct investment can lead to a blind eye on national and regional regulation of energy development. With its transportability and commodification, energy exhibits a fundamental contradistinction to water as an ‘uncooperative commodity’ (Bakker 2003); the capturability, resource-use exclusion and commodification dimensions of energy make it fundamentally different than water, which is increasingly subject to ethical claims of water as human right and water as public good.

2.1 Dynamics of the Water-Energy-Food Nexus

Over the course of a decade and a half working with the nexus in South Asia, the Americas and Europe, it has become evident to us that the term ‘nexus’ can have negative implications, as in various nexus manifestations involving crime (Mears 2001), corruption (Phy 2010), etc. In the Roman Republic, ‘nexus’ was a bond slave serving a ‘nexum’ debt bondage contract.[4] This belies the benign complexity that is intended by our use of the term and instead casts doubt by simplifying the nexus as subterfuge.

Furthermore, by placing the nexus in the resource security context, which we have done (Scott et al. 2013; Wescoat and Halvorson 2012) along with numerous

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[4] See http://en.wikipedia.org/wiki/Nexum for more information.

others (Bogardi et al. 2012), one is exposed to the military and intelligence situation-room conception of strategic resources to be protected through military force, espionage and the exercise of state power. This ‘guns, gates, and guards’ view is indeed the origin of the concept of security. International and transboundary initiatives for water management, for example, increasingly must avoid ‘security’, which nation states view in sovereignty terms, in relation to the United Nations Security Council (Varady and Scott 2013). Here, our intent is not to engage directly in debates over the securitization of resources (Zeitoun et al. 2013; Fischhendler and Katz 2012; Mollinga et al. 2012), but instead to relate the nexus to the more benign human and ecosystem dependence dimensions of resource security (e.g. Scott et al. 2013 for water security). Critical to enhancing water security is an improved understanding of complex socio-ecological systems, causes of declining resilience in such systems and the role that adaptive management can play in mitigating the effects of such trends.

Complex socio-ecological systems are evident at different levels: from a policy/legal perspective, complexity is evident in ‘rules in use’ that affect decisions relating to allocation of resources, coordination of financial and human resources and equity effects on human populations. Examples of allocation rules include formulas or criteria for allocation of water among different water uses like industry, agriculture and water supply. Coordination rules could include rules that guide allocation of central funds by regional departments/ministries or criteria for monitoring water quality standards for river systems. Examples of equity rules could include daily allocation norms for water supply between rural and urban areas or criteria for allocation of central grants for wealthy and resource poor regions/communities or households. Organizational rules are evident in formal rules in operation within public sector and extent of discretion that is allowed by administrative culture that characterizes the work of line departments and ministries.

Complex socio-ecological systems that successfully deal with ‘shocks’ in the policy, environmental or socio-economic realm are usually characterized by resilience. Some have argued forcefully that resilience is a measure of: (a) the amount of change the system can undergo and still retain the same control on functions and structure, (b) the degree to which the system is capable of self-organization and (c) the ability to build and increase the capacity for learning and adaptation (Resilience Alliance 2001). Resilience is an important property of a system because the loss of resilience moves a system closer to a threshold, threatening to flip it from one equilibrium state to another (Berkes 2002). Highly resilient systems can absorb stresses without undergoing a flip; they are capable of self-organization based on relationships of trust and have the ability to respond to unpredictable ‘events’ through approaches that place a premium on learning by doing and trial and error (Kurian and Dietz 2013).

The concept of resilience is based on the assumption that cyclical change is an essential characteristic of all social and ecological systems. For example, resource crises such as a forest fire are important for renewal of ecosystems in as much as demographic growth and educational opportunities can serve to renew communities. But such processes of renewal and change are seldom linear and predictable leading to uncertainty. Systems theory emphasizes that uncertainty can be addressed in part by understanding inter-dependence and inter-connectedness of social and bio-physical systems. Robust feedback loops between policy/programme interventions, structural changes within communities of resource users and bio-physical processes are key in regulating the effects of uncertainty (Berkes 2002; Scoones 1999). Systems that respond effectively to uncertainty are usually supported by flows of information on biophysical and institutional processes. Information flows are verifiable, disaggregated and more amenable to decision-making processes (Kurian and Turral 2010).

The notion of adaptive management can resonate with decision-makers in developed economies who are confronted with challenges of a loss of capacity to exploit a system's potential for novelty (examples include rigidly interconnected water and energy infrastructure), declining redundancy of critical components (e.g. sole-source dependence on groundwater for irrigation in water-scarce regions), and the risks of cascading failure arising from heightened connectivity (e.g. energy-dependence of urban water supply systems). On the other hand the concept of adaptive management in the context of developing and/or emerging economies can relate to building capacity for dispersed problem solving. The first generation debate on political decentralization furthered the idea of dispersed problem solving by emphasizing autonomy. The second-generation debate on fiscal decentralization should emphasize issues of political accountability (Kurian and McCarney 2010). The goal of adaptive management should not be limited to the highest biological or economic yield but on furthering our understanding of how accurately socio-ecological systems can predict 'uncertainty' by using feedback from management and institutional outcomes to shape policy and programme interventions at appropriate scales, thus contributing to enhanced autonomy and accountability in decision-making processes and structures (Kurian and Dietz 2013).

2.2 Governance Challenges for the WEF Nexus

Environmental governance in developing and emerging economies suffers from fragmented approaches to planning and policy implementation. Fragmented approaches arise from competition among urban and rural local governments for central fiscal transfers, overlapping jurisdictional boundaries and inadequate management coordination among line departments and ministries. In many instances fragmentary approaches are supported by a poor evidence base on the relationship between infrastructure construction and environmental outcomes. For example, absence of disaggregate, reliable and more frequent information at appropriate scales makes it difficult to predict the environmental outcomes of constructing dams, tube wells or storm drains in terms of sediment capture, aquifer recharge and wastewater reuse respectively. Institutional fragmentation is also supported by weak feedback loops between legal and policy formulation, spatial and temporal variation in biophysical environment and socio-economic change within communities of environmental resource users. As a result decision-makers cannot design programme and project interventions with precision and may be unable to respond effectively to feedback from consumers on changes in service delivery parameters (affordability, reliability or quality) or to the effects of increased variability in frequency, intensity and duration of environmental shocks (droughts or floods).

2.3 Expanding the Conventional WEF Nexus: An Institutional Perspective

In the context of developing and emerging economies, an institutional perspective on the WEF Nexus would encompass three broad questions: (a) Intersectionality: what are the critical mass factors at the intersection of material fluxes, public financing and changes in institutional and biophysical environments that can define the scope and relevance of the nexus approach to environmental management? (b) Interactionality: how can feedback loops be structured to capture both vertical and horizontal linkages among (i) legal and policy reform, (ii) structural changes in economy and society and (iii) variability in the biophysical environment? (c) Hybridity: what role can trans-disciplinary approaches play in building capacity through support for innovative planning instruments and monitoring and assessment methods, advances in pedagogic and didactic techniques, formative and summative assessments and accreditation and certification of blended learning curricula that support the achievement of nexus competency.

There are at least three ways to examine institutional dimensions of the WEF Nexus. One important method starts with institutional ‘levels’ of analysis (sometimes mislabelled as ‘scales’), beginning at the smallest household level and increasing to the community, municipal, substate regional, state, interstate, macroregional, national, binational and multinational levels. As each level often has a different legislation, organizations and guiding rules for resource management in the water, energy and food sectors, it is valuable for analytical as well as descriptive purposes to identify the relevant levels and examine how they interact within and across sectors.

If the first perspective analyses institutional structures, a second perspective can focus on institutional functions. The roles of public institutions for resource management, for example, span the range of state functions (e.g. Clark and Dear 1984). These include fostering social consensus, enabling increased economic production, promoting social integration through education and ritual activities, and administrating laws and regulations justly. Insofar as these public institutions promote economic production, they converge with some of the functions of private institutions; while insofar as they promote social consensus and integration, they converge with some of the functions of non-governmental institutions. Ostrom (1990) elaborates and instrumentalizes these structural and functional relationships of resource management institutions in her ‘institutional design principles’ for common property resource management.

Ostrom's research also points toward the rich human breadth and depth of resource management institutions in the water-energy-food nexus; which invites consideration of a third perspective on institutions in relation to human wants and needs. These are often articulated in sectoral assessments of emergent resource problems and solutions, for which existing institutions are generally inadequate. Examples include the Millennium Development Goals, Kyoto Protocol, Hyogo Convention on disaster risk reduction, etc. These often address the lower half of the pyramid of the oft-cited hierarchy of human physiological and safety needs (Maslow 1943). However, it is worth considering that many of these problems originate from, and are sometimes addressed by, the purportedly higher needs of esteem and self-actualization. While simple hierarchies and dynamics of nexus institutions appear logical, they are in practice more heterogeneous and complex over space, time and cultural context.

3 Trade-off Between Efficiency and Effectiveness: Illustrative Cases

3.1 Water for Energy: Carbon and Nuclear Legacies and the Transition to Renewables

The breathtakingly rapid post-World War II expansion of the world economy would not have been possible without the development and harnessing of fossil fuels (including coal, petroleum and natural gas, as well as non-renewable nuclear fuels, which impose many of the same environmental and social 'legacy' impacts as carbon-based fuels). The widespread quality-of-life benefits of conventional energy development have come at staggeringly high costs to the environment, especially climate change driven by carbon emissions. Additionally, social transformation and ecological devastation have been spatially displaced from consumption. For example, cheap fuel at filling stations worldwide but chiefly in high-demand developed countries like the U.S. has wrought war and irreversible pollution in the Niger Delta. This is far more than 'collateral damage'. Furthermore, the impacts of current consumption are temporally deferred, including the intergenerational effects of atmospheric carbon and social-environmental devastation, as cited in the two examples above, but also the technological, financial and political difficulties inherent in reversing decades of lock-in to fossil-fuel energy dependence. But reverse we must, and the transition is underway, in countries like Germany where solar and other renewables account for a growing share of energy portfolios and where, for the first time, there is a serious and sustained national dialogue on alternative energy futures. For example, what are the energy supply, technology development and financial models to support the transition? What are the respective roles of civil society and the state? The path is not without hazards; in the U.S., for example, natural gas development through non-conventional (but now increasingly conventional) fracking has reasserted the grip of petroleum giants and lowered gas costs to such an extent that, in just a few years, nascent initiatives to transition to renewables have been undone or set back.

The water and food dimensions of renewable energy futures will require improved technology, management and policy in order to diminish the energy intensity and dependence of the water and agricultural sectors. Localized forms of production, low-impact agricultural practices, surface- and gravity-irrigation including through rainwater harvesting, all offer important potentials.

3.2 The Large Dams Debate: Irrigation, Hydropower and Environment

Large dams constitute one of the largest, and most contested, movements of twentieth century water management (World Commission on Dams 2000). Some issues date to antiquity, physical and cultural traces of which still survive at the Marib Dam originally built in eighth century BCE, and failed for the last time in sixth century CE. The Qur'an (34:15–16) refers to the failure of this dam as a 'sign' for those to see what happens to the arrogant, sinful and unfaithful.

Debates in the mid-twentieth century were different, though they sometimes involved hubris. On the one hand, were those who felt dams should serve a single primary purpose, such as flood control storage, to avoid trade-offs among competing aims that could jeopardize public safety (White 1957). There were advocates for numerous small structures and watershed management versus advocates for a smaller number of massive dams and levees in a river channel engineering framework (Leopold and Maddock 1954).

A major shift in the mid- twentieth century saw the move from single objective-single means to multiple objective-multiple means water management (White 1957). Multipurpose storage was deemed a major component of integrated river basin development. After a massive wave of both patterns of development, their environmental and social impacts, and consequent overestimating of net economic benefits became increasingly evident (www.IRC.nl website 2013). Opposition to large dams grew internationally, albeit with passionate resistance from countries like Brazil, India and China. To address these controversies a World Commission on Dams was established that commissioned scores of reports and yielded a summary report that established best practices for future dams. Although on one level it was a remarkable achievement in international negotiation, it was criticized by dam building countries and organizations for its constraints on implementation.

Ten years later, a major set of essays reflected upon the legacy of the WCD report (Water Alternatives 2011). The World Bank and other multilateral lenders moved away from multipurpose storage projects. Some nations proceeded on their own. China completed the Three Gorges Dam, India, the Narmada Dam and irrigation scheme, Turkey, the GAP project, and so on. However, as regional energy demand escalated, aggravating regional power outages, a 'race to the top' was renewed in the Himalayan, Andean and Southeast Asian regions. In this wave of projects, estimated hydropower benefits outweighed irrigation, leading to debates once again about run of river versus multipurpose storage projects (Siddiqi and Wescoat 2013). The International Hydropower Association is currently developing a streamlined assessment project.

3.3 The Groundwater Irrigation Power Nexus

One of the reasons for continuing emphasis on surface water storage projects arguably stemmed from the almost worldwide failure in modern times to manage groundwater resources. From antiquity, shallow groundwater lifts were likely the most pervasive means of domestic water and local food supply. This was certainly the case in semi-arid plains environments prior to large-scale colonial canal irrigation. Canal irrigation employed gravity flow and in some cases generated hydropower for milling and transportation. A monumental example of successful gravity-fed groundwater development involved qanats (aka qarez, foggara, aflaj) emanating from Persia and found from the Americas to China.[5] They involved intensive control of piedmont groundwater aquifers, tapped by drilling 'mother wells', avoiding well interference, managing time-based water shares, as well as maintaining subterranean channels over the course of centuries.

Groundwater pumping technologies changed these early patterns of groundwater dramatically from the 1950s onwards with the development of increasingly deep pumping technologies. Cities drew upon water supplies with more consistent temperature and water quality conditions. But it was groundwater pumping for irrigation with tubewell and centre pivot irrigation systems that vastly increased irrigated areas including those with variable terrain (Green 1981).

Groundwater appealed to farmers for their more precise individual control over the timing and quantities of irrigation supply. Naturally, some farmers could afford individual pump sets while others could not, which gave the former additional markets, generally monopolistic, over their less prosperous and more dependent neighbours. Other farmers joined together to co-purchase movable pump sets, while still others set themselves up in the business of pump rental services.

As groundwater pumping expanded, so too did food production, but at a cost and in unsustainable patterns. Well interference was an early concern. In places where it was obvious which well dewatered its neighbour, it became a source of litigation, remedy and progressive development of groundwater law. In other areas, groundwater drilling cut through saline aquifers that leaked into fresh ones, diminishing crop yields. In other areas groundwater injection contaminated supplies for domestic and irrigation use.

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[5] For more information see http://en.wikipedia.org/wiki/Qanat.

More problematic at a regional scale were water level declines ascribable to all wells rather than some, and for which the initial remedy was deeper drilling or boring. This triggered the energy dimension of the water-energy-food nexus, as it became apparent that depletion may ultimately take land out of production more due to increased pumping costs than to absolute scarcity. Some governments, notably states such as Punjab in western India addressed this by subsidizing or providing free electricity for irrigated farms, which only accelerated depletion, and which few politicians have had the courage to reverse. The adjacent Punjab province in Pakistan provides a valuable comparison, as it does not receive as large an electricity subsidy or have as reliable an electric power supply, it has relied on diesel pumping (Siddiqi and Wescoat 2013). This has reduced water level declines and helped sustain groundwater management. The ‘third Punjab’ in central California faces similar problems, particularly so in the grips of severe drought in 2014, the consequences of which include dramatic areas of land subsidence, which necessitate drainage and pumping and thus further increased energy costs.

These groundwater market failures are symptomatic of broader water-energy-food nexus failures. Whereas surface water rights and uses were relatively easy to define, visually monitor and publically administer, groundwater development is highly dispersed, located on individual lands, difficult to measure, and seemingly impossible to administer. There is rarely a market in groundwater supplies, only in their costs, and even these markets are often distorted or absent. This situation is described in South Asia as ‘anarchic’ (Shah 2008), which may apply in many other if not most regions of the world.

3.4 Wastewater Reuse for Peri-Urban Agriculture

Approximately 20 million hectares worldwide is estimated to be under agriculture that relies on wastewater reuse (Rijsberman 2004). It has been argued that policy support for encouraging wastewater reuse for agriculture after adequate treatment would increase water use efficiency in agriculture. Some have even argued that when wastewater is managed better, significant economic benefits can be derived in developing countries through reuse for productive purposes like agriculture, kitchen gardens and poultry rearing (Kurian et al. 2013). Further, by encouraging freshwater swaps, wastewater reuse in agriculture could also potentially enhance source sustainability of water supplies, especially to urban centres. A study in India also found that effective wastewater reuse in agriculture had the potential to mine organic nitrogen, potassium and phosphorus and thereby reduce the country’s reliance on expensive imports of fertilizers. But one specific knowledge gap that prevents the realization of efficiency and productivity gains relates to a lack of consistent and agreed upon water quality standards for different crop and production systems. This knowledge gap constrains the development of standardized policy guidelines that could facilitate wastewater reuse.

3.5 Waste Remediation, Resource Recovery, Water Reuse

The term ‘waste’ and its underlying conceptual understanding represent the ultimate example of resource-impact externalization. This results as much from disciplinary and operational specialization as it does from practices on the ground, where indeed reuse and recovery of urban wastewater in this particular case are common despite official bans on the practice. We have described the transition from waste ‘disposal’ to ‘resource recovery’ in past work (Scott et al. 2004a, b; Drechsel et al. 2010); however, here we offer a targeted WEF Nexus view on water reuse and recycling. The most common use of treated or untreated effluent is agriculture in its broadest sense, taken to include irrigation of livestock fodder (for reasons of perennial flow, nutrients and human health-risk aversion), as well as landscaping irrigation (in many developed country contexts). Treatment and redistribution of reclaimed water is highly energy intensive; for example, in Tucson, Arizona, planners and the public are transitioning toward aquifer storage and recovery (itself not without energy costs) due to financial, infrastructural and public-acceptance challenges of dual water-supply and ‘purple-pipe’ reclaimed water networks.

In the developing country context, agriculture and food production are central to water reuse schemes, and will remain so in the future due to water, nutrient and urban proximity imperatives. An excellent example is Bolivia, where UNU-FLORES and the University of Arizona are keen to engage with local researchers and stakeholders to systematically develop the technical guidelines and institutional norms for safe and productive schemes for water reuse in agriculture.

3.6 Renewable Energy: The Water-Land Nexus

Wastewater reuse has tremendous scope to advance the nexus through fostering opportunities for multiple uses of water. But although a huge potential exists for wastewater reuse in agriculture, its effectiveness as an adaptation pathway may depend on critical aspects of local farming practices, market conditions, crop varieties and implementation of cost-effective treatment measures that facilitate wastewater reuse. For example a case study in India revealed that cultivating with wastewater may be less financially viable as compared to cultivating with well water. Further, when health risks for humans and livestock and returns on crops were considered, a number of interesting perspectives emerged (Kurian et al. 2013). First, because of better nutrient value of wastewater, farmers do not apply fertilizer. Further, due to assured availability of wastewater, farmers can grow two crops. On the other hand, farmers spend more on pesticides due to high incidence of pests (whitefly and jassid) under well irrigation. Wastewater reuse for agriculture is sensitive to soil and crop type; in our study area only paddy could be grown using domestic wastewater. Crops grown using wastewater sell for less in local markets compared to crops grown using well water. The study also found that better wastewater management had the potential to increase returns of wastewater agriculture by up to six times because of double cropping and lower expenses incurred on fertilizers. Depending on the location of individual plots, farmers also potentially stood to benefit from higher crop yields because of lower risk of flood damage and pest attack.

3.7 Biofuels and Food Trade-offs or Complementarities

Although increasingly evoked as a new problem, trade-offs between biofuel and food production are once again an issue with ancient origins. Consider the situation of villages that deforest watershed hillslopes for fuel, at the expense of agricultural land productivity downslope. Likewise, water-food trade-offs include land cover change through hillslope grazing that aggravates watershed sedimentation, erosion and flooding. A third trade-off occurs in the decision of how much fodder versus food crops to supply, at both farm and larger agro-ecological scales. Fodder is a food and fuel for animal nutrition. Animal draft power (energy) has declined in most regions, as has reliance on animal dung for fuel versus manure. Fodder for dairy production (the 'white revolution') is increasing, and is more demanding than simple grazing.

Perhaps the greatest source of current concern, however, has arisen from the late twentieth century shift in water and cropping to supply biofuels production, mainly through maize for ethanol production (Berndes 2002). National Research Council (2007) cited water quality problems (increased nitrogen runoff), as well as consumptive use of water for biofuels rather than food and fodder production. It also cited the economic inefficiencies of biofuels production subsidies, and the potential social impacts of higher food prices. The vision of decreased water demands, non-food crops for cellulosic ethanol production, such as switchgrass, have not proven commercially viable on a large scale to date (National Research Council 2011). These concerns, and tensions among the water, energy and food sectors are yielding a new politics in which multinational food and beverage corporations are coming out in opposition to using any water for biofuel production. Some of the same companies, sometimes accused of human rights violations when they impinge on common property water resources or push for privatization and market pricing of water supplies, are advocating for a human right to water for basic domestic needs, realizing that it does not impinge upon gross industrial water demand.[6] This position does not extend to a human right to water for basic food needs, however, as that would constitute a significant volume of consumptive water use.

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[6] See World Economic Forum 2011, Water Security: The water-energy-food-climate nexus.

3.8 Small-Scale, Appropriate Tech Approaches

Parastatal agencies such as irrigation and forest departments in developing countries have historically played an important role in creating physical assets (such as dams and trees) and arranging for their maintenance (Brookfield and Blaikie 1987). However, over the years there has been a realization that the public sector has failed to ensure cost-effective management due to rent seeking behaviour by public officials and resulting conflicts with local communities (Peluso 1992). Such trends have impaired mechanisms to monitor access to common pool resources such as forests and exacerbated problems of soil erosion. In recent years, public choice theory has successfully argued that community-based organizations can provide low-cost arenas for management of forest and soil resources (North 1995; Ostrom 1990). Scholars have pointed out that factors such as trust, density of social ties, shared norms and minimal recognition by governments of the rights of citizens to organize may significantly lower transaction costs of monitoring access to soil and forest resources. But studies on co-provision involving partnerships between government agencies and community need not always deliver predicted outcomes on account of simplistic assumptions guided by notions of linearity between human-environment interaction (Kurian and Dietz 2013). For one, low accountability involving infrastructure construction may prevent the establishment of a basis for community cooperation for management of environmental resources. Second, successful community cooperation need not always lead to predicted environmental outcomes on account of the influence of confounding variables such as slope and soil type. Third, for successful environmental outcomes at the level of watershed to be replicated at the basin scale would require robust feedback loops that support both vertical and horizontal institutional linkages that can respond to vagaries of both socio-economic heterogeneity and also bio-physical change and variability.

The cases presented briefly above demonstrated that three-way linkages among water, energy and food are exceedingly complex. Specific interactions among two resources or sectors (for instance, energy and water) raise important challenges for biophysical resilience and institutional dynamics not simply for these resources but additionally for the third (food). Consideration of these case examples in historical perspective also indicates that there exists accumulated knowledge and management experience. In the concluding remarks, we outline opportunities to seize the WEF Nexus to improve human quality of life, enhance ecosystem resilience and respect planetary boundaries.

4 Conclusion: Harnessing the WEF Nexus for Global Change Adaptation

Based on our review of the conceptual development of three-way linkages among water, energy and food that are now firmly established as a nexus of resources and institutions, we turn to the WEF Nexus as a management and policy tool that offers real potential to address global change and indeed modify development trajectories and outcomes. This is especially salient in the lead up to the 2015 transition to Sustainable Development Goals.

The water-food nexus, in other words, irrigation and virtual water, have been recognized for some time. The food-energy nexus, similarly with the intensification and mechanization of agriculture plus requirements for transport of food, is also plainly apparent from the dual perspectives of resource use and management. In this chapter, we treated the evolution of the concept of the water-energy nexus, both as water for energy and energy for water. There is growing awareness of the need for policy measures to address the institutional dimensions of the water-energy nexus.

Taken together, the three resources form the WEF Nexus, which we have shown carries multivalent implications for human society and ecosystem resilience. Notwithstanding the heightened complexity, new insights on the WEF Nexus point to the three-way coupling of resources and multi-level institutional linkages that have profound implications for human well-being, societal welfare, ecosystem resilience and ultimately the sustainability of life on the planet as we know it. The WEF Nexus, in other words, is a pivotal concept for scientific research and a policy tool that allows for operationalization of links between sets of two resources (water-food, food-energy, water-energy) building up to a triple nexus or triad approach to adaptive management.

If we consider resource use efficiency in Lankford's (2013) terms where conservation of resources leads to real savings that must then be subject to common-property management in the 'para-commons', we are presented with a unique set of opportunities to internalize saved resources to offset depletion, mitigate third-party or off-site damages, or for future use. The internalization of resources that previously had been externalized is the essential nexus challenge. There is no longer any scope to externalize impacts; the planetary system is ultimately bounded and we must allow for resource use and waste recovery to be practiced in such a way that does not perpetuate with the conceptual fallacy of externalization.

Finally the WEF Nexus is particularly evident in countries such as India that exhibit both emerging economy status and particularly acute constraints on resources. While the nexus has emerged in contexts such as agriculture in South Asia, it will increasingly play out in broader scales in this region. This poses particular opportunities for innovation and experimentation. The principal challenges that remain, having demonstrated a series of resource linkages, are to upscale innovative management concerns from local levels to address the policy and institutional dimensions that we have indicated form the under-pinning societal and ecosystem resilience practices leading to a virtuous cycle of sustainable and equitable development.

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Chapter 3
The Nexus Approach to Managing Water, Soil and Waste under Changing Climate and Growing Demands on Natural Resources

Rattan Lal

1 Introduction

The human population has increased more than a thousand times from 2–20 million at the dawn of settled agriculture about 10–12 millennia ago to 7.2 billion in 2013. It is projected to reach 9.6 billion by 2050 and ~11 billion by 2100 (UN 2012). The unprecedented growth, not only in the number, but also in the affluent lifestyle, is impacting Earth's biogeochemical processes, and some even beyond the planetary boundaries (Rockström et al. 2009). The agroecosystems and related activities are already covering 38 % of the Earth's terrestrial surface, emitting 30–35 % of the global greenhouse gases (GHGs) and using 71 % of the global freshwater withdrawal (Foley et al. 2011). With the focus on agricultural intensification since the 1960s, the irrigated land area has increased by a factor of two, fertilizer use by five and nitrogen use by eight. The present water use by agriculture of 3,100 km^3/year is expected to increase to 4,500 km^3/year by 2030 (McKinsey and Co. 2009). Consequently, global food production must be increased by 50 % by 2030 and 100 % by 2050 (OECD 2010). Above all, 24 % of the terrestrial ecosystems are degraded and more are prone to anthropogenic perturbations (Bai et al. 2008), and land, water and air quality are at risk (Tilman et al. 2011). Estimates of food-insecure population in 2012 vary from 868 million (FAO 2012) to 1.33 billion (Small Planet Institute 2013). Despite large appropriation of global net primary productivity (NPP) by humans, more than one out of seven persons are food-insecure (Small Planet Institute 2013), two out of seven are prone to deficiency of iron and other micronutrients (WHO 2013), and almost all of the food-insecure people live in developing countries where natural resources are already under great stress (FAO 2012). Faced with these challenges, and the concern that the current increase in crop

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yields may not feed the human world, what is next for agriculture (Beddington et al. 2012)? There is a strong need to explore innovative options towards sustainable intensification of agroecosystems. The strategy is to understand the linkages and inter-connectivity among resources and the underlying mechanisms governing critical processes, which are determinants of principal functions and ecosystem services.

1.1 Natural Resources and Human Wellbeing

Food security remains a major among global issues of the twenty-first century. Principal determinants of food security are the availability and quality of soil resources, and their interactions with water resources and vegetation (crop species) through energy-based inputs using managerial skills for optimizing the net primary productivity or NPP (Fig. 1). The latter is specifically affected by critical linkages that govern specific functions of nexuses between: (1) soil and water for the plant, available water capacity by influencing water retention and transmission, conversion of blue and grey into green water, and moderating the effects of pedologic and agronomic droughts, (2) soil and vegetation for biogeochemical cycling, which determines elemental budgets (C, N, P, S), nutrient use efficiency, root distribution and turnover and soil/root respiration, (3) vegetation and energy for energy/mass transformation and influencing energy productivity, ecosystem C budget, and biomass feedstocks for biofuel production, and (4) energy and water affecting the hydrological cycle with specific impacts on water and energy balance on a landscape, energy use in irrigated systems, and moderation of the hydrological/meteorological droughts (Fig. 1). These nexuses affect and are affected by climate change and variability on the one hand and anthropogenic perturbations (human demands) on the other (Fig. 1).

The importance of nexuses and inter-connectivity is also documented by a close relationship between soil security, climate security, water security, energy security, economic security and political security (Fig. 2). Indeed, an important ramification of the strong nexuses among natural resources is the human wellbeing based on specific needs, which are increasing because of the growing population and affluent lifestyle. For example, the food security (availability, access, nutritional quality, retention) strongly depends on soil security (quality, resilience), water security (renewability, availability, quality), energy security (supply, price, dependability), climate security (optimal temperature and moisture regimes, and low frequency of extreme events), economic security (income and access to resources), and political stability (peace and harmony) (Fig. 2).

Indeed, both economic and political securities are closely linked with food security on the one hand and security of natural resources on the other (Fig. 2). Therefore, the co-productivity generated by the anthropogenic use of primary resources (soil, water, climate) and secondary inputs (fertilizers, amendments, irrigation, tillage) must be optimized. Understanding and judiciously managing the

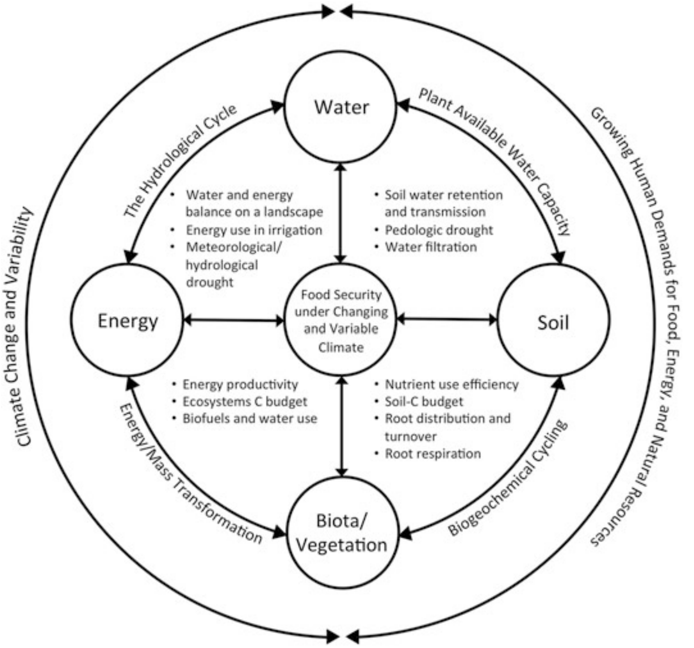

Fig. 1 Soil-water-energy-vegetation nexus affecting food security under a changing climate

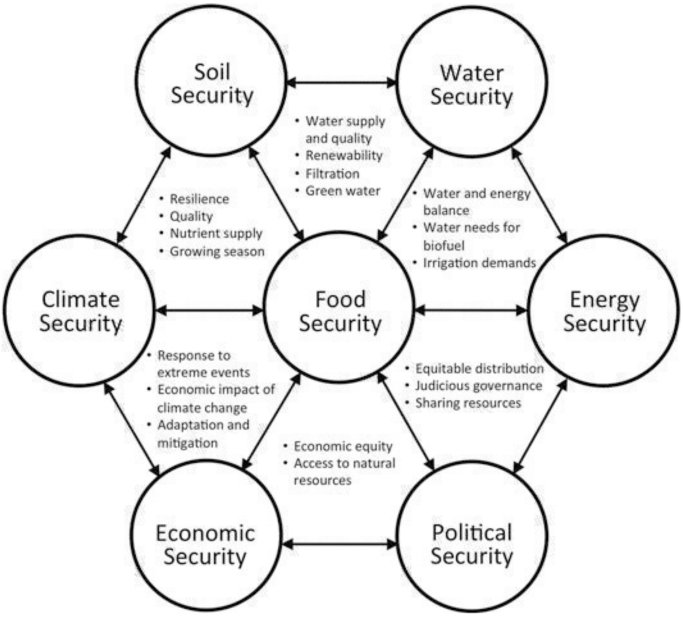

Fig. 2 Interdependence of food security on security of natural resources, and economic and political security

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water-soil-waste (WSW) nexus for food security is important to achieving the sustainable use of natural resources, enhancing human wellbeing, improving the environment and sustaining ecosystem functions and services.

1.2 The Nexus Approach

Nature does not recognize waste, from every death emerges a new life through a meticulous recycling of essential elements contained in the so-called "waste". There are strong inter-linkages and inter-dependencies among factors and processes impacting food security and resource use (Fig. 2). Rather than perceiving it as a great risk (World Economic Forum 2011), the WSW nexus provides an opportunity to enhance the use-efficiency of natural resources, recycle the waste (co-products), and close the cycles of carbon (C), plant nutrients (N, P, S, K) and water.

Therefore, the objective of this chapter is to deliberate opportunities and challenges of the nexus (linkages) approach to sustainable intensification of the natural resource so that the resource use efficiency is enhanced, losses (water, nutrient, energy) are minimized and the flow of environmental/ecosystem services is increased. Also discussed is the relevance of the nexus approach to urban agriculture, skyfarming (or vertical farming) and to explore the significance of soil-less agriculture using aeroponics and hydroponics to enhance food production for urban populations (Lal 2013).

2 Materials and Methods

This chapter is based on collation, assessment and synthesis of some relevant literature on the nexus approach. The literature is collated with a focus on integrated and holistic approach to sustainable intensification of some managed ecosystems. The literature review presented herein is specifically focused on application of the nexus approach to: WSW, energy-water, poverty-environment, soil-waste, water-soil, soil-climate and food security nexuses. Specific focus is on the WSW nexus. The review also explores applications of the nexus approach to skyfarming for addressing issues of food security and environment in urban ecosystems.

3 Results

Results of the literature-based review of the nexus approach are presented below on the basis of thematic issues listed in Sect. 3.1 with a focus on the WSW nexus.

3.1 Water-Soil-Waste Nexus

There exists a strong interconnectivity in WSW nexus. Soil can recycle waste, purify water and use the by-products to improve NPP. Conversion of organic waste to compost for use as a soil amendment has beneficial impacts on soil quality. Rather than taking biosolids to landfills, composting biosolids and using as soil amendment has numerous ancillary benefits. Soil applications of waste from plant and animal residues can alleviate some constraints and enhance soil quality. For example, application of manure can improve aggregation, nutrient retention and availability, microbial biomass C, water retention and transmission, earthworm activity, etc. Organic waste can also be converted into vermicompost. Soil application of vermicompost can enhance plant-available water-holding capacity and help in sustaining favourable components of the hydrologic cycle (Munnoli and Bhosle 2011). Long-term improvements in soil quality have been reported through application of olive mill pumice compost in Andalucia, Spain (Garcia-Ruiz et al. 2012). Using biomass urban waste (lawn clippings) can improve quality of urban soil and strengthen its ecosystem services (Washbourne et al. 2012); conversion of organic waste to compost can reduce emissions of GHGs (Kong et al. 2012); thus linking mitigation and adaptation through composting (Ayers and Huq 2009). In Santa Catarina, Brazil, Palhares et al. (2012) observed that managing the use of animal manure with optimum chemical fertilizer use and installing riparian fencing might also be a mitigation option for protecting the water quality.

Production of cellulosic or second-generation biofuels can also provide effluent/waste, which can be used as a soil amendment. Long-term ecological benefits of a bioethanol system can be realized through a system approach to biogas recovery and adoption of agricultural practices to enhance agronomic productivity without input of chemical fertilizers (Silalertruksa and Gheewala 2011). Conversion of municipal solid waste into biofuel is another co-benefit of adopting the WSW nexus approach. Shi et al. (2009) reported that globally up to 82.9 billion litres of waste paper-derived cellulosic ethanol can be produced replacing 5.36 % of the gasoline consumption. It is important, however, to reduce the risks of nitrous oxide (N_2O) emissions to enhance the environmental sustainability of biofuels (Carter et al. 2012). With a high global warming potential (GWP) of N_2O (298) and of methane (CH_4, 21), any benefits of biofuels can be negated by the emissions of these gases. Composting from food waste and applying it to the soil to conserve waste and enhance fertility at the community centre is another option to avail the benefits of soil-water-waste nexus (Schwalb et al. 2011).

Rather than composting for improved soil quality, some biowaste can also be used/converted into animal feed and their dung used as manure. Moreover, animal manure can also be used for algae production as a biofuel feedstock. In an outdoor experiment, Bai et al. (2012) reported that pig sludge could be used to produce algae (e.g., *Chlorella* spp., *Scenedesmus* spp., *Arthrospora* spp.) with 141–152 Mg/ha of annual dry yield on a 12-day long rotation period. The biomass can be used as a biofuel feedstock.

Being essential for life, soil-water management is crucial to agricultural productivity and ecosystem sustainability (Loucks and Jia 2012). With increasing scarcity of freshwater, the wastewater can be used to enhance soil quality and improve productivity. Thus, wastewater systems have been considered to assess emissions of GHGs from both reservoirs and wastewater treatment plants (Hall et al. 2011). When used for irrigation, wastewater application can reduce the C footprint, earn C credits and enhance crop yields (Hanjra et al. 2012). Thus, wastewater is a valuable resource of irrigation water in arid and semi-arid regions (Babayan et al. 2012). However, risks of environmental and health hazards must be minimized. Continuous application of wastewater may lead to accumulation of heavy metals in soils. Thus, rate of application must be assessed in relation to soil type, crop species, etc.

The runoff water generated from a mixed-farm landscale unit may be enriched in plant nutrients. There exists a strong relationship between the sources of pollution (e.g., cows, pigs, poultry) and quality of water runoff (Palhares et al. 2012). Under such conditions, installing a riparian buffer may be useful to mitigating non-point source pollution. Similar to the municipal wastewater, the winery wastewater can also be used for irrigation. However, the high salt loading of winery wastewater is an issue that must be addressed (Laurenson et al. 2012). Emission of ammonia (NH_3) from slurry emits bad odours. Thus, separate management of solid and liquid fractions, covered manure storage and band spread slurry application may be some mitigation options (Dinuccio et al. 2012).

Another ramification of WSW nexus is the transport of soluble nutrients in surface runoff from cropland and grazing lands receiving manure. Technological options to minimize nutrient losses include (Harmel et al. 2009): (1) combining application of organic and inorganic fertilizers, (2) providing alternate fertilizer sources, and (3) enhancing understanding of the farming communities. There also exists a water market and soil salinity nexus, which is an important issue with regards to secondary salinization risks (Khan et al. 2009).

It is widely recognized that linking traditional pedology with soil physics and hydrology, called hydropedology, can improve soil-water relationships across spatial and temporal scales (Lin 2003; Lin et al. 2005, 2006). Hydropedology is an intertwined branch of soil science and hydrology that embraces inter-disciplinary and multi-scale approaches for harnessing the benefits of linking pedological and hydrological processes. Societal benefits of such an approach include those related to water quality, soil quality, nutrient cycling, denaturing pollutants, waste management, climate change mitigation and numerous ecosystem functions.

In terms of water, the strategy is to look beyond the watershed, minimize hydrocentricity (Allan 2006a, b) and carefully evaluate the importance of hydropedology (Schoeneberger and Wysocki 2005). Soil hydrology is relevant to understanding transport of water and nutrients over and through the soilscape. The WSW nexus must be carefully managed, especially in arid and semi-arid regions. Thus, the importance of integrated management of natural resources, and especially integrated water resource management cannot be over-emphasized (Twomlow et al. 2008).

3.2 Energy-Water Nexus

Water and energy, two basic necessities of any civilization, are closely intertwined (Gentleman 2011; Schnoor 2011). Most ancient civilizations were based on access to water and its energy (the hydric civilization). The water-energy nexus involves bi-direction consequences originating from coupled processes and factors governing use efficiency of resources involved. There are three types of water: blue, green and grey. Plants can utilize only the green water (transpiration). Thus, conversion of blue (runoff, stream flow, groundwater) and grey (human waste) into green water requires energy. It is needed for transformation of blue (uplift) and grey (purification) water for increasing plant uptake and improving the NPP. Thus, increase in global material consumption also increases the water demand and vice versa. About 20 gallons per megawatt-hour are consumed by evaporation of hot water from the surface of the receiving body, and a power plant with cooling towers requires 400–500 gallons per megawatt-hour for evaporation (Hightower 2011). Indeed, water use is expected to grow globally by 30–100 % for the energy sector, 20–40 % for agriculture, and 20–40 % for domestic water supply. Yet, the supply of blue water may decrease by 25 % because of reduction in surface water flows in the mid-latitude region due to projected climate change (Hightower 2011). Thus, enhancing the use efficiency of water and energy for diverse uses and conversion of grey into green water are critical strategies. Indeed, sewage, flowing (blue) water and warm wastewater are potentially important energy sources (Venkatesh and Dhakal 2012).

In the context of fossil fuel consumption, C footprint must be assessed through life cycle analyses (LCA) at all stages of the production chain, and the baseline or system boundaries must be carefully defined. Because of the increasing urbanization, with more than 50 % of the world's population already living in urban centres and 80 % projected to be urbanized by 2050, the water-energy nexus is more important than ever before for the cities of the future. Thus, there is a strong need of achieving net zero C and pollution through reuse and recycling of water and recovering the plant nutrients and other resources. Production of biofuel feedstocks, through establishment of energy plantations is also water-intensive. Both C and water footprints are sub-components of the overall environmental footprint (Table 1). There are large differences in water required per unit quantity of biofuel (ethanol) produced from different biofuel feedstocks, and for different management systems. Thus, problems must be addressed rather than shifted, because the water-energy nexus is a high priority at regional (CEC 2005), national (Hardy et al. 2012) and international levels (Venkatesh and Dhakal 2012). In terms of policy interventions, localized challenges are diminished when approached in the context of broader perspectives. Similarly, regionally important challenges cannot be prioritized locally (Scott et al. 2011).

The water-energy nexus is also linked with the virtual water and the water footprint in relation to the production-consumption patterns. Virtual water is defined as the amount of water needed to produce the goods and services to be consumed by a country or individual. It is the amount of water needed to generate a

Table 1 Water footprint (WF) for renewable energy from biomass

		m^3 H_2O/GJ			
Crop	Latin name	Brazil	The Netherlands	USA	Zimbabwe
Cassava	*Manihoe esculenta*	30	–	–	205
Coconut	*Cocos nucifera*	49	–	–	203
Cotton	*Gossipium hirsutum*	96	–	135	356
Groundnuts	*Arachis prostrate*	51	–	58	254
Maize	*Zee mays*	39	9	18	200
Miscanthus	*Miscanthus gigantus*	49	20	37	64
Palm Oil	*Elaies guineensis*	75	–	–	–
Poplar	*Populus alba*	55	22	42	72
Potatoes	*Solanum tuberosum*	31	21	32	65
Soybeans	*Glycine max*	61	–	99	138
Sugarbeets	*Beta vulgaris*	–	13	23	–
Sugarcane	*Saccharum officinarum*	25	–	30	31
Sunflower	*Helianthus annuus*	54	27	61	146
Wheat	*Triticum aestivum*	83	9	84	69
Rapeseed	*Brassica napus*	214	67	113	–
Average		62	24	57	142

The WF is negligible for wind, 0.3 m^3 /GJ for solar, and 22 m^3 /GJ for hydro
Source Gerbens-Leenes et al. (2009)

product such as 1 kg of wheat or 1 kg of beef for meat (Allan 1993; Allan 1994). Thus, virtual water can be traded, exported and imported (Veláques et al. 2011). In comparison, water footprint refers to "the volume of water necessary to produce the goods and services consumed by the inhabitants of a country" (Hoekstra and Chapagain 2007). The water footprint of different food products are given in Table 2.

Table 2 The water footprint of some food products

Food	Litres of water per kg	Relative
Vegetables	322	1
Starchy roots	387	1–20
Fruits	962	2–99
Cereals	1,644	5–11
Pulses	4,055	12–56
Chicken meat	4,325	13–43
Bovine meat	15,415	47–87

Source Adapted from Mekonnen and Hoekstra 2012)

3.3 Poverty-Environment Nexus

There exists a strong poverty-environment nexus (Dasgupta et al. 2001). Indeed, when people are poverty stricken and miserable, they pass on their sufferings to the land (Lal 2008). Poverty is strongly linked with access to basic resources (e.g., water, energy, soil). Thus, poor households exacerbate environmental and resource degradation. Agricultural, industrial and economic development are closely interlinked with the environment and climate. Therefore, any developmental strategies must address the environment (climate change), food and energy (biofuel) security, and land restoration. As such, development and climate (environment) nexus is an important consideration (Davidson et al. 2003). In addition to agriculture, the urban ecosystems (refer to urban agriculture in Sect. 4) are also affected by the water-energy-environment nexus. Global climate change may exacerbate these challenges (Novotny 2011; Smit and Parnell 2012). Thus, there is a need to improve resilience of urban and agricultural ecosystems.

3.4 Soil-Water-Food Nexus

Two important determinants of global food security are soil and water resources. These resources are finite, unequally distributed over the landscape and prone to degradation and pollution by misuse and mismanagement. Rapid depletion of ground water and salinization are examples of misuse and mismanagement of soil and water resources (Khan et al. 2009). The low productivity of smallholder agriculture in drier areas of the developing world may be attributed to the limited availability of good quality soil and water resources (Twomlow et al. 2008). It is the water movement in and through the soil regolith that impacts salinity and numerous other pedogenic processes (Schoenberger and Wysocki 2005). Annual per capita water availability is decreasing in the Indo-Gangetic Plains, North China Plains, south central parts of the US Great Plains, etc. Thus, producing more crops and livestock products per unit of agricultural water invested within the soilscape is a key strategy of achieving food security.

3.5 Food Security-Natural Resources Nexus

Food security depends on an adequate availability of good quality soil, water and nutrients, and on the ability to recycle water and nutrients through biogeochemistry processes, which also enhance adaptation to climate change and other extreme events (Fig. 3). The nexus between integrated natural resources management and integrated water resources management is important to improving productivity of smallholder agriculture (Twomlow et al. 2008). Being in short supply, sustainable

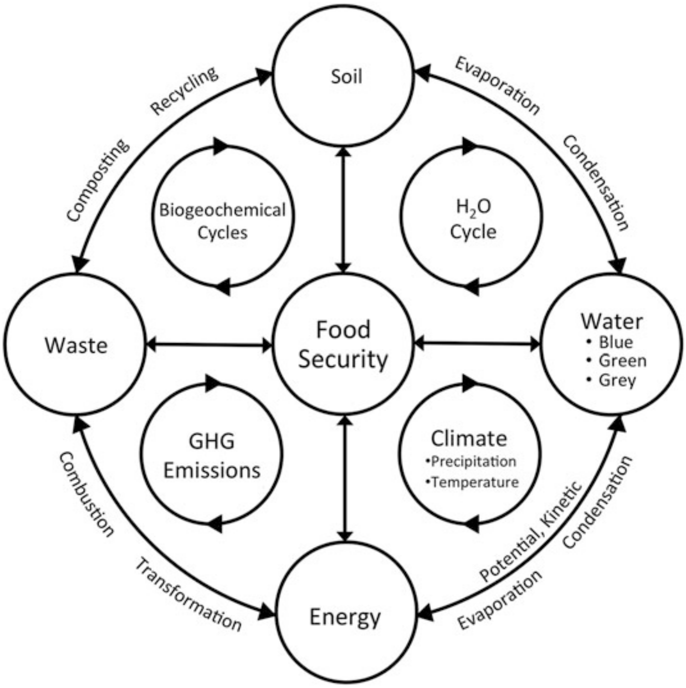

Fig. 3 Inter-linkages among natural resources in relation to food security, sustainability, resource use efficiency and resilience

intensification (Pretty et al. 2011) of these limited resources is critical. Sustainable intensification, producing more from less by reducing losses, is relevant to resource scarcity. Further, simultaneous management of water and energy is also essential to addressing climate change (Beal et al. 2012), and developing climate-resilient agriculture. In this context, virtual water and the water footprint are also inter-related (Velázques et al. 2011), and constitute important issues of global significance. Water mismanagement and lack of provisions for adequate drainage can also exacerbate the adverse effects of soil-water-salinity nexus (Khan et al. 2009), which is a major problem in irrigated agriculture in arid and semi-arid biomes. The strategy is to avoid deforestation and conversion of natural to agroecosystems and effectively use resources already allocated to agroecosystems. It is thus important to protect arable land, biodiversity and ecosystem resilience (Jacobsen et al. 2013), functions and services.

The water-food security nexus is more important now than ever before because of growing water scarcity caused by increasing population pressure. Water available for agriculture is a major factor for food security in arid and semi-arid regions of the world (Rosegrant and Cai 2001). The strong nexus between agriculture, which depends on water availability and economic development, cannot be overlooked (Rahman and Mikuni 1999). The changing and highly variable climate is especially important in rapidly developing economies such as China (Mu and Khan 2009). Further, 60 % of the global population may suffer from water scarcity by 2025 (Qadir et al. 2007). Thus, identification of non-conventional water resources (e.g., grey water, desalination of seawater) is crucial to the wellbeing of the population in arid regions. The importance of water-saving techniques and increasing water productivity cannot be over emphasized (Hamdy et al. 2003). In this context, there is an urgent need for rethinking of virtual water with regards to global food trade and policy perspective (Kumar and Singh 2005). Thus, the nexus approach is critical to advancing food security in the water-scarce world.

4 Linking the S-W-S Nexus Approach to Urban Agriculture

Most of the land suitable for crop production is already being cultivated. Unused land exists in regions that are too dry, too wet, too cold, too hot or otherwise inaccessible. Further, some of the potentially available land exists in ecologically-sensitive ecoregions (e.g., tropical rainforests). Yet, the per capita arable land area has decreased to about 2,500 m^2 (0.25 ha). Whereas sustainable intensification to narrow the yield gap in developing countries (e.g., Sub-Saharan African, South Asia, the Caribbean, Andean region) is needed and must be pursued, there are ecological limits to what can be achieved. The soil-less agriculture is not a new concept, and it has been used in research for decades throughout the twentieth century. The soil-less culture refers to “an artificial means of providing plants with support and a reservoir of nutrients and water” (Johnson et al. 1985). There are several types of soil-less cultures. Floating gardens, a form of hydroponics, has been used in South Asia (Haq and Nawaz 2009; Irfanullah et al. 2011; Wikipedia 2013) and Central America (Squier 1851). The “Chinampas,” small floating islands constructed from mud and plants, were used by Aztecs to grow crops. Aztecs expanded the city’s land surface to cover more than 12.5 km^2 or 5 square miles.[1] Nonetheless, floating gardens now constitute modern technology (Sweat et al. 2013).

Traditionally, urban agriculture (UA) involves conversion of abandoned land previously under homes, buildings and parking lots, etc. into agricultural land for production of vegetables and other short-season horticulture crops (Lal and Augustine 2011). To reduce food mileage and recycle nutrients in human waste, there is a growing interest in modern UA. It is also called skyfarming or vertical farming. Skyfarming is an innovative option of enhancing food production by utilizing the food-waste nexus in urban ecosystems and involves indoor crop production within purpose-built multi-storey buildings (Germer et al. 2011; Fischetti 2008). It minimizes resource use (land, water, nutrients) per unit of crop production,

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[1] For more information, see http://www.instructables.com/id/Build-an-Aztec-Water-Garden/.

and facilitates soil-less culture where nutrients and water can be supplied through one of the following options: (1) *aeroponics* involves spray of nutrients on roots growing in air, (2) *hydroponics* involves floating the roots in a pond of water, (3) *nutrient-film-techniques* involves periodic flooding of roots with nutrients, and (4) *aquaponics* involves combination of raising fish and plants for recycling nutrients in wastewater. The basic principle is to eliminate runoff from agricultural ecosystems, reduce adverse impacts on the environment and include skyfarming as an integral component of urban planning (Despomer 2009). Nutrients contained in grey water (urban wastewater) and biosolids (e.g., lawn clippings) can be effectively and efficiently recycled through skyfarming. The world's largest indoor vertical farm (FarmedHere, 8361.3 m^2 or 90,000 ft^2) is located in a suburb of Chicago, IL.[2] Another 0.8 ha (2-acre) vertical farm is planned for Milwaukee, WI and operated by the Growing Power Vertical Farm Company.[3] The 5-storey utility includes south-facing greenhouses and aquaponics for production of vegetables year-round. A downtown Tokyo office operates a vertical farm.[4] Singapore, a city-state with little arable land, operates A-Go-Gro vertical farm, which is 9 m high (three storeys) for growing leafy vegetables.[5] Another vertical farm, Jack Ng's City Farm, has a capacity to produce 1 tonne (1,000 kg) of fresh vegetables every day.[6] Vertical farming is also being used in Middle Eastern countries where scarcity of water is the principal constraint to traditional farming. Being water and nutrient-conserving because of the closed loop systems, aeropoinc systems (providing nutrients to plant roots by a mist) were developed using a reusable cloth medium rather than soil. The so-called 'AreoFarms: Soil-less Solution' uses artificial lighting in old or vacant warehouse-type buildings in crumbling downtown lots of major cities. The controlled lighting system, operating 24/7, has numerous advantages including rapid growth cycles, no pesticides, complete absence of contamination and reusable cloth media.[7] The innovative concept of skyfarming is also being included in modern art. An example of such an artistic vision is "Farming the Land and Sky: Art Meets Cosmology in a Sustainable Environment" (Bertol 2006).

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[2] For more information, visit http://www.mnm.com/your-home/organic-farming-gardening/blogs/; http://www.plantchicago.com.

[3] For more information, visit http://www.growingpower.org/verticalfarm.html.

[4] For more information, visit http.//gizmodo.com/this-downtown-tokyo-office-tower-contained-a-vibrant-ver-1140007476.

[5] For more information, visit http://skygreens.appsfly.com/media.

[6] For more information, visit http://www.amusingplanet.com/2013108/singapores-vertical-farms.html.

[7] For more information, visit http://www.greenprophet.com/2010/05areofarms_vertical-farming/.

5 Bioregenerative Life-Support Systems

The nexus approach is applicable in bioregenerative life-support systems. Recycling and utilizing the waste is integral to space agriculture for providing the life support system through exploitation of the food-waste nexus on extraterrestrial bodies (e.g., moon and Mars). The space agriculture technology is critical to developing a Lunar Outpost for any space exploration initiative (Hossner et al. 1991). The goal of a nexus approach is to design a bioregenerative life-support system.

NASA developed a Controlled Ecological Life-Support System or CELSS for long-duration human habitation on the moon or Mars. Salisbury (1992) outlined some challenges and researchable priorities in designing a Lunar or Martian microgravity CELSS. Technological challenges listed by Salisbury included: (1) creation and control of gas composition (CO_2), light and the rooting media, (2) equipment for waste recycling, (3) techniques for environmental monitoring and control, and (4) identifying appropriate species, cultivars and optimal growing conditions. Several life-support systems have been designed and technologies tested for growing plants in space (Morrow et al. 1994) and for manned space missions (Aydogan-Cremashi et al. 2009; Nelson et al. 2008). Simulation modelling has been used to assess mass balance for a biological life-support system (Volk and Rummel 1987), the C balance in bioregenative life-support systems (Wheeler 2003), and equipment for composting on Mars (Finstein et al. 1999a, b), by the use of hyperthermic aerobic composting bacteria (Kanazewa et al. 2008). The first space vegetables were grown under the CELSS project by means of controlled environmental conditions (Ivanova et al. 1992).

Principal researchable challenges include understanding the pedological, microbiological and physiological processes under microgravity conditions (Hoson et al. 2000; Maggi and Pallud 2010a, b). It is important to understand the biophysical limitations in physiological transport and exchange processes of plants growing in microgravity (Porterfield 2002). There is a need to understand the effects of hypogravity on transpiration of plant leaves (Hirai and Kitaya 2009), water distribution and flow (Jones and Or 1999; Helnse et al. 2007), capillarity in porous soil (Podolsky and Mashinsky 1994; Jones and Or 1998), water supply and substrate properties in porous root matrix systems (Bingham et al. 2000), and modelling heat and mass transfer for human habitation on Mars (Yamashita et al. 2006).

Since the discovery of water on the moon (Hand 2009) and Mars (Grotzinger 2009), there has been a growing interest in space agriculture. Using the principles of bioregenerative strategies for long-term life support in extraterrestrial conditions, soil-based cropping is considered a more effective approach for waste decomposition, C sequestration, oxygen production and water bio-filtration than those of hydroponics and aeroponics cropping (Maggi and Pallud 2010a, b). Silverstone et al. (2003) proposed soil-based bioregenerative agriculture. The proposed closed system included a wetland wastewater treatment system similar to that of the Biosphere 2.

The nexus approach can be extremely useful in developing bioregenerative life-support systems for terrestrial and extraterrestrial ecosystems.

6 Discussion

There are numerous inter-connected issues with regard to WSW and other nexuses discussed herein. These issues, with numerous manifestations and ramifications, can be appropriately addressed through the nexus approach. All of these considerations are important because if not sustainably managed, ignoring these nexuses can be a serious threat to the terrestrial-based human civilization (Diamond 2005). Improved provisions of food, energy and water necessitate policy interventions (Baziliana et al. 2011) to optimize resources and enhance use efficiency. As managing the WSW nexus is important, so are energy-water (Hussey and Pittuck 2012), soil-water, soil-waste, climate-waste, climate-soil, and soil-water-energy-waste-climate nexuses. The bottom line is integrating waste recycling and reuse at all levels of the production chain. Yet, the safe operating space must be clearly defined (Beddington et al. 2012) because agriculture is a major force affecting the environment even beyond the planetary boundaries (Rockström et al. 2009).

Rather than using soil as the medium of agricultural production, the nexus approach is crucial to developing soil-less culture (Fig. 4). The growing food demands of 9.6 billion by 2050 and ~11 billion by 2100 (UN 2012) leaves all options on the table including aquaponics, aeroponics and skyfarming. In this context, the nutrient-rich grey water from urban centres can play a significant role, for which there exists a strong need for development of appropriate technology (Li et al. 2008, 2009a, b). Earthworms are useful organisms to enhance and treat high-strength wastewater (Charawatchai et al. 2008), and can be critical to minimizing the risks of reusing wastewater (Zaidi 2007), through appropriate technology (Wendland et al. 2007). The use of bacterial cultures and synthetic biology (Balmer and Martin 2008) are relevant to enhancing environmental security. Potential challenges of large-scale water storage in surface reservoirs need to be assessed (Lindstrom et al. 2012) for site/region specific situations. Nanotechnology industry can be used in managing environmental issues by using the principles of green chemistry and development of biodegradable goods (Vaseashta 2009). However, the nanotechnology itself is generating a new form of waste stream called nano-waste (Musee 2011), which may need additional research.

The nexus approach is also crucial in sequestration of atmospheric carbon dioxide (CO_2) through either biological measures (soil, trees, wetland, oceans) or engineering measures (geological sequestration). For example, stable isotropic techniques can be used to assess leakages in geologic sequestration (Lackner and Brennan 2009), and in determining the old vs. new carbon in the soil (Puget et al. 2005).

There exists a strong link between soil and climate on the one hand, and soil and ecosystems C on the other. World soils have been a major source of atmospheric CO_2 since the onset of agriculture, but can be a sink (storehouse) through

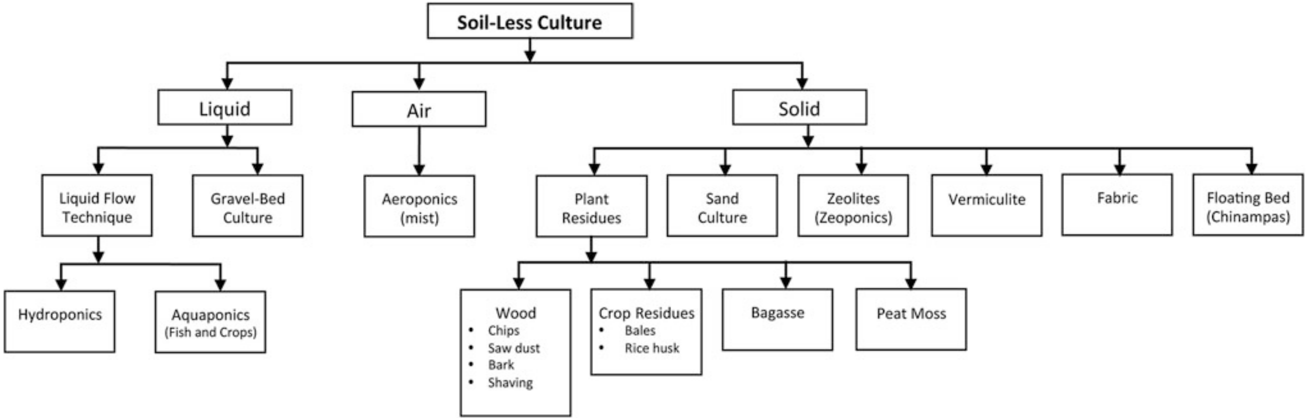

Fig. 4 Types of soil-less culture with application to modern urban agriculture approaches

conversion of degraded and desertified lands to restorative ecosystems, and adoption of recommended management practices. In comparison with the C capture and storage (CCS) technology in geological strata at US$600 to $800 per Mg of CO_2 (Anonymous 2012), the biological technique of C sequestration in soils may have negative costs because of numerous co-benefits such as enhancing soil quality, increasing use efficiency of inputs and improving agronomic productivity (McKinsey and Co. 2009). However, several CCS programmes in Norway and in the US have been cancelled or put on hold (Wald 2013). While the US has allocated the US DOE some $6 billion to spend on CCS-R&D since 2008, the CCS technology has not been proven to work at commercial scale in the US or elsewhere. In addition, CCS can add another 3 % to the cost of generating electricity (Kintisch 2013). Thus, biosequestration of C through soil-climate nexus may be a natural fix to reducing the net anthropogenic emissions.

The use of biomass input application of organic waste, green manure and other amendments to improve quality of soils under sugarcane production (Cheong et al. 2009) strengthen and validate the importance of the nexus approach in addressing complex issues. The LCA conducted throughout the production chain is also important and useful to performing the GHG accounting for emission trading (Cowie et al. 2012).

7 Conclusions

The chapter supports the following conclusions.

- Increase in anthropogenic demands has jeopardized natural resources and exacerbated soil and environmental degradation.
- The nexus approach, based on inter-connectivity among resources and the underpinning processes, is essential to minimizing losses and maximizing use efficiency.
- Sustainable intensification of agroecosystems involves exploring the connectivity among WSW, water-energy, water-waste, soil-waste, soil-climate, and food production-water-energy nexuses.
- Because of numerous functions and ecosystem services provisioned by soil, it is prudent to protect, restore and enhance soil resources and protect for nature conservancy. Thus, use of soil-less culture is important to protecting soil resources.
- In addition to meeting the food demand of the growing population, the nexus approach is also critical to adaptation and mitigation of climate change.
- Urban agriculture, including skyfarming is useful to produce food for urban environments by utilizing and recycling waste through principles underlying the nexus approach.

- Developing techniques of simulating extraterrestrial farming is crucial to research on planetary exploration.
- Bioregenerative systems, based on the nexus approach and utilizing Lunar and Martian regoliths, can be used to develop principles of space farming.

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Part II
Financing of Infrastructure Projects: Implications for Sustainability and Accountability

Chapter 4
Intergovernmental Fiscal Relations: Questions of Accountability and Autonomy

Linda Gonçalves Veiga and Mathew Kurian

1 Introduction

Decentralization, the transfer of power and resources from the central government to subnational governments, is a complex concept involving fiscal, political and administrative dimensions. The topic is particularly relevant for developing and emerging countries, where well-designed reforms have a higher potential to promote efficiency in the provision of public services and to enhance the development of integrated and sustainable strategies for the use of water, soil and waste. Additionally, it is important to ascertain the capacity of other alternatives to central government provision, such as those involving the private sector and local communities, to improve the quality of service delivery to citizens.

This chapter[1] starts with an overview of decentralization around the world and over time (Sect. 2). It then discusses the normative and political economy issues, which should be considered to establish sound fiscal relations across government levels, namely the assignment of functions to different levels of government (Sect. 3), intergovernmental fiscal transfers (Sect. 4), and subnational governments' fiscal autonomy (Sect. 5). The importance of establishing good budgeting practices

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[1] This chapter is based on Veiga et al. (2014). The book provides a more comprehensive discussion on intergovernmental fiscal relations in the context of the nexus approach to water, waste and soil.

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and of stressing governments' accountability for service delivery is analyzed in Sects. 6 and 7. Good governance practices and clear accountability, at all levels of government, are key ingredients to enhance the efficiency of local resource management. In the absence of an appropriate degree of accountability, greater discretion may actually lead to the misuse and abuse of the new powers, to the capture of power by local elite groups, and to the continuity of poor service delivery. Section 8 presents a literature review of the main factors influencing decentralization outcomes and discusses the impact of decentralization on governance. Recent trends in service delivery involving higher participation of the private sector and of local communities are covered in Sect. 9, along with new financial models designed to reinforce providers' accountability in a way that creates incentives for better performance. Finally, the implications for the nexus approach to the management of environmental resources are presented in Sect. 10.

2 Decentralization Around the World and Over Time

There is great diversity around the world regarding the organization of governmental activities. First, the number of administrative tiers of government varies across countries. Gómez-Reino and Martinez-Vazquez (2013) analyzed a sample of 197 countries and report that, although the majority of countries has two levels of subnational governments, 50 countries have three tiers and 35 have only one. Second, fragmentation within each tier of government also varies[2] leading to a diversity of situations regarding subnational governments' size in terms of population and area. Third, the degree of power and functions transferred to subnational governments also varies widely. Figure 1 provides a general view of decentralization across the world according to a decentralization index developed by Ivanyna and Shah (2014). As can be seen from the picture, developed countries are the most decentralized, while African economies tend to be the least.

From a historical perspective, the importance of studying and researching intergovernmental fiscal relation issues has been gradually increasing because major decentralization reforms have been taking place worldwide, reshaping national budgetary competencies across different layers of government.[3] In Latin America, reforms were implemented mainly during the 1980s and 1990s and were part of the democratization process that resulted from the fall of autocratic regimes. African countries also adopted decentralization measures, particularly in recent years, due to pressures arising from political changes resulting from the end of long civil wars, the increase in the number of multi-party political systems, and requests of regional and ethnic groups for more autonomy. However, Africa remains the

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[2] The two extreme cases are Kiribati with no local government and India with more than 240,000.

[3] For recent reports on decentralization, see United Cities and Local Government (2010) and European Commission (2013).

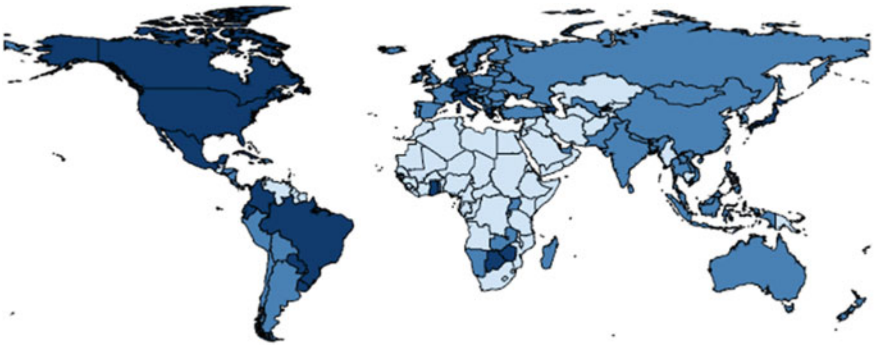

Fig. 1 Decentralization across the world. *Note* shades of the colour correspond to 0–12th, 25–50th, 50–75th, 75–100th percentiles of index of decentralization. *Source* Ivanyna and Shah (2014: 21)

least decentralized continent, as can be seen in Fig. 1. In the Asia-Pacific region, several countries adopted decentralization measures in order to improve service delivery to large populations. The trend is particularly strong in East Asia. In transition countries, the decentralization process was part of the institutional changes resulting from the collapse of the socialist economy. Finally, even industrialized countries witnessed significant progress towards decentralization in recent years.

These decentralization reforms had significant repercussions in sensitive areas for citizen well-being, especially the poor, since subnational governments are particularly important actors in areas such as education, health, housing and community amenities and environmental protection. Subnational governments play an important role in the management of environmental resources and in guaranteeing access to basic services, such as water and sanitation. The recent financial and economic crisis, rapid urbanization and demographic changes, as well as economic globalization and regional integration, represent additional challenges that subnational governments have to face as key players on governing the nexus approach to water, soil and waste.

In the water sector, increased dissatisfaction with national public monopolies generated a trend towards decentralization that was particularly impressive in Latin America (Foster 2005). Although most of the studies analyzing these reforms conclude that the effects of decentralization were positive, some argue that it did not result in a more efficient and sustainable use of resources.[4] Regarding education, most of the authors found positive effects of decentralization reforms on access to education and education outcomes. For health services, evidence is mixed. A better understanding of the causes of decentralization successes and greater capacity

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[4] For positive evidence, see Santos (1998), and Faguet (2008), among others. For negative effects see Wilder and Lankao (2006), Asthana (2010), and Vásquez and Franceschi (2013).

building by local officials implementing the reforms is, therefore, essential. The next sections discuss important normative and political economy issues for the design of the intergovernmental fiscal framework.

3 Sharing of Responsibilities Among Levels of Government

Decentralization of economic activities to lower tiers of government increases the proximity between citizens and public decision-makers, which has the potential to match public policies with the needs of the population better.[5] The more heterogeneous the preferences of individuals living in different geographic areas, the greater the gains that can be accomplished from diversifying the bundles of public goods and services supplied by subnational governments. Political reasons may also justify decentralization. By increasing the proximity between citizens and governments, decentralization fosters the accountability of politicians and creates additional spaces for democratic representation.

However, excessive fragmentation in the provision of public goods may generate losses of economies of scale and coordination problems resulting from spillovers generated by public goods and services supplied by subnational governments (e.g. police protection and pollution reduction). The creation of an excessive number of subnational governments may also increase costs associated with new administrations, numerous local elections and coordination problems. In activities related to recycling and disposal services, water supply and solid waste collection, service provision by consortiums of subnational governments or by an upper level of government frequently generates savings.

Mobility is also an important issue in the division of responsibilities among different levels of government. If subnational governments are responsive to the needs and preferences of their population, they will offer different combinations of goods and services, and charge different local taxes. In case of strong mobility, individuals will reveal their preferences for public goods by moving to the jurisdiction that better fits their preferences. Therefore, mobility may increase the efficiency gains from decentralization by creating communities that are more homogeneous and by increasing the competition among subnational governments to attract population.

Nevertheless, regarding redistributive policies, differentiation among subnational governments may result in unsustainable policies if resources are highly mobile. As poor households move to jurisdictions that are more generous, and the rich concentrate on less redistributive communities, welfare policies become unsustainable. Therefore, equity promotion under mobility of tax bases requires policy

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[5] Refer to Oates (1999) and Ahmad and Brosio (2006) for surveys on fiscal decentralization. For analyses focusing on developing countries, see Smoke (2006), Shah (2008), and Fedelino and Ter-Minassian (2010).

coordination. Centralization may also be justified under the argument that the equity pattern should be national, and not local, in order to avoid inequality among citizens living in different geographic areas. Because capital is even more mobile than individuals are, the setting of capital taxes by subnational governments also requires coordination. Otherwise, they may engage in an inefficient race to the bottom, offering lower taxes to attract capital. Furthermore, they may choose to tax less mobile resources, namely workers, which induces additional concerns.

4 Intergovernmental Fiscal Transfers

Sustainable local finance is essential for subnational governments to undertake the responsibilities assigned to them by upper tiers of government, and contribute to the well-being of the population. Because subnational governments' own revenues are frequently insufficient to finance their activities, revenue sharing between tiers of government is necessary. Intergovernmental fiscal transfers[6] may also be justified by the need to reduce fiscal imbalances among jurisdictions of the same level of government, and to stimulate subnational governments that engage in activities generating positive externalities to neighbouring communities. Usually, the central government is responsible for collecting the main national taxes and transfers a substantial part of revenues to subnational governments. A well-designed system of intergovernmental fiscal transfers is, therefore, crucial to ensure a good subnational government's performance. In developing and transition countries, the weight of intergovernmental fiscal transfers on subnational government's total expenditures is about 60 %, while in OECD countries it is about 30 %.

Intergovernmental transfers can be unconditional or conditional. Unconditional transfers allow the recipient government to decide on how to spend the resources. They are mainly used to correct vertical and horizontal imbalances among governments. Vertical imbalances occur when subnational governments lack funds to undertake the functions assigned to them. Equalization transfers can be used to reduce horizontal disparities in wealth across jurisdictions. Conditional transfers impose input-based or output-based restrictions on the recipient government. With input-based restrictions, the donor government forces the recipient government to spend the transfers on specific expenditure items. Under output-based restrictions, transfers are conditional on the achievement of certain results in service delivery. This latter type of transfer induces higher responsibility in local management by making the recipient government accountable for results. Conditional transfers often require the recipient government to supplement the funding provided from the upper level of government with their own outlays. These are called matching transfers. When the granting government specifies the maximum amount it is willing to contribute, we have a matching closed-ended transfer.

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[6] On this topic, see Boadway and Shah (2007) and Geys and Konrad (2010).

To increase equity, efficiency and transparency in the distribution of national funds to subnational governments, the allocation of intergovernmental transfers is often based on formulae that take into account indicators of population needs and of local fiscal capacity. Population is usually the main variable used to capture local needs for public goods. Additional frequently used indicators are population density, age structure of the population, area of the jurisdiction, and the incidence of poverty or diseases. The fiscal capacity of subnational governments, that is, their ability to raise revenues from own sources, is evaluated through macro measures of the jurisdiction (e.g. gross domestic product or income) or tax measures. This latter approach is more frequently used because subnational data on the tax-system is usually more accurate and timely than the macro indicators. In this case, transfers are used to equalize the tax base across jurisdictions using the national mean or median as reference. Richer jurisdictions are asked to contribute with funds to help poorer jurisdictions.

Even when intergovernmental transfers are established by formulae, they are subject to political pressures, which may prevent the achievement of the normative objective explained above. Extensive literature on the political economy of intergovernmental transfers has highlighted several issues that need to be taken into account. First, transfers can be used opportunistically before elections to increase the likelihood of victory of incumbent governments. Second, they may be subject to manipulation in order to favour the incumbent government's electorate in the allocation of funds (Cox and McCubbins 1986; Lindbeck and Weibull 1987) or localities with many swing voters that are easier to influence (Dixit and Londregan 1996). For empirical studies analyzing developing countries, see Case (2001), Khemani (2007) and Allers and Ishemoi (2011).

5 Subnational Government's Fiscal Autonomy

As discussed above, fiscal transfers from upper levels of government, foreign governments and international organizations represent an important source of revenue for subnational governments, particularly in developing countries. In some of these countries, tax decentralization has not kept pace with political and expenditure decentralization, decreasing local officials' accountability to citizens. When local public goods and services are financed by subnational government's own revenues, citizens have a better perception of their costs, which enhances efficiency, accountability and good governance. Besides transfers, state and local governments receive revenues from borrowing and from a variety of taxes, charges and user fees.

OECD countries rely mainly on taxes on income, profits and capital gains. These taxes can be used strategically by subnational governments to attract populations and businesses. In non-OECD countries, taxes on goods and services tend to be more important. They are particularly relevant in India, Thailand and Brazil. These taxes are easier to administer and govern than property taxes but, when applied to all merchandise, they are clearly regressive.[7] Most subnational governments also have access to other miscellaneous taxes on specific goods and services, such as tobacco, alcoholic beverages and the extraction of natural resources (severance taxes). Both in OECD and non-OECD countries, taxes on property represent an important source of tax revenue (more than 30 %). Property taxes are levied on land and capital (buildings and equipment). Their main advantage is that they generate a stable and relatively easily predictable income. Unlike any other tax, subnational governments determine both the tax rate and the tax base of property taxes. The tax base is the value of property, which is assessed by the subnational government. Since not all property is transacted annually, its market value has to be estimated, and is always subject to error. Therefore, property taxes are hard to administer and subject to arbitrariness. Another drawback of these taxes is that they are frequently regressive, as landowners transfer the tax burden to tenants, and because they more severely penalize those with fixed income (e.g. retired people).

In addition to taxes, subnational governments' own revenues include user fees, which consist of prices charged for the provision of goods and services (e.g. water and sewer charges), licence taxes and fees required to develop a certain activity. User fees increase citizens' perception of the costs associated with the good/service provision and fairness in the distribution of costs.[8] When necessary, user fees also have the advantage of moderating consumption. They can be used to moderate access to overcrowded facilities or promote an efficient use of a good or service. However, because low-income persons are frequently the ones benefitting the most from government intervention, user fees can impose an excessive burden on them. Furthermore, they may involve large administrative costs to subnational governments and compliance costs to users (e.g. time costs). In several developing countries, high administrative costs associated with use measurement and fee collection in water and sanitation services, together with the perception that citizens are unable to pay for the services, have led governments to waive the fees (Kurian and Ardakanian 2014).

Subnational governments can also rely on debt issuance to finance their activities. Debt is justified primarily for inter-temporal equity reasons, when it is necessary to invest in long-life capital infrastructures that generate benefits for several years and involve high costs that cannot be supported by own revenues and transfers from upper levels of government. In these situations, subnational governments frequently also engage in public-private partnerships.[9]

Debt issuance is self-limiting because when the credit-worthiness of a subnational government decreases, lenders demand higher interest rates, which reduce the

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[7] Because the poor spend a higher proportion of their income than wealthy persons do, taxes on goods and services penalize them more severely. To overcome this inconvenience, governments frequently exempt basic goods and services, such as milk, bread, drugs, electric and gas utilities, from taxation.

[8] Only those who benefit from the good/service have to pay for it, and non-residents benefitting from it are also required to pay.

[9] Refer to Alam (2010) and OECD (2012).

propensity for additional borrowing. Therefore, to avoid excessive interest costs and to ensure financial sustainability, debt has to be issued and managed with prudency. Although subnational governments' debt is frequently constrained by law, several countries face problems of fiscal indiscipline. When lower levels of government are highly dependent on intergovernmental transfers, they tend to accumulate deficits and debt. This is known as the common pool problem, and results from the fact that subnational governments take credit and perceive the benefits associated with their expenditure choices, but fail to fully internalize the costs that all national taxpayers must bear. In countries where the central government is expected to bail-out subnational governments in financial distress, the incentive to accumulate debt is aggravated (soft-budget constraint problem). Political issues may also explain subnational governments' indebtedness. During electoral campaigns, incumbent politicians may engage in opportunistic fiscal policies by increasing expenditures and reducing taxes, in order to convey competence and win the election (Rogoff and Sibert 1988). Politicians may also extract rents while in office and, when expecting to be ruled-out of office, they may use debt as a strategic variable to constrain the options of the opposition candidate. Government fragmentation and political instability are also likely to contribute to loose fiscal finances. Furthermore, conflicts among generations may also lead to an increase in debt, as the older generations leave a negative bequest to the younger ones.

To prevent excessive indebtedness by subnational governments, several countries have implemented numerical targets for budgets, including balanced-budget rules. However, fiscal rules are hard to enforce and they may generate incentives for creative accounting. The context in which they are implemented, namely the existence of good budgeting institutions, is crucial for their effectiveness.

6 Importance of Budgeting for Sound Fiscal Policy

A budget is a fundamental tool for any organization to manage its resources and activities properly and, therefore, for the accomplishment of its objectives. While in the private sector, profits are typically the target, for public institutions the main objective is the improvement of population welfare, which is much harder to quantify.

For subnational governments, budgeting is an exercise of planning, intended to balance revenues and expenditures and encounter the best use for the available resources, in order to satisfy the needs of the community better. The budget defines which activities will be implemented (and consequently the type, quantity and quality of the goods and services provided to citizens) and which resources to use to fund them, as well as how those funds will be obtained. The budget also has a political function since it involves negotiation between political parties. The executive body of government is responsible for the elaboration of the budget proposal, but the proposal usually has to be approved in a committee formed by elected representatives. During and after its execution, comparisons between what was planned in the budget and the actual flow of expenditures and revenues allows public officials to monitor government activities and, if necessary, to adopt corrective measures. For citizens, budgets are also an important tool to evaluate government priorities and performance.

Accurately forecasting expenditures and revenues is critical for good financial management. Because the time available for preparing the budget proposal is limited, and changes involve complex and costly negotiations, sometimes only marginal changes are introduced from one year to the next. With incremental budgeting, public programmes are simply rolled forward for an additional year, without questioning whether they are still necessary, leading to an upward bias in expenditures and to the accumulation of deficits. In the 1970s, zero budgeting was introduced in the US. As the name suggests, each spending agency starts from a zero budget and has to justify all its spending needs. The main advantage of this procedure is that public officials must re-evaluate the validity of the policies implemented in the past. The discontinuity of some programmes may free resources for other activities that are currently more necessary. However, in practice, it is very difficult to implement a zero-budget approach, as it is very demanding in terms of time, information and negotiations. Furthermore, political pressures may distort decisions, deviating from the budgeting process. Another attempt to match budgets better with the needs of the population is participatory budgeting. It was first introduced in 1989, in the Brazilian city of Porto Alegre, and given its success in improving citizens' lives, particularly of the poor; it has been adopted in other countries. With participatory budgeting, citizens are directly involved in the formulation of budget proposals. They propose, discuss and vote spending ideas knowing that the subnational government will implement the most popular ones. Although a more open and inclusive budgeting process should, in principle, improve subnational government performance and enhance democracy, it is important to avoid its capture by pressure groups whose only interest is to extract rents from the implementation of public projects (Shah 2007).

The establishment of good budgeting practices is crucial for government performance.[10] Transparency is very important for budgeting. It is essential to include all expected expenditures and revenues in the budget in order to avoid off-budget activities. The use of standard classifications for reporting expenditures and revenues is also relevant for comparisons over time and across governments. Typically, there is more concern about discriminating expenditures than revenues because governments, especially at the subnational level, have more discretionary power over them. During all the phases of budgeting, reporting, auditing and evaluation should be present to increase fiscal policy transparency and soundness. Audits can be performed by internal or external agencies. The growing concern about governments' fiscal sustainability has recently led several countries[11] to create

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[10] Several international organizations (namely the World Bank) provide, on their webpages, extensive information on international good practices and reference models in public budgeting.

[11] On the role of fiscal councils in promoting sound fiscal policy, see Hemming and Joyce (2013).

independent fiscal councils and to adopt medium-term expenditure frameworks. New regulations were approved at the European Union level establishing that member states must have independent fiscal institutions and requiring additional reporting by national authorities to the EU on the country's fiscal performance. According to the World Bank (2013), by the end of 2008, two thirds of the countries had adopted medium-term expenditure frameworks (MTEF). MTEF expand the time horizon of a typical single-year budget for several years, allowing for a multi-year commitment of resources to policies and the consideration of possible trade-offs between short and medium-term objectives. Their adoption enhances allocative efficiency and sound fiscal discipline.

To make governments more accountable for service outcomes and results, several countries have also introduced performance budgets. Common examples of performance budgets are programme budgets, which associate resources and results in a specific programme, allowing for cost-benefit analysis.

7 Subnational Government Accountability

The quality of public service delivery varies considerably across countries, especially in the developing world, and frequently services fail poor people. Good governance requires effective and accountable socio political and administrative systems with transparent and participatory processes that address human needs taking environmental sustainability into consideration. Therefore, decentralization measures need to be accompanied by a strengthening of subnational governments' accountability. Otherwise, subnational governments may abuse and misuse their new discretionary powers or these can be captured by local elites eager to extract rents.

Accountability has several dimensions. Subnational governments are politically accountable to citizens-voters on the policies implemented and the type, quantity and quality of services provided. Decentralization involves giving administrative autonomy to subnational governments on issues such as recruitment, procurement, legislation and regulation. Therefore, subnational officials are accountable to their top administrative officers and outside bodies on the administrative decisions they adopt within their discretionary powers. Finally, financial accountability refers to responsibility on issues related to the management of local finances and its outcomes. Accountability can be fostered from a public or supply side perspective and from a social or demand side point of view. The former refers to institutional practices that increase requests for public authorities to explain how they are carrying their responsibilities, while the latter considers the pressure for accountability, which comes from the civil society and citizens.

The political accountability of subnational governments is stronger when elections are free and fair, several parties and candidates run for office (local political competition), there is a clear separation of powers between the executive and the legislative branches of government and courts are independent. Examples of public or supply side measures to foster political accountability include improvements in the electoral system that stimulate independent candidates to run for office, reserving seats in local councils for minority/vulnerable groups of the population, and increasing transparency of election and campaign financing. From a social or demand side point of view, political accountability can be enhanced by introducing mechanisms that increase citizens voice (e.g. public hearings, public petitions, administrative complaints) and the creation of formal bodies for citizens oversight.

Regarding administrative accountability, public or supply-side measures to enhance it include, among others, the creation or reinforcement of independent judicial/quasi-judicial agencies to investigate misbehaviour and corruption by public officials, external audits by independent agencies, reinforcement of administrative courts, procurement rules, standards for service delivery, and flexible and performance-oriented career management. From the demand-side approach, measures that increase citizens' ability to monitor subnational government and to participate in the public decision-making process usually foster administrative accountability.

Finally, financial accountability requires transparency and prudency in local financial management. Supply-side measures to increase it include, among others, clear and publicly announced rules on the allocation of intergovernmental fiscal transfers, transparent public audit systems and clear rules on subnational governments' budget constraints and borrowing. These measures can be supplemented with demand-oriented measures such as improvements on public visibility of governments' financial accounts, introduction or reinforcement of participatory budgeting practices and public expenditure tracking systems.

8 Factors Influencing Decentralization Outcomes and Impact on Governance

The decentralization trajectory chosen, its shape and outcome in a particular country are determined by contextual factors involving demographic, social, economic and political features of the country (LDI 2013; Faguet 2014). The existence of a democratic framework and of a participatory political culture fosters citizens' participation in decision-making, thereby increasing accountability. Regarding the water supply and sanitation services, WELL (1998) stresses that user participation and involvement in decision-making is particularly important. Kurian and Ardakanian (2014) also recognize the importance of consumer participation for the development of the nexus approach to water, soil and waste. Jütting et al. (2004) suggest that in countries where the central government performs poorly, decentralization may worsen service delivery to the poor.

The institutional design adopted for decentralization is also a crucial factor. It is important to define correctly, which functions should be decentralized, and to which extent, while avoiding overlapping mandates, excessive fragmentation, unclear responsibilities and coordination problems. Additionally, subnational governments must have the financial resources to perform the functions assigned to them. For sound fiscal policy, subnational governments must have discretionary power over their own revenues, but tax sharing among different layers of government is also fundamental. The challenge is to achieve the correct balance between the two. Dinar et al. (2007) argue that decentralization in water resource management positively depends on the local share and discretion over central government funding and on the share of users paying tariffs. Mechanisms that improve local transparency and accountability are also essential ingredients to reduce misuse of public resources and, therefore, for the success of decentralization. According to Gonçalves (2014), participatory budgeting practices increase citizens' awareness on local public finance issues, fosters accountability of local officials to citizens, and improves the living conditions of the poor namely in the areas of health and sanitation.

As stressed by Weingast (2014), political economy aspects also influence the outcome of decentralization. Even with a well-designed federal system, the existence of a predatory central government will lead to the malfunctioning of decentralization. The central government may use decentralization to consolidate its party's interests rather than to improve service delivery. This problem is particularly acute in the developing world. The existence of corrupt and self-interested local politicians is also a negative factor. If local officials are able to capture the new powers assigned to subnational governments to extract rents, the quality of service delivery may actually decrease (Bardhan and Mookherjee 2000). At the local level, it is also crucial that subnational governments have the required competencies to perform the new functions attributed to them by decentralization measures and that residents engage in finding solutions to local public problems, participate in local decision-making and hold subnational governments accountable. The success of decentralization measures in water supply, sanitation and irrigation is positively related to users' involvement in management. As pointed out by Kurian and Ardakanian (2014), the development of capabilities and knowledge of public officials is fundamental for the success of the introduction of technological changes to address environmental challenges, and for the sustainable and integrated management of water, soil and waste resources.

However, decentralization may also influence governance. Regarding the size of government, there are two theoretical dissenting views. Brennan and Buchanan (1980) argue that decentralization reduces the government's dimension in the economy as it increases tax competition among public authorities in the context of geographic mobility of taxpayers. On the other hand, Oates (1985) points out that decentralization may lead to larger governments due to losses in economies of scale, poor quality of local officials and soft budget constraints. Empirical evidence on this issue is mixed, although when measured by the number of employees most studies conclude that decentralization increases the size of government.[12]

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[12] For a cross-country analysis, see Martinez-Vazquez and Yao (2009).

Political decentralization may foster democratization as increased political competition, through local elections and greater civic participation, stimulates local officials to offer better services and reduce corruption (Myerson 2014). However, if there is an unbalanced power between local and national elites, decentralization may lead to undesired results (Weingast 2014). According to Boadway and Shah (2009), decentralization may reduce corruption by increasing accountability and competition by subnational governments, providing exit and voice mechanisms, higher transparency and reducing perceived gains from corruption due to higher probability of detection and punishment. However, decentralization may also lead to the opposite effect because of weak monitoring systems, larger number of officials involved in public management, and greater incentives for accepting bribes due to low salaries (Bardhan and Mookherjee 2000). Which of the effects dominates depends on the specific country analyzed, but most of the recent empirical studies using panel data suggest that decentralization reduces corruption.

In heterogeneous countries with strong ethnic or religious subnational differences, decentralization may reduce conflicts and risks of secession by allowing subnational governments to serve the specific needs of the community better and give local leaders additional power. However, according to Myerson (2014), subnational governments' differentiation may increase social and ethnic cleavages, and lead to the creation of regional parties that favour separatism. To avoid these problems, Myerson (2014) suggests the establishment of smaller jurisdictions and the choice of parliamentary over presidential democracy.

9 Recent Trends in Service Delivery and Financing Models

As recognized by World Bank (2004), separating the policymakers from providers, and making the latter more responsive to clients is crucial to enhance the accountability of service providers and improve the quality of service delivery to citizens. Besides decentralization, other alternatives to central government provision include contracting out to the private sector and Non-Governmental Organizations (NGOs), selling concessions to the private sector, community participation and direct transfers of resources and responsibilities to households.

The trend towards public ownership and private provision (namely in water, sanitation and electricity) started in the United States and the United Kingdom, during the Reagan-Thatcher era. Since then, and particularly since the 1990s, private participation has grown significantly across the world. Public-Private Partnerships (PPP) were expected to improve the quality of service delivery by increasing management expertise, financial resources and commercial orientation. Like decentralization, private participation may foster accountability by separating policymakers from providers through compacts and voice (World Bank 2004). In fact, when negotiating compacts, private providers usually require contracts to establish their responsibilities clearly, as well as those of policymakers. The voice mechanism is stronger when all stakeholders are involved in the decision process.

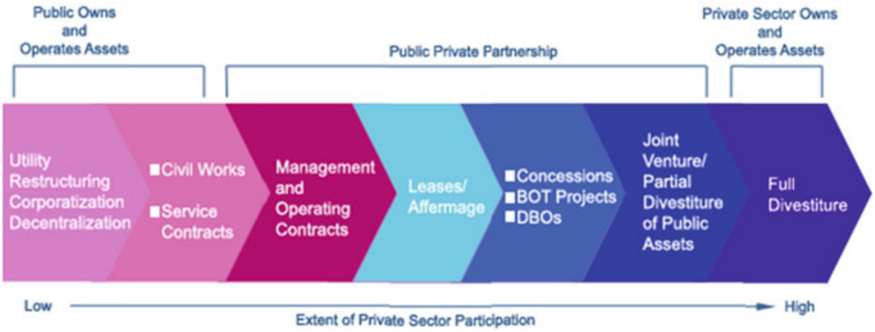

Fig. 2 Extent of private sector participation. *Source* www.worldbank.org/ppp

The establishment of delivery standards and the need for services to reach poor people are issues frequently discussed in the policy debate of private involvement in service delivery.

As illustrated in Fig. 2, the extent of private sector participation can vary considerably between the extreme cases of decentralization, where the public sector owns and operates assets, and full divestiture. Frequently used forms of PPPs, involving increased private sector participation, include management and operating contracts, leases/affermages, concessions, Build-Own-Transfer, Build-Own-Operate or Design-Build-Operate projects, and joint ventures.

In developing countries, the scarcity of financial resources and the strong need for public infrastructures, contributed to the acceptance of shifting investment responsibility to private providers. As can be seen in Fig. 3, the total amount of private investment in infrastructure in middle and low-income countries has grown

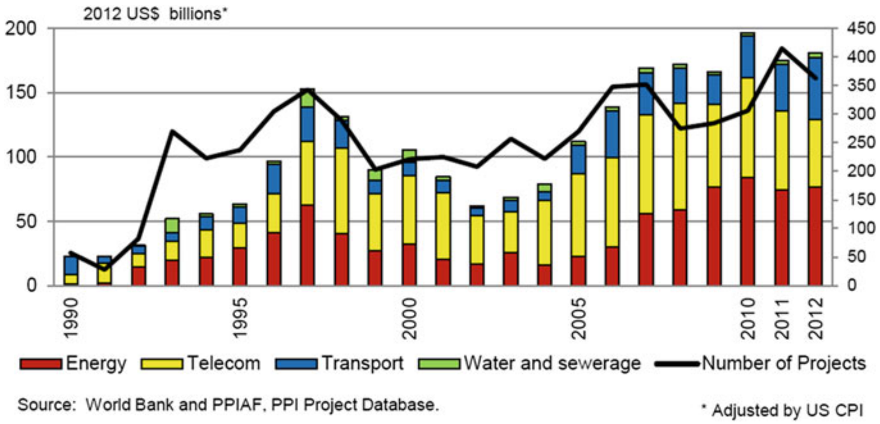

Fig. 3 PPPs in middle and low-income countries

considerably since 1990, and most of the investment has been concentrated in the energy and telecom sectors.

Possible explanations for water and sewerage projects to have a residual share are the existence of archaic land tenure arrangements and insufficient guarantees (due to political interference) that users will pay for services (Kurian 2010). As suggested by OECD (2009), in order to attract sustainable flows of finance it is necessary to implement reforms in this sector's governance and to use strategic financial planning with a long-term perspective.

Urban water services may also be improved by enhancing the role of small independent providers (World Bank 2004), such as household vendors, small network providers, private entrepreneurs and cooperatives. In rural areas, community-managed networks/systems are more common. They have been involved in the design and management of water systems, paying for operations and maintenance costs. Although community-managed networks/systems put the client at the centre of the process, they face numerous challenges such as avoidance of elite capture, loss of economies of scale and the adoption of efficient technologies due to a village-level association focus.

Regarding financing models, there is a trend towards results-based financing (RBF), which means that payments are dependent upon the achievement of previously agreed results/outcomes. In contrast to input-based approaches, with RBF the delivery of funds is focused on objectives clearly identifiable and measured rather than on payments for improved capacity. This approach transfers risk from donors to recipients and increases pressure on the latter to fulfil their promises. It is expected to improve transparency, accountability, efficiency, private sector engagement and the sustainability of public finances.

The most common RBF approaches are output-based aid (OBA), conditional cash transfers, cash on delivery and performance-based contracting. Output-based aid has been increasingly used by international agencies to deliver basic infrastructures and social services to the poor. Its usage in water and sanitation sector represents around 5 % of the total volume of OBA by the World Bank (transport and health sectors have the largest shares) and is mostly concentrated in Africa. Although RBF improves aid effectiveness (IDA 2009), it is difficult to use because funds are delivered only after the project's implementation and it involves high costs for data collection and auditing. Additionally, RBF may also distort development priorities since the outputs of some relevant projects are not easily quantifiable. In countries that made substantial progress in sector reform, it is appropriate to move forward from sector-wide approaches to budget support operations, as the latter allows for a broader development perspective (Kurian 2010).

Given the importance of the local context for the outcomes of decentralization and of other models of service delivery, reliable indicators of accountability and governance are essential for effective policy, programme and project design. Regardless of the purpose for which indicators are used, three rules should be observed (UNDP 2007): use a range of indicators instead of a single one; use an indicator as a first question—not a last; and understand an indicator before you use it. Two of the most widely used and comprehensive databases of indicators are the

World Governance Indicators—WGI (World Bank) and Country Policy and Institutional Assessment—CPIA (World Bank—IDA).[13] There is considerable room for improvement regarding indicators. The implementation of the nexus approach to the management of environmental resources and the elaboration of quantitative trade-off analyses requires the development of indicators that address sustainable resource use, human well-being and equity, as well as integrated assessments of water, energy and food sectors (Kurian and Ardakanian 2014).

10 Implications for the Nexus Approach to the Management of Environmental Resources

Decentralization of governmental activities and other alternative forms of service delivery to central government provision have the potential to match better the supply of goods and services with citizens' demands. However, in order to boost the positive impact of reforms several issues need to be taken into account.

First, decentralization measures should stimulate sound fiscal relations across government levels. In order to do so, the sharing of policy responsibilities needs to be clearly defined to avoid the shifting of responsibilities among layers of government. It is also important that subnational governments have access to a stable financing system that allows them to fulfil the functions assigned to them. This involves the definition of a transparent mechanism of tax sharing among levels of governments for the allocation of intergovernmental fiscal transfers, together with the establishment of the correct amount of tax autonomy by subnational governments. The establishment of mechanisms to monitor the behaviour of all levels of government, to guarantee that public resources are properly used, and that fiscal policy is sustainable is also fundamental to ensure the proper functioning of a decentralized fiscal framework.

Second, the social, political and economic context should be carefully taken into consideration in service delivery reforms, as solutions that work well in a country may lead to disastrous results in another.

Third, active participation and engagement of citizens and the increase of capacity building among local government units, NGOs and communities are also key elements for the sustainable and integrated management of water, soil and waste resources. As suggested by Kurian and Ardakanian (2014), the development of multi-disciplinary competencies is essential to address questions of intersectionality correctly among material fluxes, public financing, heterogeneity and changes in institutional and biophysical environment, relevant to the nexus

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[13] WGI provides indicators for six dimensions of governance: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. CPIA rates 81 International Development Agency (IDA) recipient countries against a set of 16 criteria grouped in four clusters: economic management; structural policies; policies for social inclusion and equity; and public sector management and institutions.

approach to environmental management. Therefore, institutions such as UNU-FLORES can play an important role in providing blended learning curricula for the training of policymakers, administrations and members of NGOs and local communities.

Fourth, although evidence suggests that private participation in service delivery increases operational efficiency and the reliability of services, it is important to introduce enforceable requirements that affordable services will be available to all, namely the poor. Given that the amount of private investment in the water and sanitation sector is relatively small, PPPs should be seen as a device to improving operational efficiency and service quality rather than as a major source of finance. For the attraction of additional private investment, it is essential to establish solid legal and policy frameworks, as they are essential to guarantee that costs will be recovered.

Finally, regardless of the delivery form chosen, the institutional framework should give incentives for good governance and providers should be made accountable for the services they deliver. The existence of reliable indicators, that actually record intended results and do not create perverse incentives, is essential to programme evaluation and monitoring, especially in the scope of results-based financing, and there is considerable room for improvement in this area. RBF, namely output-based aid, have the potential to allocate donor funds more efficiently and to increase transparency, accountability and efficiency in service delivery. However, it is important that financing mechanisms do not distort local development priorities. In countries that have made substantial progress in sector reform, it is reasonable to move forward from sector-wide approaches to budget support, as the latter allows for a broader development perspective.

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Chapter 5
Results-Based Financing and Its Potential Role in Advancing the Nexus Approach

Mario Suardi and Mathew Kurian

1 Introduction and Context

The need to improve the effectiveness of development financing provided by multilateral and bilateral development institutions led to the design and adoption of some results-oriented financing tools that aim to incentivize the delivery and sustainability of the pursued results (outputs and outcomes) that serve long-term objectives. However, as the development community takes a closer look at the interrelations between the different sectors in which the interventions have been traditionally structured, the need to ensure that improvements in one sector do not cause deterioration in the situation of other sectors becomes evident. The nexus approach aims to provide a rational framework to deal with this complex challenge.

This chapter scratches the surface of potential collaboration between the nexus and Results-Based Financing (RBF) approaches, beyond the use of Payments for Environmental Services (PES), which is an RBF tool naturally fit to contribute to advance the nexus approach.

After this brief introduction, this chapter shows some of the challenges facing the nexus approach and a simplified introduction to the RBF universe that, despite efforts made to keep it to the bare minimum, may seem long in the context of this chapter. This explanation is provided to ensure that all readers, even those unfamiliar with RBF, understand the discussion regarding how RBF instruments could contribute to advance the nexus approach.

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Even though RBF schemes have been in use for some time now, it is still a relatively new approach and many modalities have arisen, including some with a very narrow definition and designed to tackle very specific problems. However, the different tools can be adapted to other circumstances, as they are mostly based on certain principles rather than rigid models with strong procedural focus.

Nevertheless, some of the tools that could be more useful to advance the nexus approach, like Cash on Delivery (COD) have not been broadly used, while others like Output-Based Aid or Output-Based Disbursements have been used on a small scale or only recently have been implemented on a larger scale. However, the fact that the RBF mechanisms link payments to the achievement of results measured through certain indicators provides a good opportunity to define indicators that consider the nexus approach and make those payments dependent on progress towards improvement on all nexus components combined. At the same time, as RBF mechanisms require a detailed analysis at the design stage, the efforts made during that stage could take a more thorough consideration of the effects of the planned intervention on all components of the nexus and incentivize the right solutions to maximize positive impacts and neutralize or minimize the negative ones.

2 Challenges Facing the Nexus Approach

Given the broad range of possible scenarios and the complexity of the socioecological challenges that development professionals and government officials would have to deal with when focusing on the nexus approach to design the interventions pertaining to the management of water, waste and soil resources, it is not possible to apply ‘off the shelf’ solutions (with minor adjustments) to resolve the issues at hand. Even though there are some strategies that have shown effectiveness in certain circumstances, like integrated water resources management (IWRM), decentralization and participation, they are not suitable beyond certain limits and there are still many challenges for which new strategies need to be developed.

So far, some principles regarding how to embrace the nexus approach in resolving development issues have been enunciated (Hoff 2011), but still one or more sets of principles could be adapted with a more focused aim to provide guidance in tackling scenarios that are more specific. To this end, focusing on categories of interventions within the nexus, like increasing resource productivity, using waste as a resource in multi-use systems, etc., could be well served by setting specific principles to guide the design of each specific intervention within a category.

Beyond the question of defining what the principles that should guide the actions of the development community are, there are other challenges worth noting within the scope of this chapter.

Knowledge gaps (Op. cit. extract):

(1) The need for more data on sustainably available water resources, in particular on safe aquifer yields and for so-called ‘economically water scarce’ regions, such as sub-Saharan Africa.
(2) Insufficient knowledge on the impacts of hydropower and other water resource development on aquatic ecosystems.
(3) The relationships between river flows, the state of aquatic ecosystems and their services are not well established.
(4) Uniformly applicable ‘water footprint’ frameworks do not yet exist that would allow comparison of water use efficiency for different forms of energy or food production. Such water footprint frameworks would have to integrate consistently water productivity with water scarcity and opportunity costs in any particular location.
(5) There is a lack of consistent and agreed upon water quality standards for different crops and production systems, which would standardize and promote wastewater reuse and hence increase water use efficiency.
(6) There is no harmonized ‘nexus database’ or analytical framework that could be used for monitoring or trade-off analyses. Hence, the effects of increasing energy or water scarcity on food and water or energy security, as well as potential synergies between land, water and energy management, are not well understood. Questions include to what extent can higher availability of one resource sustainably reduce scarcity of another, and how might this work at different spatial scales?
(7) Much like in the case of IWRM, it is not clear how to deal with the increasing level of complexity that comes with higher levels of integration. Implementation of such broader concepts is not straightforward and tensions arise when integrating across sectors, institutions, levels and scales. For example, IWRM is still not sufficiently integrated with sustainable economic development. These challenges may be aggravated by inertia, stubborn adherence to existing paradigms and preference for linear thinking.

Institutional concerns (Op. cit.):

(1) The need to overcome institutional disconnect and power imbalances between sectors (e.g. blue and green water generally falling under different ministries), or energy often having a stronger voice than water or environment, indicating that the nexus may not be traded off equally.
(2) Accountability issues regarding allocations of financial and human resources within the public sector related to decentralization, notably intergovernmental fiscal transfers to agriculture, water and public health departments.
(3) Little awareness and lack of capacity in all development actors (governments, financing institutions, communities, etc.) regarding the nexus approach.

Lack of a Framework: To develop and implement a nexus-focused strategy to find the right incentives to promote the right behaviour of each stakeholder.

It is not possible, within the scope of this chapter, to address all of the challenges listed above, even though the list is far from exhaustive. However, after a brief introduction to some elements of RBF provided in the next section, a theoretical approach is presented later to show different ways in which the use of the RBF approach and its tools could contribute to tackle some of these challenges.

3 Results-Based Financing Tools

RBF is a general or umbrella denomination for a suite of different financing tools that work at different levels and over different stakeholders to cause the delivery of expected results. In the following subsections, a brief explanation of some aspects of the RBF analytical framework and tools is presented, as they are relevant to the proposed discussion. As an introduction to the subject, Fig. 1 introduces the development results chain and a definition of its elements as understood by the World Bank.

Input Inputs are the financial, human and other resources mobilized to support activities undertaken by a project. Examples would include loan/credit funds and staff.

Output The supply-side deliverables, including the events, products, capital goods or services that result from a development intervention (e.g. construction of a school).

Outcome A project outcome is the uptake, adoption or use of project outputs by the project beneficiaries (OPCS 2007).

Impact The long-term effects of a development intervention.

The key distinction between an output (a specific good or service) and an outcome is that an output typically is a change in the supply of goods and services (supply side), while an outcome reflects changes in the utilization of goods and services (demand side).

3.1 Background

For many years, development efforts were focused on providing finance to pay for the procurement and construction of infrastructure and services that were supposed to produce certain expected results. Although the instruments offered evolved over time, they remained mostly focused on financing the ‘inputs’ that would lead to economic development for the client countries and a way out of poverty for their peoples.

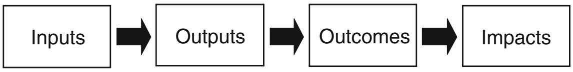

Fig. 1 Basic results chain

However, time proved that often, the results of this methodology were not as good as desired and, sometimes, the projects utterly failed to deliver the expected results. As a response to these problems, some development institutions introduced modifications to the design of their projects to make them more effective, making certain payments contingent to the achievement of certain goals or producing certain outputs. The health sector was (and still is) a notable leader in these efforts, but other sectors joined. Education, energy and water (mostly water supply) are among them.

The experience so far is somewhat limited and mostly driven by the development institutions. However, it has been positive, as many successful projects have been implemented or are ongoing, while the development community is gaining experience and gathering knowledge about the conditions for success or failure of the approach.

It is important to note that RBF approaches are not opposite to the traditional way of funding development projects but complementary. Whether a project should be financed through a traditional instrument, and RBF tool or a combination of both should be assessed in each specific case based on the issue to be solved and the conditions surrounding it, like agents' skills and capacity to absorb risks, amounts involved in each project component, availability of financing besides the public funds, among others.

3.2 RBF Analytical Framework

Designing an intervention using one or more RBF mechanisms poses several questions that demand a rigorous analytical process to improve the chances of successful implementation. Figure 2 shows the schematic interrelation of the different elements to consider.

In some cases, the answers to the questions may produce a straightforward path to the selection of an RBF tool and design of the intervention but, more often than not, once some of the questions are answered, the need will arise to revisit the different elements of the analytical framework before the final approach and design can be completed. Many of the analytical aspects could be considered simultaneously and iteratively. What is the right approach depends on each particular situation. This thinking process can incorporate a focus on relevant aspects of the nexus approach to ensure that the development interventions are in line with it. A quick look at the different elements of this analytical framework is provided in the next section.

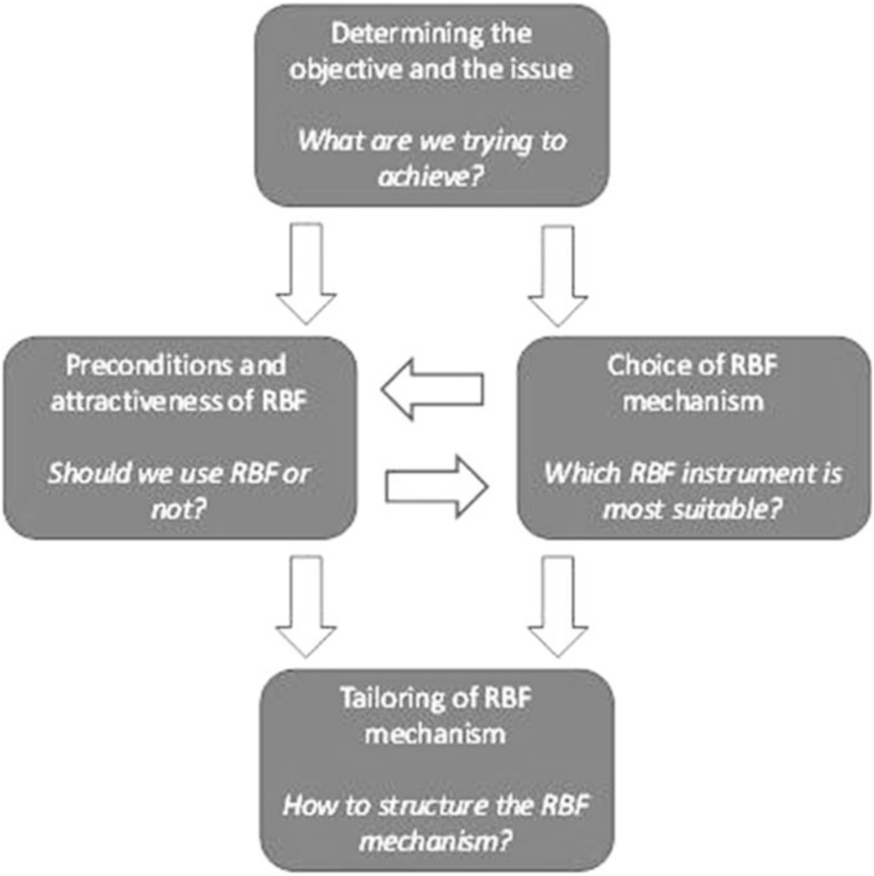

Fig. 2 Results-based financing schema

3.2.1 Objective, Results and Indicators

RBF instruments focus on results and incentivize achieving the pursued objective. Thus, analysing and understanding the relationship between objective, result and indicator (how the results are measured) is extremely important. When the chain between these three elements is robust (the indicator fairly represents the expected results that are univocally linked to the objective of the intervention), the chances for success are very high.

It is important to note that, if the results are not univocally related to the objective, the intervention may incentivize a result that will not lead to achieving the objective and, in certain cases, could produce unintended or opposite effects. This is particularly relevant to the nexus approach as a thorough analysis of the intended and unintended consequences (or positive and negative effects) of the intervention on the target sector as well as on the other related sectors is critical to minimizing the negative effects.

Without attempting to lay out a full logical framework on how to establish a strong linkage between these elements, a simple approach could be to (1) thoroughly define the objective of the intervention, (2) explore how it can be determined that the objective has been achieved and (3) identify the best way to measure such achievement. This should be based on a clear understanding of the problem that needs to be resolved.

The most critical link of the chain is the relationship between objective and result. Table 1 provides a few examples to show why some options have better chances of success than others do.

The first example for reducing irrigation water consumption at the farm level shows a weak link between objective and result because introducing a new technology does not necessarily lead to lower consumption. The farmers who install the new technology could opt to grow a more water-intensive crop, increase the number of crop cycles or cultivate a larger area on their farms leading to higher water consumption.

The second example adds a problem in the indicator. It is obvious that not checking whether the systems have been installed and paying an incentive only for buying the equipment is less reassuring that the objective will be achieved.

In the third case, it is very clear that objective, result and indicator are aligned. However, the questions arise about who receives the incentive and how the incentive is defined. As it is difficult to measure how much water goes to each individual farm, a set of rules should be set to avoid the ‘Free rider’ problem, as some farmers may be making an effort to reduce consumption while others may continue with the old practices and still receive the benefits (if paid to a water users association, for instance or distributed uniformly among all farmers within the scheme).

Despite the analysis above, it should be considered that the farmers could also have a different objective than simply protecting a water resource by limiting extraction. They may also expect to grow higher value crops while still reducing the volume of water needed to do so. A demand responsive approach should always be preferred when willing to align, to the extent possible, the interests of the different stakeholders.

3.2.2 Suitability of RBF

In determining whether an RBF mechanism should be considered as an alternative to a more conventional approach, consideration should be given to the preconditions to use this kind of tool (is RBF possible) and how compelling is it to use such a tool (is RBF attractive). In the discussion below, the ‘agent’ is the stakeholder responsible for delivering the expected results while the ‘principal’ is the entity providing the funding to the RBF scheme.

Table 1 Good and bad approaches to defining results and indicators

Problem	Objective	Result to measure	Indicator	Comment
Higher than desired consumption of irrigation water	Reduce consumption of irrigation water at farm level	Installation of water efficient technology	Number of systems installed	Weak link between objective and result
		Installation of water efficient technology	Number of systems sold	Adds a weak indicator
		Lower volume provided to tertiary canals	Volume of water provided to tertiary canals	Strong links, but ‘Free rider’ issue needs to be addressed

3.3 Preconditions

There are five aspects to be considered to determine whether it is possible to use an RBF approach.

(1) The agent is capable of assuming additional risk.
(2) The agent has access to finances to fund the project until the RBF payments are received (ESMAP 2013).
(3) The envisioned result can be captured in one or more indicators.
(4) The institutional environment enables the use of RBF.
(5) The crucial stakeholders have the capacity and competences to deal with the RBF mechanism.

Even though there are ways to deal with these issues, if these conditions are not met, using an RBF approach will not be possible. Notwithstanding this fact, for our current objective of analysing the potential contribution of RBF in advancing the nexus approach, the first two preconditions are not necessarily relevant, while it might be worthwhile discussing the other three in more detail.

3.3.1 Use of Indicators

As mentioned above, a clear definition of the problem and the possibility to resolve it through the achievement of specific, easily measurable and verifiable results is determinant of the possibility of using RBF instruments to provide a solution to the issues at hand. It is essential to ensure a direct link between the issue to be solved, the objective of the project and the incentivized result to avoid negative incentives that would prevent the project from achieving its objective.

However, it is also critical to define indicators that suit the need to measure and verify the results easily. So, the selection of indicators that thoroughly represent the intended results triggering RBF payments is an important element to ensure a smooth reporting and verification process leading to enhanced confidence for the agent that payments will not be delayed due to disputes about whether the results were achieved or not.

In relation to the nexus approach, indicators that are specific to individual projects can be used as building blocks for more complex indicators reflecting how those individual projects contribute to a higher level objective defined from the nexus perspective. As an example, indicators related to interventions focused on (1) reduction in the use of pesticides and fertilizers, (2) improvement of wastewater treatment and (3) adequate solid waste disposal could be combined in a higher level indicator related to the improvement in the quality of water resources.

No matter how complex the concept behind any indicator may be, each indicator should represent the associated result as closely as possible and should be easy to determine or calculate. Whenever possible, existing indicators should be used (national statistics, agency accounting systems, official records, etc.), provided that they are trustworthy.

3.3.2 Enabling Environment

Besides other elements discussed in this section, other aspects contribute to an adequate enabling environment. These are the legal and regulatory environments such that principal and agent can exercise their rights and perform their obligations in a trusting atmosphere and with certainty that any discrepancies in interpreting any clause of the legal agreement will be resolved following acceptable legal process. However, as the agent will take additional risks, as compared with that taken in input-based projects, the design of the RBF project should provide more certainty about the capacity and willingness of the principal to fulfill its obligations in a prompt and fair manner.

From the strict RBF perspective, creating special vehicles for disbursement, like escrow accounts, selecting fiduciary agents that will disburse automatically once the specified conditions have been met and verified, and preventing any political intervention will go a long way in the desired direction. This would reduce payment risk and give more confidence to potential agents to enter into an RBF agreement.

From the standpoint of the nexus approach, the regulations should provide a rational and mutually agreed framework to evaluate the effects of an intervention that benefit a certain subset of stakeholders on the situation of the other stakeholders.

3.3.3 Capacity and Competencies

The principal should be in a position to administer the scheme and collaborate with the agent in resolving implementation issues. This requires understanding of the principles behind the RBF approach and how they come into play to design the specific project or programme.

Much like RBF, interventions are tailored to each situation based on these principles, available funding and institutional options. The nexus approach requires solutions to be crafted at the appropriate scale combining strategies like IWRM, decentralization and participation with the appropriate tools depending on specific sociopolitical and environmental contexts to tackle the complex socioecological challenges at hand.

From the RBF perspective, the principal should also be able to provide assurance that it has the capacity to oversee project implementation and follow up on the independent verification process. The agent should have the technical qualifications and capacity to deliver the results, as in input-based projects, but should also have the financial capacity to absorb the additional risk and to obtain the funding required to deliver the expected results before being paid. Beneficiaries should be ready to play their role, paying for their part of the deal, adopting new practices, habits or technologies so the project can progress smoothly.

Depending on the previous experience of each stakeholder and the kind of intervention planned, substantial awareness and capacity building may be required for successful implementation of an RBF intervention. Given the complexity of elements that will need to be handled by the stakeholders and the interactions between them, the same is valid for the nexus approach.

One noticeable point of contact between the nexus approach and RBF is the RBF mechanism known as PES. This mechanism requires a broad understanding of the value of the environmental services involved, which is not always obvious to some of the stakeholders. Developing this capacity to understand not only the value of the services, but the mechanisms to determine that value and the process to recognize and pay for them provides an opportunity to advance both the nexus and RBF approaches.

3.4 RBF Attractiveness

Even if the preconditions are satisfied, RBF also requires more up-front preparation than traditional development projects do. Transaction costs of developing and independent verification of results can be higher than in a conventional scheme. However, there is a trade-off between preparation and supervision costs, as supervision tends to be lighter in RBF projects due to the focus on results and, precisely, the inclusion of the independent verification agent (IVA).

In addition, transferring additional risks to the agent will lead to higher pricing. Therefore, assessing the RBF attractiveness requires a cost benefit analysis comparing an RBF approach to a conventional approach, addressing additional costs (transaction costs and risk pricing) and additional benefits (economic effects of better results and increased certainty of these results) of the RBF approach. Conducting this analysis underlines the level of control or confidence that the intervention at hand can generate the desired output/outcomes. In turn, this confidence level is strictly linked to the possibility to measure and predict such results, so that the risk compensation for the agent can be properly set.

Integrating RBF tools with the nexus approach could add to the benefits, as the information gathered by the IVA can contribute to improve understanding of the cross effects of the intervention so that they can be taken into account for future interventions.

3.4.1 Choosing an RBF Mechanism

Depending on the specific situation and the level at which the intervention is planned, the spectrum of possible issues to be resolved is enormous, but understanding the kind of issue to be resolved could help narrow the selection of RBF tools that may be most suitable for that level of intervention and situation.

Table 2 summarizes some of the characteristics relevant to this selection process, although it is important to note that some of the tools could be adapted to other situations than the ones presented here. The idea is to give a general perspective of the issue to facilitate the discussion in later sections.

The introduction to RBF presented in Table 2 is not provided as an exhaustive explanation of all RBF tools and schemes, but rather as guidance for the reader to navigate through the theoretical discussion in the next section.

4 RBF and the Nexus Approach

It is not the intention of this chapter to present RBF as a magic bullet to advance the nexus approach. The two scenarios presented below are intended to show the potential benefits of using the RBF approach and tools in designing and implementing policies and interventions in the concerned sectors with the nexus approach in mind.

As the scenarios develop (particularly in the second one), the reader would notice two levels where RBF can contribute to tackling some of the challenges mentioned above. At a high level, RBF may contribute to:

(1) Strengthening institutions through results-based programmatic approaches that scale up pilot projects into national schemes.
(2) Decentralization through the provision of cascading economic incentives that improves effectiveness and accountability.
(3) Overcoming the natural political focus on the short term (led by election calendars or financial cycles).

Table 2 Tentative guide for selection of RBF instruments

Issue	Issue description	Possible RBF tool use
Behavioural problems	A stakeholder group should change habits (hygiene), improve practices (garbage collection) or adopt new technologies	Incentive/reward to sustain users' new behaviour like Conditional Cash Transfer (CCT)
		Subsidy, like Output-Based Aid (OBA), to make new infrastructure affordable
Access constraints	Low income population lacks access to certain products or services due to supply issues (uncertain revenues from disadvantaged areas) or demand ones (affordability)	Advanced Market Commitment (AMC) can support suppliers' investment when demand is uncertain
		Take or Pay (ToP) offers guaranteed prices and quantities for a specified period
		OBA subsidy can close the affordability gap for poor customers
Externalities	External costs or benefits are generated by an activity/service that affect members of society uninvolved in the market transaction	Payment for Environmental Services (PES) introduce payment for preservation/restoration of ecosystems
		Carbon finance (CF) allows pricing and trading of GHG emissions
Unsatisfied demand/ uncertain future revenues	Demand is not met because the required investment is too risky or the future demand volume is too uncertain	OBD schemes can redistribute the investment responsibility among different government levels
	A dominant/monopolistic position causes suboptimal quantity, quality, allocation or pricing of a good/service	ToP agreements can offer guarantees to supplier so that the optimal quantity of product/service is reached
		OBA subsidies can help buy down the capital cost of the investments required

(continued)

Table 2 (continued)

Issue	Issue description	Possible RBF tool use
High-level policy objectives infrastructure investment programmes budget execution	Need to improve performance in certain sectors or aspects within a sector	Cash on Delivery (COD) is a hands-off approach that rewards governments for progressive, long-term results
	Large investments are needed to build infrastructure	OBD schemes can improve budget execution for large investments (lower Government levels are responsible for agreed outputs)
	Government needs to improve execution of investment plans (low capacity, rent-seeking behaviours, etc.)	
Poor service delivery or operation and maintenance	A vicious cycle (often seen in irrigation) of inadequate service supply or administrative failures, together with incorrect pricing of goods and resources prevent the sustainable provision of services	Various RBF alternatives could be appropriate from high-level COD, to OBD agreements, to more output-specific OBA

(4) Improving transparency in allocation of resources through transfers and payments based on independent verification of results.

On a different level, related to implementation aspects of the RBF tools, contributions can be made on:

(1) Gathering information for the nexus databases: Expanding the scope of data gathered as part of the independent verification mechanism inherent to most RBF tools.
(2) Extending the focus of the interventions beyond the outputs into the outcomes.
(3) Addressing the issue of public versus private management models.
(4) Overcoming dichotomies like putting emphasis on efficiency versus equity using targeted subsidies.

The first scenario focuses on a specific case that includes some interactions between different nexus components that may be initially implemented in a pilot scale and later scaled up, once the interactions and crossed effects are clear. The second one introduces a broader analysis of how different RBF tools could be used to contribute to advancing the nexus approach.

4.1 Scenario 1: A Specific Case of Aquifer Sustainability

In certain circumstances (this scenario is based on an actual case), to facilitate irrigation in areas that could only use groundwater for that purpose, governments provide free electricity to farmers. This has led to over exploitation of the aquifer and its consequent depletion to the point that farmers have to drill deeper pump wells leading to higher electricity consumption to pump out the water.

In certain cases, pumps that are more powerful are installed as well and the vicious cycle not only entails more serious aquifer depletion but also deterioration of the quality of the groundwater. Depending on other aspects of the surrounding ecosystem, the damage could reach far beyond what is mentioned here.

Even though the scenario presented is conceptually simple, and it has been simplified for the purpose of this discussion, solving the problem would not be so simple, given the social implications of withdrawing from the farmers the ‘benefit’ of free electricity. Therefore, without other considerations, restoring the electricity price to a rational level would not be an option.

Broadening the view, it is clear that there are additional economic prejudices stemming from the lack of power for other productive uses (due to the over consumption of electricity by the farmers), or the poor allocation of resources to replace that power production with new sources and, depending on the technology used to produce that power, the associated environmental consequences (greenhouse gas emissions, direct impacts in ecosystems, etc.).

Reducing irrigation water consumption would reduce power consumption allowing the aquifers to recover at the same time. However, the farmers have no motivation to make such a reduction as, most likely the volume of their crops will drop and, consequently, their income too. The introduction of an RBF approach keeping a broader point of view in mind, as the nexus approach supports, could prove helpful to progress towards a more rational situation.

An RBF intervention could provide the necessary incentives to motivate the farmers to switch to more water efficient technologies or less water-intensive crops that will help them reduce water consumption. This would be the kick-start to revert the cycle of aquifer depletion in the example given.

However, the RBF intervention needs to be carefully designed to avoid negative incentives, or results opposite to what was initially sought. If farmers are not using all their potentially useful land due to scarcity of water, the introduction of these new technologies or crops could lead to more income, but not to a reduction in water and power use.

This design will depend on technical studies and economic considerations, but designed as an RBF intervention using one or more RBF tools, it will need to consider, at least the following elements:

- There might be the need to use incentives to introduce new technologies like drip irrigation and fertilizer injectors among others.
- If the incentive requires covering part of the cost of the introduction of the new technologies through a subsidy, the sources of funding for such subsidies should be identified in advance and the funds secured before starting project implementation.
- Another element to consider as an incentive for the farmers and as part of the economic analysis is that, reducing irrigation water consumption would also lead to avoidance of costs of drilling deeper wells that the farmers have to incur from time to time.

- At some point, the electricity tariff has to be set at the ‘right’ level, consistent with sound regulatory policies. This adjustment of the electricity price could be the most powerful motivator, but still other ways to incentivize the farmers to switch to less water-intensive practices may be necessary.
- The farmers and other stakeholders will have to be sensitized and provided with sound information for decision-making.
- The right change agents should be identified.
- To the extent possible, not only the farmers, but also the change agent(s) should be provided with the incentives or payments on a results basis.
- Depending on the extent of the impact of the power overconsumption in terms of availability of electricity to other users, reducing power consumption could free up enough electricity production capacity to delay the construction of new power plants. The economic impact of such delay could be assessed and used as the basis for a mechanism to secure funding for the incentive scheme.
- Along with the independent verification of results mandatory for the RBF scheme, a data collection and monitoring scheme should be set up to measure continually the effect of the RBF intervention (not only on the aquifer) and confirm the economic impact mentioned in the previous paragraph, as well as in other areas like food production and farmers income. The same mechanism funding the incentives scheme should pay for the cost of this data collection and monitoring scheme.

One of several potential ways to organize the scheme, depending on the specific circumstances could be the following: The scheme will start with a pilot scheme supported by a subsidy fund, which will be funded with a grant from an international development agency and, if possible, matching funds from the national government.

Two kinds of change agents will be organized; on the ‘soft’ side, the extension services of a local university would advise farmers on the most suitable technology and/or crop(s) that could lead them to reduce irrigation water consumption and potentially higher yields or crop values. The same (or a different) institution would certify vendors of the different technologies that could be used to reach the pursued objective. These vendors would compete to gain the farmers as customers. The farmers will be informed through awareness campaigns and workshops of the proposed scheme and the options available to them.

During the start-up of the project, while the information and sensitization campaigns are carried out, the IVA will conduct a baseline study to assess, if it was not done during project design, the volumes of water extracted from the aquifer in the pilot area and the water levels in the aquifer and estimate power consumption. That is, provided it is not being measured by the power utility (which would probably be the case given that the electricity is being provided free of charge).

The incentive scheme could be set in a way that the farmers will get a commercial credit from the vendors to install the new technology and the farmers will pay a reduced price for the hardware and installation of the new irrigation system. The rest of the price of the system will be paid for by the subsidy fund.

The vendors will be responsible for installing and assisting the farmers with the operation and maintenance of the systems and will receive part of the payment after the systems are installed and operating properly, as verified by the IVA. A final payment could be made after the first crop cycle is finished and the IVA certifies that the new systems continue to work properly and the farmers are satisfied with them.

Additionally, and in parallel, new power metres will be installed at the farms (one option is to have the same vendors manage such installation to reduce the cost to the power utility). The power company (and the IVA) would start reading the metres and issuing invoices clearly stating that the amount, even if for some time remains at 'zero' is being subsidized and what the timeframe is to 'normalize' the situation.

To this end, the electricity tariff 'normalization' could be done in one step after a long enough period of time to allow all farmers to embrace the new way of doing things or in several steps to induce behavioural change.

The IVA will monitor and report on the reduction in irrigation water consumption, the effect on the water levels in the aquifer and the evolution of power consumption, crop yields and farmers' revenues.

Provided that this information confirms the assumptions in the economic analysis, particularly those regarding the impact of the reduced power consumption in the delay of new power plants, the electricity tariff scheme could segregate a specific charge, from whatever charges are being billed for capacity increases, to continue funding the subsidy fund on an ongoing basis. This charge will be based on verified results, as the farmers would have already reduced their power consumption, contributing to a more efficient allocation of resources and a better utilization of the installed capacity (already leading to overall reduced production costs).

The pilot scheme, if successful, could be then extended to other areas with secured funding (not only for the subsidy but also for the data collection and monitoring in scheme) and already capable stakeholders could provide support to the new entrants.

The subsidy scheme could be organized in a way that would prioritize those farmers with the lowest income levels and have the better off ones pay in full for their systems. The way to target the subsidies could vary, depending on the information available at the time of designing the intervention. Targeting the subsidies will promote equality while not sacrificing the effectiveness and efficiency of the scheme, as those farmers who can afford to pay for their systems will still be motivated to install them due to the impending increase of the electricity tariffs.

4.2 *Scenario 2: Broader Scope, Long-Term Focus and Cascading Incentives*

The scenario presented is necessarily theoretical and extremely simplified with the purpose of introducing the subjects for discussion. At some point, there are some similarities with the previous scenario, but this was inevitable at this time. However, this scenario focuses on a different level of analysis and, hopefully, it will not sound repetitive.

4.2.1 Background

The proposed setting below assumes that the National Government of a particular country is committed to a rational approach to development based on or with strong focus on the nexus approach.

It also assumes that, after a thorough discussion process with a broad spectrum of stakeholders, a decision was made as to:

- The range of sectors and subsectors that will be included in the initial stages.
- The sectors that may join in the future, if not included from the onset.
- The geographical areas where the policies will be implemented and the different interventions will take place.
- The levels of government that will lead the efforts in each sector and subsector.
- The institutions that will perform supporting, but critical roles like data gathering, processing and analysis to improve the policies.

Let us also assume that the main problems identified linked to the nexus components are:

- Water resources pollution
- Soil pollution
- Flooding in urban centres
- Water productivity at farm level (revenue and protein productivity per unit of water used)

Furthermore, notwithstanding the imperfect understanding of all the causes related to such problems, it has been established that some of the most critical contributors to the current situation are:

- Poor solid waste management practices, from household garbage being thrown into creeks and streams that are consequently obstructed causing flooding upstream and pollution downstream.
- Poor solid waste disposal practices, using inappropriate dumpsites leading to soil and aquifer pollution.
- Inadequate use of fertilizers and pesticides leading to water resources pollution.
- Resistance to change crops and production uses at farm level.

Still, some questions remain like:

- Once the policies are set, how will these policies be sustained in the end, beyond political changes?
- How will the targets be set?
- How will progress towards those targets be measured?
- How will the policies be implemented at the national, provincial and municipal levels?

A possible way to go about these questions and approaching the issues would be to use an RBF point of view as attempted in the next section. The analysis is proposed in a way that higher, lower level objectives can be defined and targeted through different RBF tools.

4.2.2 High-Level Analysis

Even though some budget support instruments, like the Development Policy Operations funded by the World Bank, are used to support reforms at higher levels of government, one of the most suitable RBF tools to support high-level objectives is the COD approach. The critical elements to define are the indicators that will be used to measure the results, the baseline that will be used and how the information to calculate the indicator will be gathered, verified and processed. Adding the nexus angle to the COD scheme requires creative thinking to reinforce both concepts mutually.

The traditional COD scheme proposes that a government and a development institution will identify a problem, an indicator to measure variations on government performance in dealing with the problem, a way to measure and verify progress and a payment or compensation linked to the verified progress.

If the problem identified does not contemplate the impact in other areas (i.e. does not take into account the nexus), the whole scheme could be very effective in solving the problem at hand, but would potentially cause harm elsewhere. For instance, improving productivity at farm level could deteriorate water resource quality.

The solution that could be attempted is to define indicators for the individual problems identified and combine them in a more complex indicator that will tend to compensate for the crossed effects. Ideally, the combined indicator would mimic the impacts of one subsector on the others, but this would require a perfect understanding of the interaction between the different subsystems, which is not possible.

Mathematical models can go a long way towards supporting the definition of a complex indicator that takes into account the cross impacts of different activities on the concerned nexus components. This in turn would allow the government to plan the appropriate actions that will produce the largest improvement in the agreed indicator, maximizing the COD payments.

The programme could have a built in mechanism to calibrate the model, if the results significantly differ from model predictions or keep it up to date if it is accurate. Of course, this will require a strong monitoring scheme to track all activities potentially impacting the indicator and the variations in the values of the parameters participating in the definition or calculation of the indicator. This would be a costly exercise and would only be viable or practical if the COD payment and the economic benefits of the programme justify such scheme.

At the other end, the simplest way to build the combined indicator would be to assign weight coefficients to the individual indicators and multiply all of them in a way that tends to reflect the cross impacts. If an improvement in farm productivity, for instance, causes deterioration in the water resources quality, the two variations will tend to compensate, reducing the payment derived from the COD scheme.

As such, the way to design the indicator becomes critical to ensure that the incentives are inducing the right behaviour in each stakeholder. However, in most cases the available information is not enough to build a formula that allocates the right weight to each individual indicator. It may also be challenging the mere exercise of selecting what indicators to combine. However, if there is sufficient understanding of some of the cause and effect interrelation between the different elements that come into play, an initial formula could be proposed and a mechanism for adjusting it could be set. This adjusting mechanism should be fed through information gathered during the implementation of the different policies and interventions derived from them in each specific subsector.

One of the important elements of the COD scheme is that it leaves up to the government to decide the way the improvement in the indicator will be achieved; however, it sets a clear incentive to move in the right direction. The strength of the incentive would be a function of the associated funding committed by the development institution, and of the economic benefits that could materialize from the actions implemented towards improving the situation as measured by the indicator.

Provided that the adjustments to the indicator formula do not denaturalize the concept behind the initial objective, the proposed scheme could provide some continuity to the actions of successive governments. Maybe one administration would put more emphasis on one of the subsectors while the next one will focus on others but if the economic incentives are strong enough, the different administrations will still focus on improving the overall result measured by the combined indicator.

Using a COD scheme would provide the government with the flexibility to set the targets, if willing to do so, for each individual indicator and implement programmes and projects they consider most conducive to obtain the pursued results. It will also tend to guarantee the funding agency that the government will have strong ownership of the associated interventions in each subsector. However, to move towards each target, the policies should translate into action at the right institutional levels using similar or other RBF mechanisms as discussed in the next section.

4.2.3 Implications for Lower Implementation Levels

Although similar schemes could be set between the national and other levels of government, the use of other RBF instruments could also be suitable in contributing to the results pursued by the higher level scheme.

Output-Based Disbursement (OBD), could be used as a form of cascading incentives between the national and lower levels of government. Combining COD and OBD (or other RBF tools down the implementation chain) could make sense, as it is most likely that a programme aimed at improving state/provincial government performance throughout the country will improve the country’s performance as a whole.

The funds that the national government would receive through the COD scheme could be cascaded down to the lower levels of government through an ODB or other RBF scheme. This funding could be complemented with funding provided by other development institutions or with government funds disbursed using RBF mechanisms as has been done in some countries, including a broad programme for improving the availability and quality of water resources in Brazil.

An OBD scheme could make disbursement from the national government to provincial ones, conditional on the delivery of certain results. These payments may represent a portion of agreed budget allocations or additional funds to serve as incentives to be spent at the provincial government's discretion. However, payment will be linked to the achievement of certain goals agreed between the parties.

These goals could also be discreet outputs, like the construction of a wastewater treatment plant or an adequate landfill for solid waste or, ideally, it would be linked to the proper operation and maintenance of those assets to ensure that the intended effect of building them is materialized. Usually a combination of payments is used to incentivize completion of the infrastructure and its proper operation.

In certain cases it would also be possible, and even necessary, to pay the incentives linked to the increase in the volume of wastewater reaching the plant and properly treated or to the volume of solid waste disposed in the landfill, for instance. Depending on the circumstances, achieving these increases in volumes would require further use of other interventions that may require the use of other RBF tools.

In certain cases, some sectors of the population may not have the resources to connect their sanitation facilities to the network, even if the utility builds the collection networks in front of their houses. Switching from onsite sanitation to a sewerage system may require some onerous modifications to internal plumbing and investment in other appurtenances that would pose an insurmountable barrier to such sectors of the population. In these cases, a targeted subsidy scheme implemented using an Output-Based Aid approach could be ideal to cater to those that cannot afford to pay the cost of connecting to the network and ensure that all wastewater in the catchment reaches the treatment plant.

In the case of the landfill operation that would also be linked to the obstruction and pollution of creeks and streams, a Conditional Cash Transfers (CCTs) scheme after an adequate awareness and sensitization campaign, could contribute to changing the behaviour of those sectors of the population that dispose of their garbage in creeks and streams. To fund this scheme, the landfill operator could use part of the funds received from the government through the OBD scheme.

In the same way some insurance companies reduce premiums if a location device is installed in someone's car, reducing flooding recurrence and severity could trigger discounts in premiums to those in the catchment participating in a scheme like the one described above. Instead of passing to the customers the potential discount in full, a partial discount could be made while the difference would be used to fund the scheme until the new habits have taken root.

If the landfill operator is not responsible for garbage collection, another scheme may be needed to ensure proper collection and transport of the garbage to the landfill, which may or may not use an RBF approach to support its implementation.

As discussed, an RBF scheme could be used to tackle issues like resistance to change crops or improve fertilizer and pesticide application practices to contribute to reduced water resources pollution and improve farm productivity.

No matter what particular schemes are needed and how they are funded, the idea of cascading the incentives through a trickle down of the RBF funds put in play could serve well the purpose of securing the achievement of the higher level objectives as defined with focus on the nexus.

It is important to mention here that the link to the nexus when thinking about these lower level interventions would be established at the design stage of the intervention. This will require as clear an understanding as possible of the interrelations between the different subsectors affected by the intervention. In the case of solid waste being disposed in creeks and streams, the link is clear with the floods and water resources pollution, but other interactions may not be as clearly defined.

Whenever some uncertainties arise regarding the full impact of some interventions, more investigation and studies might be needed or, the intervention may go ahead while foreseeing the need to monitor certain parameters to measure those unknown effects and modify the intervention if needed.

In all cases, the IVA could prove a useful link in the data gathering chain to assist in improving the understanding of the interaction between the different components of the nexus. The scope of their work could be modified beyond what is merely needed to trigger the RBF payments and expanded to make sure that all the data considered necessary to improve such understanding are collected during the intervention and, may be, beyond.

5 Conclusions

The nexus and RBF approaches are relatively new concepts intended to improve the way development policies and interventions are designed and implemented. Both have a long way to go before they mature and become more integrated in the way governments and development institutions approach the issues they try to solve. At the same time, there are opportunities for mutual benefit between the two approaches as they could be combined at different design and implementation levels to achieve results that contribute to a more balanced development. Supporting the nexus approach could provide some of the existing RBF tools with opportunities to prove their effectiveness on a larger scale than what has been done so far. RBF tools and approach to the design of development interventions could support advancing the nexus approach at different levels.

When aiming to solve specific problems where the most relevant interactions are known, but some obstacles do not allow a straightforward solution to be implemented, one or more RBF mechanisms could assist in setting up incentive schemes to overcome those obstacles and achieve those results that are in line with a more balanced development approach as shown in the discussion concerning aquifer protection and farm productivity improvement.

In these circumstances, a detailed focus on intervention design is critical to make sure that appropriate attention is paid to each of the nexus components involved. If some of the crossed effects are not sufficiently understood, making use of the focus on data gathering and verification inherent to RBF tools could provide a good opportunity to obtain the data needed to fill some of the knowledge gaps leading to a better understanding of those crossed effects.

At a higher level, when there is strong government and development institution commitment to a more balanced approach to development and/or a willingness to broader understanding of the interrelations between the nexus components, indices could be used to measure the effects of different interventions in each component and combined in an appropriate way to compound positive and negative impacts. Thus, an RBF scheme like COD could reward those sets of interventions that contribute to an improvement in all components of the nexus combined instead of focusing on sector specific improvements.

In this case, a chain of intertwined interventions could be designed to take advantage of different RBF tools that incentivize different stakeholders to deliver those results that each can provide at their level and, in that way contribute to achieving the higher level of results that were delineated with focus on the nexus.

Aiming for more balanced development interventions, as pursued by the nexus approach and using results-based incentives to support such interventions, while improving our understanding of the overall interactions affecting the sectors in focus and allocating resources in a more transparent way, could sound very attractive. The proposed combination of approaches is an almost unexplored territory and would require a bold commitment from all stakeholders with a long-term horizon and a willingness to continue to support the effort and adapt to changing circumstances and new knowledge that could modify initial assumptions to see if the proposed association could prove effective.

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Chapter 6
Life-Cycle Cost Analysis of Infrastructure Projects

V. Ratna Reddy and Mathew Kurian

1 Introduction

Developing countries are plagued with poor and fluctuating service delivery with low or no priority for environmental protection. Often these two aspects are interlinked and complement each other in aggravating the problems. The problems are conspicuous in the case of infrastructure-based basic services like water, sanitation, power, health, etc. Main reasons for this include: (1) Lack of attention to planning and designing; (2) Neglect of source protection investments; (3) Lack of allocation towards capital or asset management practices; (4) Lack of understanding regarding the linkages between different sectors like groundwater aquifers, energy sector; agricultural and household demand for water resources, etc. and (5) Absence of disaster management preparedness or fund allocations towards such eventualities (Kurian and Turral 2010; Reddy and Kurian 2010).[1]

The experience of developing countries clearly indicates that the focus, in terms of planning, has been on infrastructure provision rather than service delivery. Investments have been confined to the production phase to the neglect of pre- and post-production phases. It is observed that expenditure on infrastructure accounts for more than 80 % of the total allocations in rural water supply services (Reddy et al. 2012). This is attributed to the fact that the budgeted unit costs of rural

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[1] For African and Indian experience see WASHCost project publications covering four countries http://www.washcost.info/page/196.

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drinking water services do not take source protection or system rehabilitation costs into account. As a result slippage[2] of service levels has become a regular phenomenon, i.e., service levels deteriorate or fluctuate between full coverage and partial coverage or unsafe resource situations (Reddy and Batchelor 2012). It is argued that unit costs are not only below the required levels but also the composition of costs is biased in favour of infrastructure to the neglect of source protection or natural resource base.

Natural resources, especially water resources, play a critical role in the agriculture dependent economies of developing countries. The linkages between land, water and energy need to be understood for enhancing the production efficiency of each sector as well as the combined efficiency for enhanced and sustainable food security. In most cases, natural resource systems are being utilized in unsustainable manner in most countries. Besides, their productivities, individually or combined, are very low and vary widely across countries. As a result, these growing economies experience increasing environmental impacts. Fostering sustainable development and mitigating environmental impacts could be possible through following a nexus approach (i.e., water, energy and food security). Following the nexus approach would pave the way for achieving green economy (Hoff 2011).

Green economy enhances welfare and equity while reducing environmental impacts. This calls for recognizing the inter-sectoral linkages and adopting a nexus approach for resource use efficiency and policy coherence rather than following sectoral approaches (Hoff 2011). In the absence of such sectoral integration, resource degradation has been the norm across the sectors, space and time. Besides, socioeconomic inequalities have been perpetuated. Water sector is the most affected in this regard. In the absence of integrated planning and policy coherence between water, energy and food sector, water resources are being over exploited due to distorted energy and food policies. On one hand, subsidies on power, fertilizers and water encourage farmers to use beyond optimum levels (inefficient allocation), on the other distorted output pricing policies often favour high water intensive crops (Reddy 2010). Similarly, subsidized inputs (fertilizer) have promoted intensive agricultural practices resulting in extensive land degradation in India (Reddy 2003).

Promotion of water conservation technologies (WCTs) such as micro irrigation, often takes only the farm level water use efficiency in consideration rather than looking at the watershed or basin scale. It is misleading to conclude that WCTs result in water savings without considering the scale aspects (Batchelor et al. 2014). Net water savings from WCTs at the basin level are much less than the observed water savings at the farm level as the latter does not take the return flows downstream from flood irrigation. Crop or product profitability needs to take its environmental impacts within and outside their respective sectors. Apart from crop water requirements, methane emissions and contribution to greenhouse gases

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[2] Slippage is used in the case of water, sanitation and hygiene services (WASH). WASH slippage is defined as the occurrence of a certain level of WASH services that has fallen back in a defined period of time to a lower level of services.

(GHG) vary across crops. Crop decisions or policies to promote crops need to take these externalities into account (Davis et al. 2008; Gathorne-Hardy 2013b).

In the absence of appropriate water pricing and regulation (economic or social), the extent of recycling and reuse of water has been very limited (Reddy and Kurian 2010). It was observed that water consumption levels vary widely across different bathroom fixtures such as flush tanks, faucets, showerheads, etc. (Reddy 1996). Unless one considers the water use (excess) externalities while pricing and taxing these products, it would result in unsustainable water use practices. In fact, of late, retailers and consumers are also looking for such information for promoting environmentally friendly products (Finnveden et al. 2009).

Perpetuation of distorted and incoherent policies in the context of climate variability has further aggravated the impacts of resource degradation on food security as well as socioeconomic equity. Climate variability has increased the risk and uncertainty in the livelihoods of the farming communities, especially in the rain fed regions. It is increasingly being realized that investment decisions and public policies need to take environmental externalities, negative as well as positive, and the risk analysis into account in order to ensure sustainable development. These observations hold well across the developing world.

Thus, the need of the hour is to formulate policies and make investment decisions addressing environmental externalities that would ensure sustainable services. That is project or programme appraisals need to be more comprehensive in order to move towards green economies. Adopting life cycle thinking is expected to take care of all these aspects and avoid shifting the burden between sectors and space (UNEP 2012). However, the progress in the adoption of life-cycle cost approach (LCCA) has been limited across the developing world despite the concerted efforts of the United Nations Environment Programme (UNEP) to mainstream LCCA into policy-making over the past decade.

Though the European Commission has taken the lead in mainstreaming LCCA into policy, there appears to be still barriers to its broader implementation (EC 2003). Important reasons for this slow progress include: (1) LCCA is data intensive and availability of required data and in appropriate formats is difficult; (2) Lack of clarity on drawing a line between what to and what not to include in the case of environmental impacts and (3) More importantly lack of awareness among the policy makers of its adoption and capacities to take up LCCA assessments. Awareness building at the policy level is the main bottleneck, as availability of data is often demand driven (i.e., data is generated as per requirements).

This chapter is an attempt towards awareness building among the policy makers, researchers and development practitioners about the importance and role of LCCA in achieving sustainable development and provision of sustainable services in the context of developing countries. Specific objectives include:

1. To discuss the rationale and relevance of LCCA in the context of developing countries.
2. To present the framework and concepts of LCCA.

3. To identify policy challenges for mainstreaming life cycle thinking at the policy level.

This chapter is based on the extensive and intensive meta-analysis of existing literature on LCCA across the world. The focus is on the role of LCCA in attaining sustainable development and sustainable service delivery with reference to developing countries. The chapter is organized into five parts. The following section presents the rationale and relevance of LCCA. The analytical framework and concepts are discussed in section three. Section 4 highlights the policy challenges in mainstreaming LCCA in the developing countries and the last section makes some concluding observations.

2 Life-Cycle Cost Approach (LCCA): Rationale and Relevance

Life-cycle cost approach (LCCA) is a comprehensive tool that is often used in project evaluation of various investments leading to products or services. Though the basic principles of LCCA are nearly a century old, its systematic use is only about 25–30 years old (Salem 1999). LCCA is an economic assessment or project appraisal tool that can be applied at any phase of the project life cycle, though it is preferred prior to the investment decisions. LCCA includes the whole chain and spread of activities from the start to end of the product life termed “cradle to grave”. LCCA takes a systems approach looking into inter-connectedness and impacts of/ and on other related sectors (i.e., including the externalities). Such a systems perspective is valid not only for the environmental dimension but also for social and economic dimensions.

The usage and adoption of LCCA has transformed over the last three decades from a project appraisal tool to an environmental impact assessment tool. During the early phases LCCA was widely used in infrastructure projects, such as construction, power, etc., for assessing project feasibility studies, affordability studies, source selection studies, repair level studies, etc. (Barringer and Weber 1996; Asiedu and Gu 1998; Korpi and Ala-Risku 2008). During the last decade or so LCCA is being propagated as an appropriate tool for environmental impact assessment and sustainable development (Lundin 2002; Chan 2007; Finnveden et al. 2009; UNEP 2012). Of late, LCCA is being adopted as an asset management tool that can ensure sustainable service delivery (Lundin 2002; Rahman and Vanier 2004; Bloomfield et al. 2006; AAMCoG 2008; Franceys and Pezon 2010; Reddy 2012; Kemps 2012). The evolution of LCCA has also experienced wider adoption across sectors during the last three decades. Initially LCCA was confined to the US defense department for procurement purposes (reducing the operation and support costs), but it has now been adopted in various sectors in public as well as private (construction, transport, manufacturing, energy, real estate, services sector, agriculture, biofuels, etc.) (Asiedu and Gu 1998; Jones et al. 2012; LNRMI et al. 2014; Harris and Narayanaswamy 2009; Batchelor et al. 2011; Davis et al. 2008; Gathorne-Hardy 2013a; Iraldo 2014). In fact, in 2002, the UNEP took the initiative to promote LCCA by providing a broader and deeper perspective to it. LCCA is being promoted as a tool and method to achieve a green economy and to be adopted in various infrastructures and other projects (UNEP 2012).

The wide spectrum of aspects and sectors LCCA is being adopted into indicates its potential to deal with number of pertinent policy issues ranging from project appraisal to achieving green economy, sustainable development and sustainable service delivery. Despite its potential in comprehensive project assessment, its application is often limited to one of three aspects [project appraisal, environmental impact assessment, asset management (service delivery)]. In addition, the coverage of life cycle phases in the assessment is limited (Korpi and Ala-Risku 2008). This is often attributed to lack of data, in terms of quality, to make comprehensive evaluations, especially with regard to environmental impacts (Ayres 1995). Besides, methodologies for assessing environmental impacts were also limited prior to the 1990s. As a result, studies have been limited to certain phases of life cycle, such as research and development (R&D), production and construction (production), operations and maintenance (O&M), and retirement and disposal costs (disposal) rather than considering the inter-connected sectors. The development of environmental economics during the last three decades has facilitated a more comprehensive use of LCCA. Moreover, LCCA, which has been a production engineer's assessment tool, is gaining acceptance with economists, planners, financial managers and policy makers.

2.1 LCCA: Beyond Project Appraisal

Until the beginning of the 21st century, LCCA was mainly used as a project appraisal or cost management tool in order to make investment decisions. It is observed that LCC is the most relevant cost management method and LCCA promotes environmental impacts instead of being a pure cost analysis tool (Korpi and Ala-Risku 2008). The increasing concern for environment and sustainable development during the 1990s has provided a new perspective and impetus to LCCA and its adoption. The Rio Summit in 2002 with its clear focus on global green economy has identified life cycle thinking as key to achieving sustainable development. That is, "If the green economy is to bring the necessary changes to guarantee a future for life on Earth, decision making on product sustainability, investment, and policy must be made using life cycle thinking and operationalised through life cycle management, approaches, and tools" (UNEP 2012, p. 13).

Life cycle thinking is capable of integrating environmental, social and economic impacts into the decision-making process thus ensuring sustainability in both public and private sector development initiatives. Life cycle thinking adopts the complete process of a product's life cycle from raw material extraction from the earth, planning, designing, processing, making parts, finished products, their usage and their disposal. In the process it not only takes into account the natural, social and economic resources that are being used in its production but also the impacts, positive and negative, the production process would cause to these resources. Thus, LCCA has the potential to achieve the objectives of nexus and green economy. Although this is not done often due to complex methodologies involved, the adoption of environmental economics methodologies has facilitated comprehensive LCA (i.e., adoption of consequential LCA against attributional LCA) (Finnveden et al. 2009).

Recent studies have shown that different crop systems can be evaluated and compared in terms of water use, energy use and emissions using LCCA. In a study of four different rice production technologies (intensive flooded high yielding varieties (HYV), rain-fed rice, systems of rice intensification (SRI) and organic rice) were compared for water, energy and GHG emissions (Gathorne-Hardy 2013b). SRI scored high when compared to other rice systems in terms of water, energy and emissions per kilogram of rice produced under the condition of low manure application. While SRI is an environmentally friendly method with less water and fertilizer requirements, the environmental benefits might get upset if excess manure (organic fertilizer) is applied. Similarly, a comparative assessment of biofuel and fossil fuel production systems using LCA has estimated that biofuel production has the largest estimated reduction of GHG when compared to fossil fuels (Davis et al. 2008).

2.2 Asset Management and Sustainable Services

Another dimension of the LCA that is less explored is its potential to ensure sustainable service delivery. The use of LCCA throughout the life cycle of an asset or assets appears restricted and undeveloped. For, LCCA is viewed as not necessarily a good budget tool (Barringer and Weber 1996). Lack of full-blown analysis covering all the phases of the life of an asset could be one reason, though life cycle costing in theory includes all costs at various stages of the life cycle. The adoption of LCCA ought to be broader throughout the economic life of the asset. In fact, LCCA is being used for economic benchmarking of assets (Boussabaine and Kirkham 2004 as quoted in AAMCoG 2008). The process helps in monitoring the economic performance of the asset in comparison with expectations set at the beginning of the project.

Such a process helps in maintaining the life of the asset and even extending the lifespan of the systems. This helps in maintaining certain level of performance (i.e., checking the slippage in services and maintaining sustainability of services).

This in the end ensures reduction in system breakdowns, minimizes costs, improves system efficiency, financial sustainability and service sustainability. That is getting value for the money invested. It is observed, “given the restricted budget available for renewal and replacement of assets, there is a need for much greater scrutiny of existing assets in relation to community worth. LCCA can be applied in this decision making process to judge, given the value of an asset to the community, if renewal or replacement is appropriate and when is the optimal time for such an event” (AAMCoG 2008, p. 13). This also minimizes the risk transfers in the case of public-private partnership contracts.[3]

As mentioned earlier, allocations are highly skewed in favour of capital expenditure, (i.e., asset or infrastructure creation with least concern for service flows from these investments). While the infrastructure focus is helpful in enhancing access and productivity in the short run, they have become dead investments with poor and inequitable service delivery in the long run (Reddy 2009; Kurian and Ardakanian 2013). The role of cost components like capital maintenance and resource protection is critical for asset management and sustainable service delivery. These cost components are often given least priority, especially in the public sector provision of goods and services (Reddy et al. 2012). The impact of the imbalance between capital and other recurrent expenditure becomes increasingly critical when coverage rates start climbing. The result is that water supply systems continue to fall out of service as fast as new ones are constructed. Although the approach has gained dominance as a service delivery model in progressively enhancing coverage, recent evidence suggests that there are critical second-generation sustainability concerns.

It is observed in the case of water, sanitation and hygiene services (WASH) services in four countries (Burkina Faso, Ghana, India and Mozambique) that allocations towards capital (asset) management are totally absent and this is one of the main reasons for the failure of WASH systems (Franceys and Pezon 2010). Even in the absence of allocations, public WASH utilities in India end up spending 5–6 % of the total cost on asset management. As there are no planned allocations these funds are often drawn from the regular O&M allocations. This in the end affects the up keep of the systems and service levels adversely (Reddy et al. 2012). In the absence of regular capital maintenance or delays in capital maintenance, there will be long periods of service breakdowns or very poor services (Fig. 1). And these break downs would often result in high rehabilitation and replacement costs pushing the unit costs higher. Thus, adoption of LCCA may in fact reduce long run unit costs (allocations) though the initial costs tend to be higher (Reddy et al. 2012) (Fig. 2).

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[3] In the case of private-public partnership projects, if the private parties do not include the capital maintenance costs, their total costs would be lower. But when these poorly maintained projects are handed over to the public or the community, the risk of failure becomes high as the adverse impacts of poor or no capital maintenance are realized after a time lag. In this way, the risk of service failure is transferred to the public sector or to the communities, while the private party saves on capital maintenance.

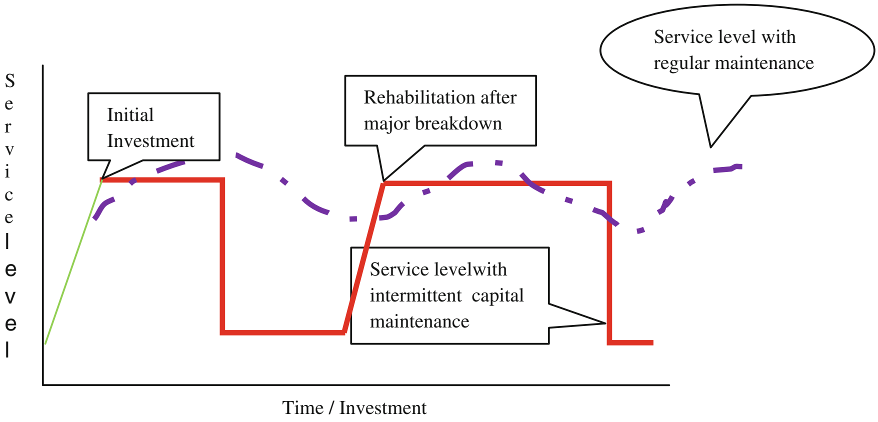
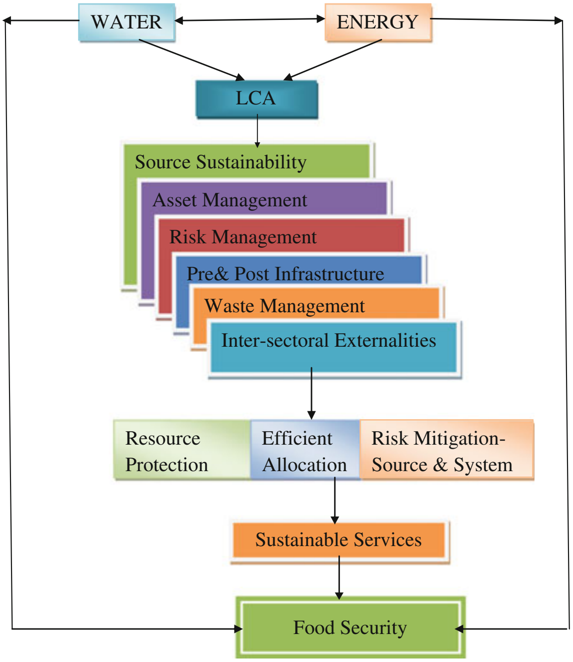


Fig. 1 Capital maintenance and service levels

Fig. 2 Nexus—LCCA—Sustainable services



2.3 *Adoption of LCCA: Scale and Intensity*

The adoption of LCCA is widespread covering numerous products in both public and private sectors. Most of the products, however, pertain to manufacturing sector covering construction, energy, transportation, etc. And the purpose of these studies are mostly for design trade-offs (45 %); source selection (38 %) and repair level analysis (13 %) and very few studies have taken all the phases of life cycle into account while making the assessments (Korpi and Ala-Risku 2008). However, this trend has changed since the beginning of this century. As observed above, adoption of LCCA has spread beyond manufacturing covering service sector as well as natural resources. These include water and other natural resources (Koehler 2008; Batchelor et al. 2011; Koroneos et al. 2013); crops (Iraldo et al. 2014; Gathorne-Hardy 2013b) and biofuels (Davis et al. 2008). Of late LCCA is found effective in service sectors like water and sanitation (WASHCost 2010; Jones et al. 2012).

Most of these studies have been framed in narrow life cycle boundaries thus limiting the potential for achieving sustainable development/green economy goals. There is need for enhancing intensity as well as scale of the LCCA adoption. This calls for policy changes making the adoption of LCCA mandatory at various levels and providing guidelines for achieving green economy objectives. For example, life cycle thinking is an important element of European environmental policy. A new law in Switzerland requires a complete LCCA of biofuels in order to quantify the fuel tax to be paid (Korpi and Ala-Risku 2008). Adopting life cycle thinking in all countries, especially in the developing countries where environmental protections as well as service delivery are of low priority, is important for achieving cost effective sustainable development. Awareness and capacity building for adopting LCCA methods and tools is a critical step in that direction.

3 LCCA: Framework and Concepts

As discussed, LCCA has evolved from a project appraisal tool to a more comprehensive method of incorporating sustainable development aspects in various sectors. LCCA could be conceived in the broader sustainable development framework. The framework consists of three inter-connected sustainability dimensions (economic, environmental, social). Economic sustainability concept draws from the public finance framework using financial and economic assessment of investments. Environmental sustainability is based on externalities framework (again from public good and public finance). Social sustainability draws from public policy framework where service delivery, governance and social equity are critical. Achieving sustainability on these three counts is a challenge. The nexus approach of water, energy and food security (Hoff 2011) comes close to addressing this challenge. The nexus approach provides a broader framework within which granularity exists. Here granularity is referred to the linkages within the sector and sub-sectors. For instance, within water sector, the linkages between surface and groundwater resources, between irrigation and drinking water. Similarly, within drinking water the linkages between water, sanitation, wastewater, reuse of wastewater, etc., are very much interlinked organically. The granularity is well captured in the three overarching questions raised by Kurian and Ardakanian (2013), (1) intersectionality (critical mass of factors at the intersection of material fluxes); (2) interactionality (interactions with exogenous factors, (policy, economy, environment, etc.) and (3) hybridity (building trans-disciplinary approaches).

Life cycle thinking is the conceptual idea behind LCCA that reflects the comprehensiveness of the approach in a systems perspective. LCCA takes the whole chain and spread of activities that take into consideration the nexus and the embedded granularity. It takes all the phases of the life cycle of a product or service that are required during pre-production, production and post-production into consideration. These include even the externalities of the production process (Fig. 3). It is also argued that the applicability of LCCA in development projects is limited in scope to the context of developing countries, as the all-pervasive social and political drivers are not adequately considered in the present LCCA tools (McConville 2006). LCCA is also data intensive, often making it difficult to use for development work. A life cycle evaluation of development projects must incorporate diverse factors in a practical manner with a judicious mix of quantitative and qualitative aspects. Further, lack of formal guidelines and reliable past data and difficulty in estimating future costs appear to be the main reasons for the tardy adoption of LCCA. The tool, therefore, must be consistent with successful development

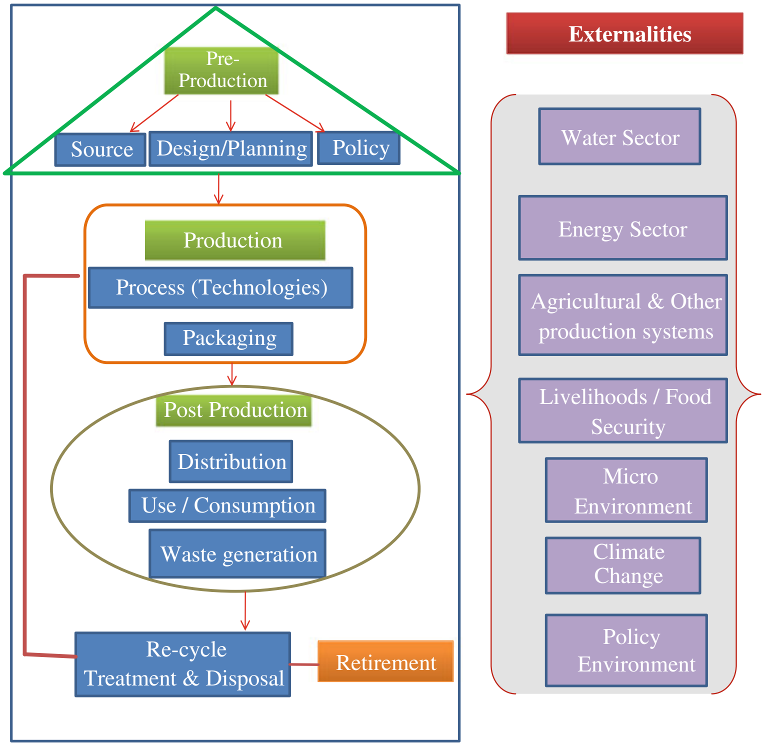


Fig. 3 LCCA framework in nexus approach

practices and simplified for use as a common tool. This could be achieved through a combination of methods and tools for understanding the dynamics.

Though LCCA has potential to deal with various externalities associated with the process, it is not possible to include and assess all the externalities associated with the process of production of any goods and services. While it is easy to scope (consequential) the externalities, it is not easy to assess the impact of these externalities (attributional). It is therefore necessary to define the system boundaries in order to reduce the complexity of assessing the impacts of all the externalities associated with the process. The choice of system boundaries depends on the nature and type of the product or service in question, which would have important implications on the results (Lundin 2002) and needs to be carefully considered. The life cycle (or functional) boundaries define the processes to be included in the system (i.e., where upstream and downstream cut-offs are set). Functional boundaries limit the various aspects that are to be included for the assessment. These are mainly related to the environmental externalities. There are three major types of system boundaries: between the technical system and the environment, between significant and insignificant processes, and between the technological system under study and other technological systems (Guineé et al. 2002 as quoted in Finnveden et al. 2009).

Here we present a generic LCCA framework that shows the possible phases of processes of product or service. These phases could be considered as system boundaries in a simplified version. At each phase, system boundaries can be a set of complex interlinkages. In this generic framework, we look at four phases and the system boundaries (Fig. 3). Pre-production phase (level 1) boundaries are defined to ensure resource sustainability and make judicious design and planning for sustainability. The assessment at this level helps in understanding potential environmental issues associated with basic source (raw material extraction). The designing and planning for the production phase is also included and need to incorporate these costs in conjunction with the policies.

The second phase pertains to production where the emphasis is on infrastructure, technologies and is usually linked to the management agency/institution/organization. This provides a more complete view of the system in terms of technologies, design efficiencies, planning (linking products and by-products) and packaging. Often the agencies, though aware, are usually constrained by financial and legislative obligations and tend to override options that allow a move towards environmental sustainability in the production phase. They either may adopt partially or may not adopt at all. Such a perspective may limit the potential of the agency to identify major environmental impacts or improvements through the life cycle.

The third phase deals with postproduction issues that are often dealt at the community/institutional/household level. These pertain to use/consumption (domestic, agriculture, industry, etc.); use practices, including waste generation, reuse, recycling, treatment and disposal. This can happen at the production phase as well and ultimately, the retirement of the uneconomic infrastructure. Often this set gets marginal attention, if not ignored, at the project planning level. This set reflects and determines the adoptability to the system in terms of capacities (technologies), affordability (finance), awareness (quality, health, etc.), attitudes (cultural), etc.

The fourth phase represents the externalities of/or to the system that are closely linked and surrounding the main system. The sustainability dimension of LCCA lies in capturing and assessing these externalities. Surrounding systems interact and are critical for the functioning of the core system. Water, energy and land are critical to any production system. While they are often part of the factors of production and included in the costs, these systems also are affected in the production process. Such costs or benefits need to be taken into account. Agriculture production or farming systems (including forestry, livestock, etc.) determine not only the demand for the products or services (fertilizer, pesticides, water, etc.) but also are affected in the process (land degradation, chemical use, etc.). These processes would affect the microenvironment in the case of waste or effluent discharge and affect livelihoods positively, as well as negatively. Other important factors like climate and policy changes add the risk and uncertainty dimension to the whole process. These need to be taken into account while assessing the costs.

This framework can be articulated in the context of water and sanitation that are mostly dependent on scarce groundwater resources in developing countries. Groundwater is exploited to supply drinking water in rural and urban areas. These resources are neither protected from over exploitation nor supported through replenishing mechanisms (like percolation tanks). There are competing demands for water from agriculture, industry and other livelihoods. In most cases, there are no policies to address these issues. This is part of the pre-production phase, where one has to include the costs of not only identifying and locating the resource but also include costs of planning and design for their sustainable use in the end. During the production phase, different technologies are used to exploit, treat and distribute the water. Here identifying appropriate technologies that provide optimum benefits are necessary for financial sustainability of the system. Besides, managing the infrastructure is critical for maintaining the life of the infrastructure and sustaining services. Energy sector plays a critical role at this phase. During the post-production phase, distribution and use are critical for social sustainability in terms of attaining equity in the distribution of services. Here, the institutional and governance aspects play an important role in ensuring social sustainability. Reuse, recycling, treatment and disposal are important for environmental sustainability. Wastewater generated from WASH services in the urban areas is used for irrigating crops in the peri-urban areas. While the use of wastewater provides livelihoods and economic benefits to communities, it also results in negative impacts like water quality deterioration, health impacts, human as well as livestock, etc. (Reddy and Kurian 2010). Apart from these externalities, the linkages between groundwater and energy also result in externalities such as resource degradation. These externalities can be internalized with judicious planning. The problems of degradation further aggravate in the context of climate variability or policy distortions. Policies like free power would increase the risk of degradation.

3.1 Cost Components

LCCA analyses the aggregate costs through the life cycle of the system or infrastructure. In a standard LCCA, acquisition costs and sustaining costs are included at the aggregate level (Barringer 2003). These costs are also termed as recurring and non-recurring costs or fixed and variable costs. Each of these costs will have various components of costs at the disaggregate level. Acquisition costs include hardware and software costs. Hardware costs include mainly infrastructure, buildings, etc., while software costs include research and design costs, capacity building, etc. Broadly, the cost components include not only the construction and operational costs but also the rehabilitation and IEC (Information, Education and Communication) costs. These are capital expenditure on hardware (initial construction cost) (CapExHrd), capital expenditure on software (CapExSoft), capital maintenance expenditure (rehabilitation cost or CapManEx), cost of capital (CoC), direct support costs (ExDS), indirect support costs (ExIDS), and annual operation and maintenance costs (OpEx). These are broadly grouped under fixed and recurring costs (Box 1).

While fixed costs include source protection and construction (hardware) along with designing and planning (software), variable or recurring costs include capital or asset maintenance; operation and maintenance costs, CoC, direct and indirect support costs, including training, planning and institutional pro-poor support. The delivery of sustainable services also requires that financial systems be in place in order to ensure that infrastructure can be renewed or replaced at the end of its useful life and to extend delivery systems in response to increases in demand (Reddy et al. 2009).

Depending on the nature of the product or service, it is likely that households, apart from public utilities or private agencies, also invest or incur costs. These costs could be fixed or variable depending on the product or service. It is observed that households often spend substantial amounts towards fixed and variable costs in order to improve the WASH service provided by the public agencies (infrastructure, such as wells, storage, toilets and operational costs, such as minor repairs, cleaning, etc.). These costs are incurred in order to overcome reliability and convenience issues related to water services. Along with these expenditures, households also spend time fetching water and money towards buying water. These are incurred to overcome access and quality problems. While monetary expenditure alone is considered in the case of financial analysis, economic analysis includes both public and household expenditure in monetary terms and opportunity costs. On the other hand, in case of sanitation, public and household expenditure are mutually inclusive, as household expenditure is a necessity and mandatory for construction of household toilets. Hence, both public and household expenditures need to be analyzed together for sanitation.

Another set of costs that are important in a comprehensive life-cycle cost analysis (green economy approach) are the costs associated with environmental externalities. These include degradation costs of natural resources like soil, water, air, etc., emissions or effluents that directly affect livelihoods, health, etc.; long term impacts like GHGs, etc. These impacts could be positive or negative. They could take place within the sector or product that is being assessed or any other sector linked to the core sector.

Box 1: Cost Components

Fixed costs

CapExHrd: Includes government expenditure on infrastructure such as water sources, pumps, storage, filters, distributions systems, etc.

HHCapExHrd: Includes household expenditure on infrastructure such as water storage, toilets, wells, pumps, etc.

CapExSft: Includes government expenditure on planning and designing costs of the schemes.

Recurring costs

CapManEx: Includes capital maintenance such as rehabilitation of sources, systems, etc.

CoC: Includes the interest paid on the borrowed capital for investment in the WASH sector.

ExDS: Includes staff salaries, and post implementation activities such as IEC, demand management, and training of mechanics.

ExIDS: Includes policy planning at the macro level, i.e., central and state.

OpEx: Includes regular operation and maintenance of the systems such as energy costs, minor repairs, filtering costs, salaries of water man, etc.

HHOpEx: Includes household expenditure on operation and maintenance of water systems, sanitation facilities, etc.

RTCost: Retirement costs include the termination costs of the infrastructure

Costs of environmental externalities

Include resource degradation costs within sector and in other sectors that are linked to the core sector.

3.2 Discount Rates, Annualization and Functional Unit

All the fixed capital investments are being made over the years and are hence cumulated over the years, as are benefit flows. When LCCA is adopted at the initial stages of the project, the capital or fixed investments are made in the current year and the recurring investments are made in the future years over the life of the system. Some of these costs are regular and expected (operation and maintenance) and others could be irregular and unexpected (capital maintenance). Benefit flows take place in future years. In order to make project appraisals comparable between products or services all these costs and benefits need to be assessed at the current year. In cases where LCCA is taken up at a later stage of the project, historical costs and benefits are used where costs and benefits would accrue in the past as well as in the future. These costs and benefits are inflated to the current year level. Various deflators (future benefits) or inflators (past investments and benefits) are being suggested in the literature (Barringer and Weber 1996). These range from the National GDP inflator/deflator (inflation based) to fixed consumption (depreciation) and accelerated depreciation or appreciation. In the case of environmental benefits, lower discount rates are often proposed.

Different systems have different lifespans, including technical, economic and useful. In order to make the projects comparable the lifespans need to be standardized by annualizing the costs. In order to arrive at the unit costs per year, all the capital costs (CapExHrd) are annualized using the normative lifespans of the systems (i.e., the technical lifespan). Arriving at the lifespan of a system becomes complicated where different components of the system have different lifespans. Using component wise lifespans for hardware such as boreholes, pumps, pump houses, overhead reservoirs, hand pumps, etc., is more realistic. While normative lifespan is determined technically, it may not hold well in reality. Systems may last longer or shorter than their normative life due to various factors such as poor maintenance, natural factors like hydrogeology; precipitation, temperature, humidity, etc., natural disasters like floods, droughts, etc. The actual lifespan is the actual number of years the component lasts. By comparing these two, one can assess whether the actual cost of provision is more or less than the estimated costs. Besides, actual lifespan takes into account the risk and uncertainty associated with the system.

Standardization is also necessary for comparing the environmental benefits or dis-benefits. Functional units are specified for each assessment and they should be comparable across the products or services. For instance, emissions per unit (kg) of produce or wastewater generated per unit of water in filtering (litres).

3.3 Components of Life Cycle Cost Model

The basic LCCA functional form should include the components as indicated in Eq. 1.

$$\mathbf{LCC}_{xt} = f\left\{\sum_{t=1}^{n}(\mathbf{CapExhw}_{xt}; \mathbf{CapExsw}_{xt}; \mathbf{CapManEx}_{xt}; \mathbf{CoCap}_{xt}; \mathbf{DsCost}_{xt}; \mathbf{IDsCost}_{xt}; \mathbf{OpEx}_{xt}) + \mathbf{CoEExt}_{xt}\right\} \quad (1)$$

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where

LCC_{xt}	Life cycle costs of specified product/service
$\mathrm{CapExhw}_{xt}$	Capital expenditure on hardware (initial construction cost)
$\mathrm{CapExsw}_{xt}$	Capital expenditure on software
$\mathrm{CapManEx}_{xt}$	Capital management expenditure (rehabilitation cost)
CoCap_{xt}	Cost of capital
DsCost_{xt}	Direct support costs
$\mathrm{IDsCost}_{xt}$	Indirect support costs
OpEx_{xt}	Annual operation and maintenance cost
CoEExt_{xt}	Cost of environmental externalities

x represents product or service and 't' represents year.

These costs are essential to carry out project appraisals that deal with environmental as well as social sustainability (service delivery) in the short to medium run at least. However, some of these costs are difficult to quantify, especially the costs of environmental externalities. All the costs need to be standardized by annualizing the costs. Some of these costs like OpEx are incurred annually while others need to be annualized. And these investments, past or future, need to arrive at the present value of these investments in order to make the investments comparable across the schemes. Accordingly, Eq. 1 can be written as:

$$\begin{aligned}\mathbf{LCC}_{xt} = f\Bigg\{\sum_{t=1}^{n} \mathbf{pvf}_{xt}(&\mathbf{CapExhw}_{xt}; \mathbf{CapExsw}_{xt}; \mathbf{CapManEx}_{xt}; \mathbf{CoCap}_{xt};\\ &\mathbf{DsCost}_{xt}; \mathbf{IDsCost}_{xt}; \mathbf{OpEx}_{xt})\mathbf{CoEExt}_{xt}\Bigg\}\end{aligned} \tag{2}$$

where

pvf	present value factor $(1 + r)^t$
r	rate of interest or inflator
t	time period

Rate of inflation or the prevailing rate of interest may be appropriate for estimating the present value or worth. Other alternatives include effective interest rate (rate of interest-inflation), national GDP inflator, etc., could also be used. Once the whole life costs are estimated, unit costs and annualized costs can be worked out.

3.4 Risk-Based Life Cycle Cost Analysis and Simulations

While normative lifespan of different systems may not vary much, the actual lifespan varies due to risk and uncertainties associated with natural factors and unexpected climate events. The risk and uncertainty are often high in the case of products and services associated with natural resources. The risk factor can be modelled using probabilistic phenomena. That is by estimating the probability of risk in a particular location due to a particular event. In the event of risk, Eq. 2 could be written as:

$$\mathbf{LCC}_{xt} = f\left\{\sum_{t=1}^{n} \mathbf{pvf}_{xt}(\mathbf{CapExhw}_{xt}; \mathbf{CapExsw}_{xt}; \mathbf{CapManEx}_{xt}; \mathbf{CoCap}_{xt}; \mathbf{DsCost}_{xt}; \mathbf{IDsCost}_{xt}); \mathbf{OpEx}_{xt}; \mathbf{CoCEExt}_{xt}[\mathbf{Psf}_{xt}]\right\} \tag{3}$$

where

Psf_{xt} Probability of risk

This formulation is more appropriate in the case of WASH services, as the dependence on groundwater is quite substantial. In this case, the total life cycle cost is modelled as a random variable that is the sum of several cost items. Of these variables, the CapManEx is a random variable. The randomness or the probability of failure could be estimated using the observed values from the real life costing in different agro climatic locations. These observations can be complemented with expert opinions.

Risk and uncertainty analysis is often carried out using the scenario building. Different scenarios are built using assumptions pertaining to the expected risks. Scenario building gives a band or range of possible options to choose from. Simulation models are used to arrive at scenarios.

4 Mainstreaming LCA into Policy

Environmental issues are increasingly gaining attention of policy makers in developing countries, though they are yet to get into the top priority list. Political economy factors constrain the promotion of environmental issues as a priority. As a result, environmental issues are often pushed through “command and control regulation” policy instruments. The experience with the implementation of these command and control instruments has not been encouraging in the absence of complementary inter-sectoral policies. Of late, voluntary approaches are being considered as effective policy instruments to complement the traditional command and control measures (Iraldo et al. 2014). The increasing demand from consumers for environmentally safe products and services is pushing the industry to address environmental issues voluntarily. Others include the use of incentive and dis-incentive structures for promoting or polluting the environment and through negotiated agreements with private sector.

There is an urgent need to promote environmental issues into the foreground in developing countries. Some of the environmental impacts are clearly resulting in unsustainable and irreversible damages (water, forestry and other common pool resources). Climate change impacts have further hastened the process of degradation. The degradation of resources coupled with the inter-linkages between different sectors are resulting in strident constraints on basic amenities like water, sanitation and power. And they are directly affecting food security in developing countries, especially vulnerable regions like rain fed areas. The linkages between unsustainable resource use patterns and the sustainability of basic amenities and food security are only vaguely understood at the policy level. At the same time, unsustainable service delivery of basic amenities and unstable food security are putting pressure on policy makers to improve services and promote sustainable resource use pattern. Hither to, policy reactions to the problems have been in the nature of managing the problems in the short run rather than solving the problems in the end. This requires a systematic and scientific approach with judicious planning.

The development experience so far has been that issues or problems are taken up or solved in isolation. Given the inter-connectedness of different sectors or subsectors within a particular sector, there is need for a systems approach. In most developing countries, there are no guidelines for project appraisal. In fact, in the case of public infrastructure projects, project appraisals are hardly carried out, though ex-post evaluations are most common. Over the last decade or so environmental impact assessments are being made mandatory in large scale projects (public as well as private) like irrigation, mining, power, etc. Of late, environmental or natural resource impacts find a place in ex-post evaluation of public funded projects like watershed development, but they are not comprehensive enough to incorporate environmental sustainability issues. One reason is that there are no guidelines on how to go about environmental impact assessments, though they are mandatory for getting approvals. As a result, environmental impact assessments are carried out as a formality rather than to achieve any objective(s) (say sustainable development).

The result is that the appraisals or evaluations remain partial in terms of addressing the inter-connected issues and keep shifting the problem from one sector to another. As revealed in this review, LCA is one of the most comprehensive tools used to assess the environmental impacts of a product or service. LCA can be used to compare different technologies not only on their financial or economic merits, but also on their impacts on environment or natural resources. Combining economic and environmental impacts provide the net returns to the technology. This provides the basis for selecting sustainable technologies/products/services. Besides, it is shown that adoption of LCA is also capable of ensuring sustainable services and food security. This could be achieved not only due to the inter-linkages between basic services and natural environment, but also due to its approach to cost analysis.

The merits of LCA in addressing environmental impacts are well recognized at the international level. Following the UN life cycle thinking initiative, number of European countries has initiated policy commitments to adopt LCA (Finnveden et al. 2009). Its adoption in developing countries is yet to take shape. Apart from low priority for environment at the policy level, awareness about LCA itself is very limited. The adoption of LCA in the private sector is also quite low in the absence of any policy guidance or regulations. At the same time, there is increasing awareness about the environment among consumers though demand for such goods and services are limited due to high environmental premiums (organic foods).

How much do the so-called environmentally safe goods and services (at the consumer level) really contribute to a green economy? It is observed that excess use of manure in the SRI would increase methane emissions and GHGs (Gathorne-Hardy 2013b). While SRI is being promoted for its water saving qualities (less water per kg of paddy produced), its other impacts are not well understood. For instance, the water saved in SRI is often used to expand the area under crops in the same location. When taken at the basin scale there will not be any water savings for environmental requirements (environmental flows). Besides, SRI does not have any return flows (which is a case for flood irrigation) and hence reduces the availability of water downstream resulting in inequity. This is observed even in the case of other water saving technologies (WSTs) (Batchelor et al. 2014).

Another case where such granularity is missed is wastewater usage for productive purposes. While wastewater is often let out into streams, ponds and rivers without treating it, its usage downstream for productive purposes not only creates jobs and income but also results in adverse health impacts. Unless the net impacts (positive-negative) are assessed, the economics of wastewater use would not be clear for making investment decisions to create infrastructure for wastewater treatment (Reddy and Kurian 2010). That is, water sector policies and investment decisions should shift from single use infrastructure to multiple use infrastructure investment decisions. Such contradictions are also observed in the case of different biofuel production processes (Davis et al. 2008). Therefore, it is necessary to understand and adopt a comprehensive approach in order to move towards sustainable development. Moreover, macro policy has a critical role in promoting such approaches and awareness in public as well as private organizations.

Given the fact that sustainable services and food security are integral to LCA, adoption of LCA could provide double benefits in developing countries, where dwindling services is a major policy concern. In this regard, LCA could provide cost effective measures as a sector-financing tool for sector efficiency. Adopting LCA to finance the sector would help to get the unit costs right and the right balance of different cost components for sustainable service delivery. In the case of environmental issues, European countries have introduced standardization processes through International Organisation of Standards (ISO). ISO has developed standard labelling like eco-labelling, environmental claims and eco-profiles for voluntary adoption (Iraldo et al. 2014). Even in Europe, the application of LCA is limited to design stage and not applied in the implementation stage (Schiller and Dirlich 2013).

While adoption of LCA provides win-win policy strategies in developing countries, there is need for awareness and capacity building for wider promotion and adoption of LCA. While LCA is not a new concept in these countries, it needs recasting to address present day concerns. Particularly since LCA is often viewed as an engineer's tool for project appraisal. Its evolution over the years as an effective tool to move towards sustainable development and service delivery has also encouraged planners and financial managers to adopt it with conviction across the world. This needs careful articulation in order to mainstream it into policy-making. Moving towards life cycle thinking and life cycle-management of infrastructure projects. It is not to suggest that developing countries need to embark on the same path followed by the developed world. Understanding the potential and adoptability of LCA to local conditions, in terms of scale and intensity, is critical.

Apart from awareness and capacities, one of the main constraints in adopting LCCA in developing countries is the huge data requirements. LCCA is known for its data intensity and sensitivity to the methods and tools used in assessing environmental impacts. Building on the data sources and ensuring data quality on various indicators across the sectors is a necessary first step. The most challenging aspect in this regard is coordination between sectors and their departments for data generation and data sharing. For instance, inter-departmental coordination and integration has been in the cards for quite some time in India, but yet to be implemented in practice. Creating information and feedback loops between the departments through centralized information system might help in overcoming this problem. Often important environmental data is not accessible to researchers or public though it is collected by the industry thus keeping the likely environmental impacts in the dark.

5 Conclusions

This chapter reviewed the work on LCCA with the intent to influence the policy understanding of why life-cycle cost assessment is central to achieving the objectives of sustainable development as well as sustainable service delivery and to influence the behaviour of sector stakeholders. The broad objective is that LCCA is mainstreamed into governance processes at all institutional levels from local to national in order to increase the ability and willingness of the decision makers (both users and those involved in service planning, budgeting and delivery) to make informed and relevant choices between different types and levels of products and services.

This chapter, based on the experience of earlier studies, argues that a comprehensive LCCA can provide win-win strategies in terms of identifying appropriate technologies, products and services that are environmentally, economically and socially sustainable. LCCA prompts policy shifts towards broader systems perspective, as it is not limited to policy planning. Adoption of LCCA evolves from life cycle thinking that needs to be ingrained in macro policies. LCCA management processes need to be put in place. This calls for awareness building and capacities at the policy and planning levels. Here we provide the key merits of LCCA that can attract quick policy attention.

1. LCCA is an appraisal tool that can be applied at any stage of the life cycle. This helps in evaluating even existing infrastructure investments.
2. LCCA has the potential to deal with the nexus approach by adopting a systems approach that includes inter-sectoral linkages and externalities.
3. LCCA is now widely used covering most of the sectors, products and services. Common or standard LCCA guidelines can help in following a systematic economy wide approach.

4. LCCA can potentially embed a 'green economy' perspective if mainstreamed in public sector procurement practices; and issue that is addressed by the next chapter on European experience with wastewater projects.
5. LCCA can be used as a budgeting tool, which can ensure allocations towards source sustainability, asset management, natural disasters, etc. This provides the much-needed sustainability of services.

Adoption of LCCA as a budgeting tool could be a quick uptake at the policy level. This needs to be taken up at the national and state level budgeting processes. There is need for more research in the context of developing countries to establish and convince policy makers in this regard. Action research on the adoption of LCCA in some key sectors would be a good starting point in this direction.

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Part III
Strategies for Implementation: Guidance on Resource Reuse and Data Visualization

Chapter 7
Applications of Life-Cycle Cost Analysis in Water and Wastewater Projects: Lessons from European Experience

Georg Schiller and Stefan Dirlich

1 Introduction

Investment decisions in water management are based on long-term considerations, as water systems are long-lasting network structures that determine the kind of water supply and wastewater treatment for a given location and time frame. Associated with the long service life of water infrastructures is the relative importance of operational and maintenance costs in comparison with the cost of the initial start-up investment. The concept of life-cycle costing (LCC) is as an adequate concept to consider these specific characteristics in water and wastewater management. The question is whether this works in practice. In this chapter, the water and wastewater sector in Germany, particularly, and Europe is analysed with respect to the practical implementation of the LCC approach in water and wastewater management. Current and future challenges for the water management sector in Germany and Europe are presented as well as the basic concept of LCC. An overview of applications of LCC in different fields of water management is given, which also considers similar approaches being applied in the sector, but not under the umbrella of LCC. Finally, conclusions are drawn based on the analysed aspects.

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2 Challenges in the Water and Wastewater Sector in Germany and Europe

Water is essential for human beings and at the same time a public good. The European Water Framework Directive (WFD) clarifies that "water is not a commercial product like any other but rather a heritage which must be protected, defended and treated as such" (EP/EC 2000, p. 1). Therefore, water and wastewater management, as part of the infrastructure systems and services for the public, carries particular meaning.

2.1 General Characteristics

Apart from water being a public good, water and wastewater systems exhibit specific features due to physical circumstances. Networks for drinking water supply and wastewater disposal are in general characterized through long-lasting systems with a high capital lock-up. Due to this structure, these systems exhibit a marginal adaptability. Once investment decisions are made, the type of water supply and wastewater disposal is influenced over a very long period.

The situation of water/waste water management in Germany is characterized through a high connection rate of 99 % for drinking water and 95 % for wastewater (Eurostat 2013a, b). The quality of the system can be identified as good or even very good. For most countries in Europe, the connection rates are comparable, ranging between 75 and 100 %. However, in some countries such as Bosnia and Herzegovina or Romania, the population connected to drinking water only amounts to some 50 %. The rates for wastewater are in general lower than other European countries (60–99 %) and in some cases, the rate is even lower (e.g. Croatia 29 %, Macedonia 9 %).

According to the statistical data of the European Environmental Agency (EEA), there are regional differences across Europe in terms of the connection to wastewater collection (see Fig. 1). While North and Central Europe have the highest rates of connection, the numbers in the south and east are lower. The connection rate in the southeast is the lowest (65 % in 2009). However, within the recent decade, many European countries with relatively low connection rates developed water systems, and in particular, the south could catch up with the leading groups. Nevertheless, the situation in southeast Europe is still characterized by a large proportion of collection without treatment.

Despite the principally good water quality, some watercourses and bodies including groundwater suffer from increased input of nutrients such as nitrates for which intensive agriculture is made responsible (UN Water 2012, p. 185). Concerning the ecological quality of surface water in Europe, the EEA, however, alludes that "…less than half … are reported to have good ecological status" (EEA 2013, p. 64). Especially in Central Europe (northern Germany, Netherlands,

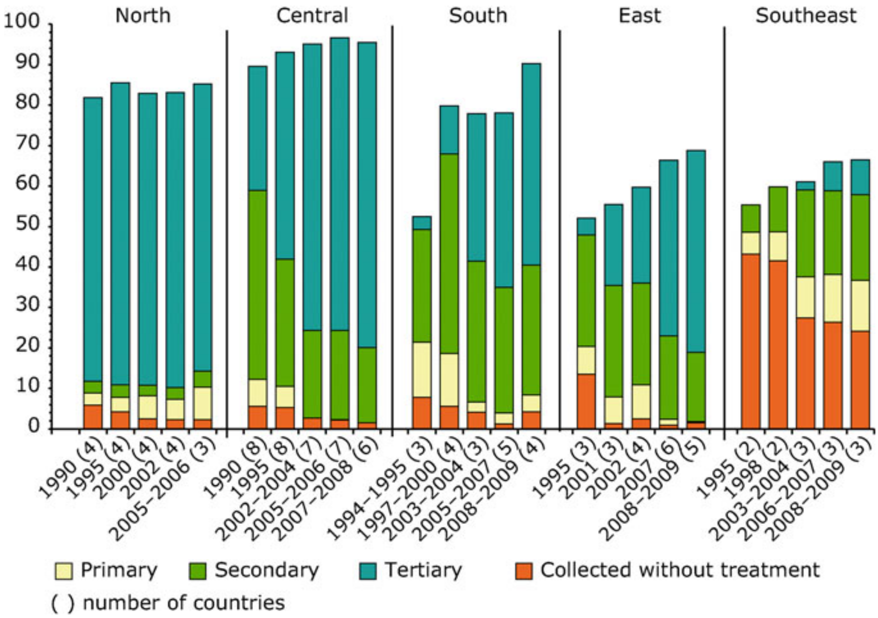

Fig. 1 Population connected to waste water collection and UWWTPs (Urban Waste Water Treatment Plants). *Source* EEA (2013). *Notes* Primary (mechanical) treatment removes part of the suspended solids. Secondary (biological) treatment uses aerobic or anaerobic microorganisms to decompose most of the organic matter and retain some of the nutrients (around 20–30 %). Tertiary (advanced) treatment removes the organic matter even more efficiently and generally includes phosphorus retention and in some cases nitrogen removal. *North* Norway, Sweden, Finland and Iceland. *Central* Austria, Denmark, England and Wales, Scotland, the Netherlands, Germany, Switzerland, Luxembourg and Ireland. *South* Cyprus, Greece, France, Malta, Spain and Portugal. *East* Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovenia, Slovakia. *Southeast* Bulgaria, Romania and Turkey

Belgium), the ecological status of water is not good (EEA 2012, p. 12) due to intensive agriculture. Nevertheless, the EEA acknowledges in its Environmental Indicator Report 2013 that some pollutant emissions have been reduced significantly in the past 25 years. Furthermore, the agency observes a significant improvement of the chemical quality of water within the last three decades; however, "… 10 % of Europe's surface waters … have poor chemical status" (EEA 2013, p. 67). The European WFD is intended to interfere at this point aimed at reaching a good ecological and chemical quality of waters until the year 2015 (EP and EC 2000). In this context, there is a particular need for action for the original polluters (e.g. agriculture), while the impact of water and wastewater management on the water quality is principally positive.

2.2 Changing Demand and Future Challenges

Beside the maintenance of existing networks of the infrastructure system, water and wastewater management faces currently a number of challenges particularly resulting from implications of demographic changes and climate change.

In many European regions, water and wastewater systems react to the effects of a stagnating or even shrinking population development. Figure 2 demonstrates the spatial dispersion of the population dynamics in the countries of EU-27. Besides areas of growing population there are regions, specifically in central Europe, but in southeast Europe as well, which are confronted with a declining population. In such cases, the cost-intensive, pipeline-bound water infrastructure reaches its limits due to financial constraints, which appears particularly in rural areas. In addition, it

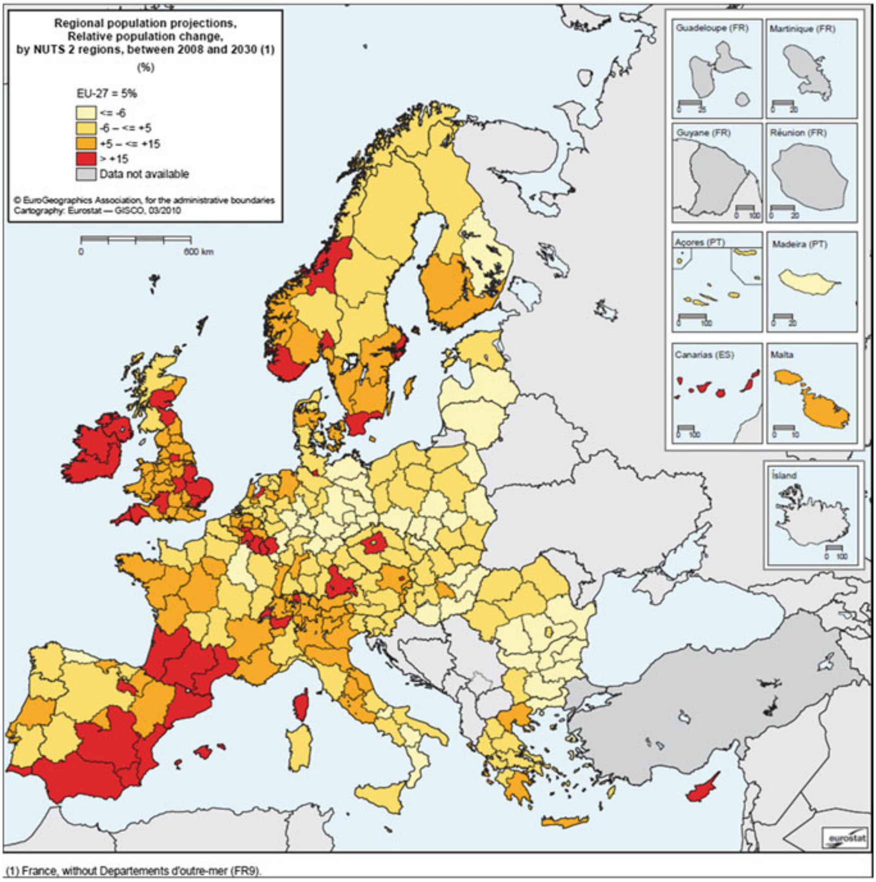

Fig. 2 Regional population projections, relative population change, by NUTS2 regions, between 2008 and 2030. *Source* Eurostat (2013b)

should be made clear that the smaller the spatial scale of analysis, the more intensely the dynamic development must be differentiated.

Further challenges arise in the context of climate change, which possibly leads to quantitatively increased and intensified events of extreme weather (heavy rainfall, droughts) with considerable implications for the managed amounts of water. The dimensioning of the pipes and the entire network must consider these extreme conditions.

2.3 Resource-Efficiency and Water-Energy Nexus

In water management, there are certain potentials for implementation of more resource-efficiency and even a nexus between water and energy.

In water and wastewater networks, there are currently many activities to improve resource-efficiency. Yoshida et al. (2013) for example analysed current studies on life-cycle assessment of sewage sludge management. In their list, the majority of studies had been driven by either phosphorus recovery or energy recovery (p. 1085).

In light of ever-increasing energy prices, water and wastewater management is interested in higher energy efficiency as well. Hence, there are numerous research activities targeting this direction such as using renewable energy to power the water and wastewater facilities.

Moreover, a nexus can be achieved between water and energy as well (e.g. Novotny 2013). Wastewater for example provides several potentials in this context. The biogenic substances (sewage sludge) contained in wastewater could be utilized by drying and incineration, which is currently done in Dresden, Germany, where the sewage sludge from wastewater treatment is energetically utilized (Urban Drainage Dresden 2014).

Further options include the direct use of thermal energy of wastewater through the installation of heat exchangers, as well as the utilization of gravitational and kinetic energy of running water.

3 Life-Cycle Costing: Concept and Regulations

The approach to integrate life cycle costs into cost and investment decisions follows the perception that costs do not only occur during the construction of an asset, but also during all phases of the life cycle starting with the extraction of raw materials to production and operation up to the final disposal (see Fig. 3). Basis for the current debate on life-cycle costing (LCC) is the standard work by Fabrycky and Blanchard published in 1991. The scientific debate ranges from theoretical aspects such as the relationship between LCC and Life-Cycle Analysis (LCA) (Rebnitzer and Hunkeler 2003) to more practical questions of how LCC can support decision

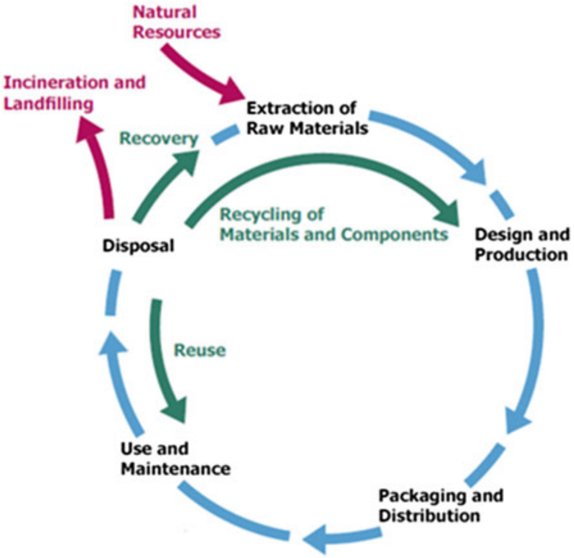

Fig. 3 Product life cycle. *Source* UNEP/SETAC (2007, p. 12)

makers in their investment decisions (Jayaram and Srinivasan 2008; Fonseca et al. 2011; Molinos-Senante et al. 2012).

There are different perspectives in which the life cycle can be applied to a product (Ulmschneider 2004, p. 49). The consumer bases his/her decision for a certain product on the price, but may additionally consider operational costs as well, if these are available (consumer-oriented LCC). The producer, however, has a different perspective on the life cycle, which is oriented on the product life cycle from design and launch of a product to its degeneration phase. For the water and wastewater sector, both perspectives can apply; nevertheless, many authors tend to associate the consumer-oriented LCC with water management. In practice, the differences actually do not affect the LCC analyses much.

LCC is understood as part of the more holistic life cycle management, which also for example includes life-cycle analysis (LCA) (i.e. life cycle oriented assessment of environmental impacts of products, systems and services). To some extent, the LCA provides the methodological framework for various tools such as LCC (Reddy 2014).

The approach to consider the costs over the entire life cycle originates in business administration. The construction sector adopted this life cycle approach applying it to construction materials but even more to objects of the built environment such as buildings. Buildings, however, generally exhibit a distinctively longer life expectancy than consumer goods. Therefore in the case of buildings, it is more relevant to assess the functional life time and thereby the useful economic life than relying on the technical service life.

With respect to LCC, efforts were made to standardize the approach. In international context ISO 15686-5: “Buildings and constructed assets - Service-life

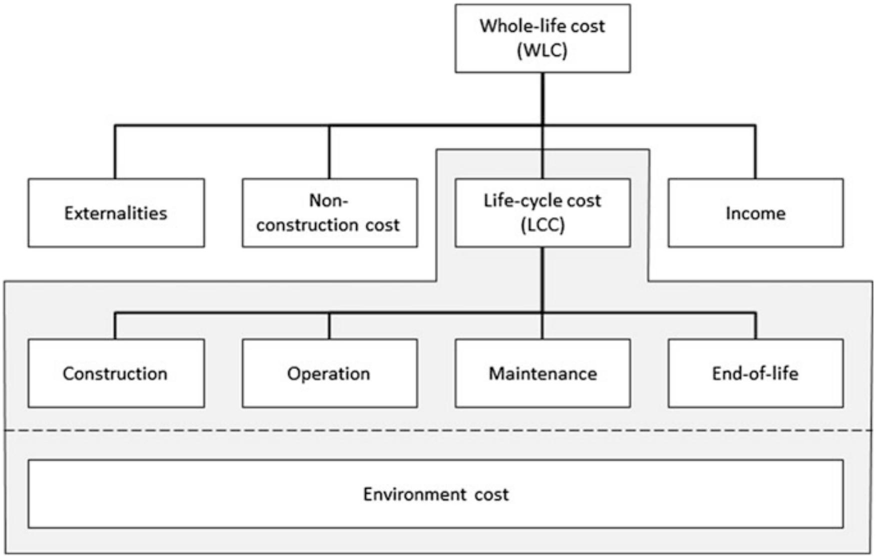

Fig. 4 Elements of whole-life costs and life-cycle costs. *Source* ISO 15686-5 (2008, p. 6)

planning - Part 5: Life-cycle costing" is relevant, which forms the basis for the following definition, examination and debate.

According to the standard, LCC analysis is a "methodology for systematic economic evaluation of life-cycle costs over a period of analysis, as defined in the agreed scope" (ISO 15686 2008, p. 2). Life-cycle costs are differentiated into different categories: construction, operation, maintenance and end-of-life costs (see Fig. 4). LCC are distinguished from whole-life costs (WLC), which apart from LCC also take into account externalities, non-construction costs and income. Environmental costs introduced by environmental legislation (e.g. cost premiums for the use of non-renewable resources) can be part of both approaches; WLC as well as LCC, depending on whether the environmental cost impacts are external to the constructed asset or not (ISO 15686-5 2008, p. 22).

Conventional LCC is a management instrument that differs only marginally from the discounted cash flow (DCF) analysis. DCF[1] is a method of valuing a project, company or asset using the concepts of the time value of money (Wöhe and Döring 2013). All future cash flows are estimated and discounted to express their present values. In comparison to DCF, the LCC approach focuses on costs, such as negative

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[1] In finance, discounted cash flow (DCF) analysis is a method of valuing a project, company or asset using the concepts of the time value of money. All future cash flows are estimated and discounted to give their present values (PVs). The sum of all future cash flows, both incoming and outgoing, is the net present value (NPV), which is taken as the value or price of the cash flows in question. Present values may also be expressed as a number of years the purchase of the future undiscounted annual cash flow is expected to arise (Wikipedia 2014).

cash flows (Termes-Rifé et al. 2013, p. 469 ff.). Such instruments of cost accounting like DCF are part of the internal reporting and aim to assess internal processes and to support the various steering tasks of management. This type of reporting is not bound to legislative requirements, and can be shaped according to the specific goals to fulfil the required steering tasks and decision-making processes (e.g. Damodaran 1996; Stahl 2006; Horngren 2013; Wöhe and Döring 2013). On national level, there are relevant standards as well. The German DIN 18960 (operational costs in structural engineering) is used for buildings above ground. Additionally, costs for construction, rehabilitation, reconstruction and demolition and disposal are considered in DIN 276-1:2006-11. These standards, though, do not cover infrastructural systems such as water and wastewater management. Relevant in this context are, however, recommendations of the German Working Group on Water Issues (LAWA) of the Federal States and the Federal Government represented by the Federal Environment Ministry. These recommendations are published by the German Association of Water Management, Waste Water and Waste (DWA) in their "guidelines for dynamic comparative cost methods" (DWA 2008, 2012). In Sect. 4, these recommendations are discussed more in depth.

When transferring the concept of LCC to water and wastewater management, one should be aware that those costs required for the construction of water networks and systems should be considered. Additionally, costs for operation, maintenance, renewal and disposal must be incorporated into investment decisions. Consequently, Burr and Fonseca (2013, p. XI) stress that "life-cycle costs comprise capital expenditure; minor operation and maintenance expenditure; capital maintenance expenditure; expenditure on direct support (sometimes known as post-construction support); expenditure on indirect support and the cost of capital." This consideration of operation costs is particularly relevant as the rigidity of water systems leads to long-term (economic) impacts.

4 Applications of LCC: Experiences and Limits

The tasks of infrastructure planning are diverse. Correspondingly, the fields of application of LCC are diverse as well. Strategic planning of existing infrastructure assets can be differentiated from new infrastructure development projects. A third group of projects deals with the transformation of existing structures where different perspectives are taken. The cost of sprawl criticism led to approaches that address costs of infrastructure in the future by means of settlement development, and positively affect these. Further projects focus on the adaptation of existing infrastructures concerning new demand as a consequence of modifications in settlement structures due to demographic change, climate change or shifting societal conditions. The following examples pick up some of the mentioned points.

4.1 Asset Strategy Planning Towards Sustainable Infrastructure Networks

As presented in Sect. 1, large shares of cities and communities in Europe have high connection rates to water and wastewater systems and infrastructures. The maintenance of these facilities is one of the focuses of infrastructure planning in Europe. Good practices pursue long-term-oriented concepts of maintaining existing structures. The security of supply and disposal is the main aspect. Further objectives are the maintaining of the asset value, the reduction of technical and financial risks, the perpetuation of future investment and repair costs, and an appropriate development of water fees. In order to achieve the formulated objectives, long-term development strategies are simulated and compared to each other (see Fig. 5).

Beside technical aspects, financial impacts along the life cycle of the facilities are considered. Therein, the costs of investment into the maintenance of existing facilities are as relevant as the costs that occur for the operation of the infrastructural systems such as inspections and continuous repair measures (see Fig. 6). Another important issue in this context is the ever-increasing price for energy.

Major uncertainties exist in particular concerning the evaluation of probabilities of fall-out of existing sewers and pipes (Kropp and Baur 2005) (see Fig. 7). Sewers and pipes of different construction types have diverging life cycles and ageing behaviour. The ageing behaviour is not linear and differs from usually linearly

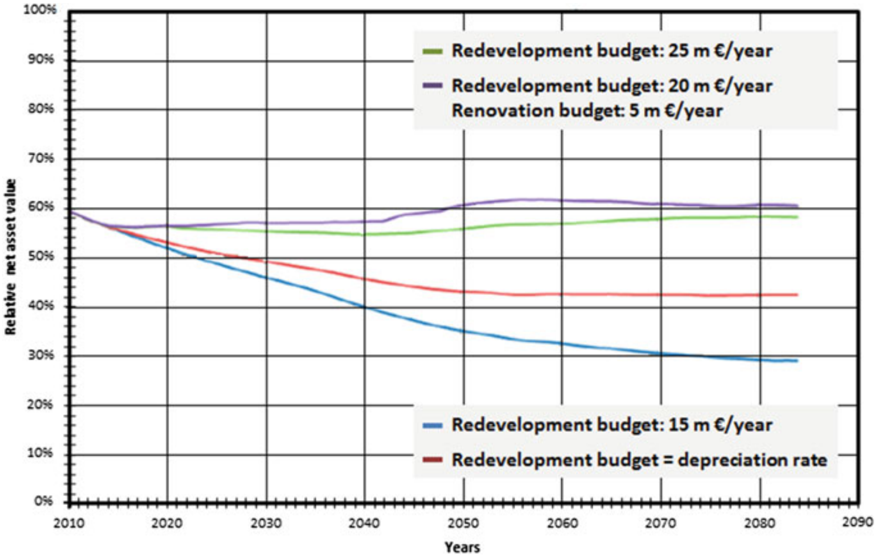

Fig. 5 Long-term development of the relative net asset value (Relative net asset value = net asset value/replacement costs. German Water Association (DWA) regulation requires a relative net asset value greater than 50 %) of the canal system of alternative capital preservation strategies. *Source* City of Düsseldorf (2013, p. 22), amended

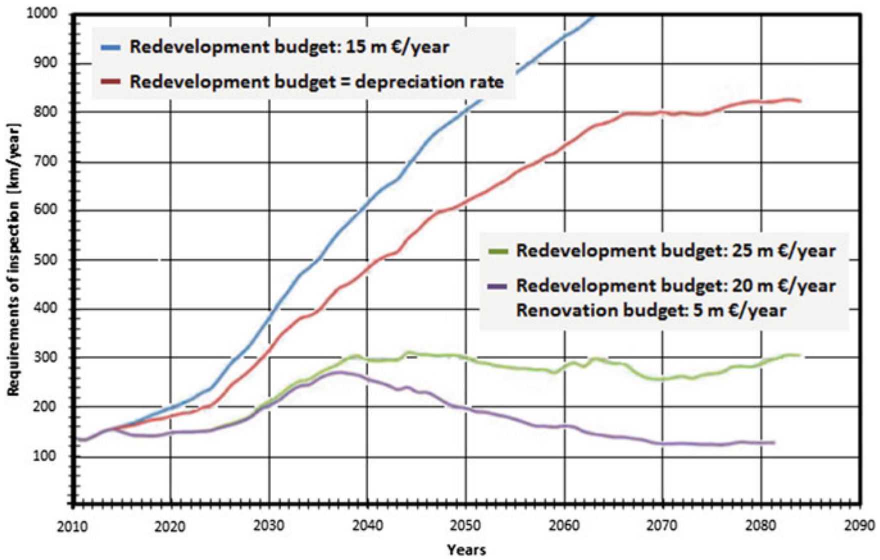

Fig. 6 Inspection costs of alternative investment-strategies. *Source* City of Düsseldorf (2013, p. 16), amended

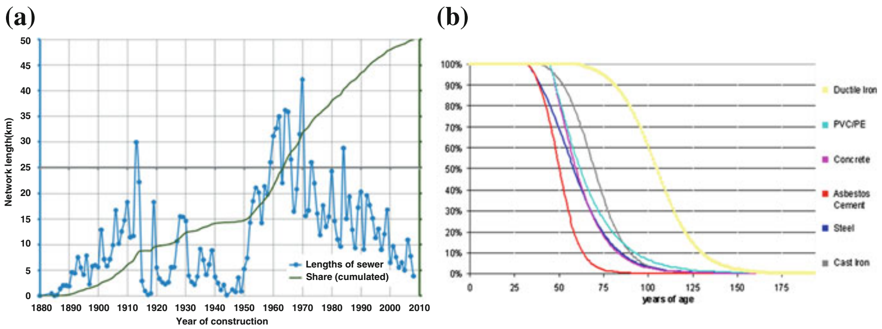

Fig. 7 **a** Age structure of sewage main network of a German city (*figure on the left*). **b** Survival *curves* for types of water mains (*figure on the right*). *Source* **a** City of Düsseldorf; **b** Herz and Lipkow (2002)

running economic depreciation curves (Herz 1996). With increasing planning horizons and heterogeneity of networks, the insecurity of assumptions is increasing and consequently the validity of results.

Long-term strategies for maintaining networks usually serve merely the principal strategic alignment while the operative planning is principally based on technical criteria. These day-to-day decisions impact only a few years; therefore life cycle considerations only play a minor role.

4.2 LCC in New Infrastructure Development Projects

Despite the high connection rates in Germany and Europe, new developments are relevant. Principally, two different cases can be differentiated: (1) Accession of new settlement areas (extension areas of settlements); (2) Accession of insufficiently connected settlement areas, which predominantly occur in rural areas (see Fig. 8).

In case of extending settlements, the connection is generally conducted considering technical boundary conditions of the present system in existing settlements neighbouring the new development. Wastewater treatment plants and drinking water supply facilities are mostly amply dimensioned; therefore, the existing alignment of the system is generally retained. Prevailing technical and hydraulic conditions (e.g. combined or separate rainwater and sanitary sewage system) are pivotal for the outline of the new drainage system while life-cycle costs only play a minor role.

In case of new developments of settlement structures or settlement areas, which so far had been insufficiently connected, the technical degree of freedom is much higher due to the missing or qualitatively inadequate connection. Because of the low density of such settlement areas, diverse development options of the water systems are conceivable (e.g. centralized/decentralized, full or gradual construction). When faced with such decisions, sensible alternatives are commonly compared based on LCC. In Germany, such a decision-making process is explicitly requested in the guidelines for dynamic comparative cost methods mentioned above. These guidelines are edited by the German Working Group on Water Issues of the Federal States and the Federal Government represented by the Federal Environment Ministry (LAWA). In these guidelines, recommendations are given for the comparison of alternative system solutions using dynamic comparative cost methods, considering all relevant types of costs such as investment costs (construction and development costs, maintenance costs) and running costs (costs for personnel, energy, tangible

Fig. 8 Rural villages: Focus of new infrastructure development. *Source* SMUL (2004), *photo* by Aerobild (2000)

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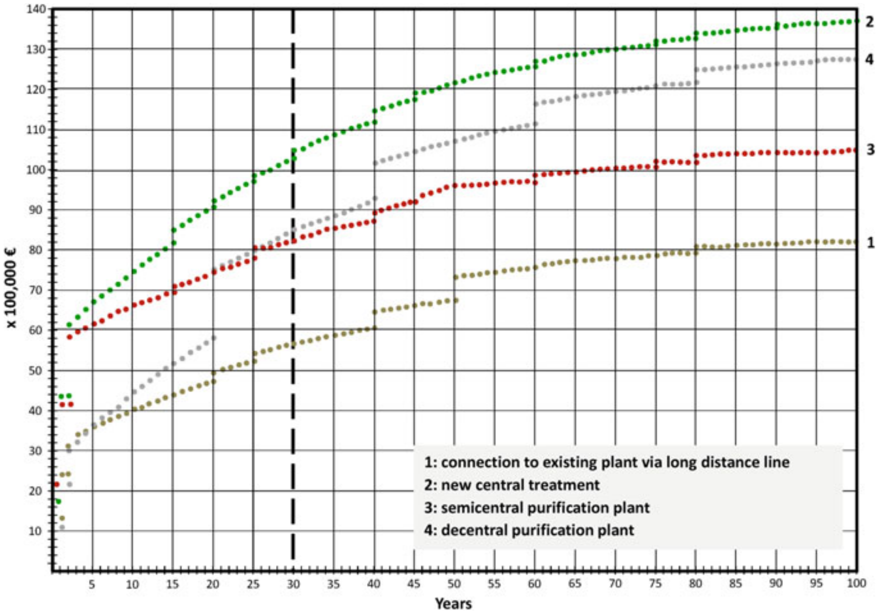

Fig. 9 Curve of present value course for alternative sewerage systems of a rural area in Germany. *Source* SMUL (2004, p. 38), amended

means). The period under consideration is oriented on the service life of the water engineering facilities (e.g. 50–80 years for canals, 10–15 years for small sewage plants). In Fig. 9, the results of a dynamic comparative cost calculation for different system alternatives of wastewater treatment in a rural community are shown.

Alternative 1 is the most cost-effective over the considered period of 100 years while alternative 2 is economically unfavourable. Considering alternatives 3 and 4, in the medium-term, decentralized plants (separate sewerage systems) are superior to semi-central plants/ones (collective sewerage systems) due to lower investment costs. This leads to a trade-off associated with higher operational costs, and with a period under consideration of more than 30 years, the advantage changes from decentralized to semi-central plants. From the cost perspective, alternative 1 is favourable, but further considerations such as the autonomy of communities may lead to preference for other options. In this context, LCC can provide objective reasons for such discussions.

4.3 Cost of Settlement Development

Infrastructure costs and life cycle considerations are also important and relevant aspects from the viewpoint of settlement planning. The question raised in this context is, how expensive will settlements be in the future. The “cost of sprawl” is the technical term for it, and the related research investigates the effects of urban form on public costs induced by investment, operation and maintenance of network-related technical infrastructures (such as water and energy supply, sewage disposal and roads). Several research projects as well as implementation projects have been dealing with this topic for more than a decade (Burchell et al. 1998).

Long-term cost effects, which are to be expected for different paths of settlement development, are in the foreground of these considerations and were mainly discussed under growth conditions. In light of stagnating and shrinking populations, this topic has been receiving increasing attention in practical settlement development in Europe and Germany, in particular (e.g. Schiller and Siedentop 2005; Siedentop and Fina 2008). This takes into account a distinct and often empirically confirmed correlation between urban density specific infrastructure costs per user. The higher the density is, the lower the per capita length of water distribution lines or sewer collection lines, roads, etc. is (see Fig. 10). This is true for most types of settlements found in developed countries. Exceptions from this rule can occur in metropolises with extremely high densities. Due to multifaceted overlaps of usage, additional infrastructures are necessary (e.g. in underground or vertical development through high-rise buildings). In sparsely populated rural regions, the infrastructural standards frequently do not meet those of urban settlements, so that the dependency between infrastructure costs and density does not apply that strictly.

The principles of an approach for infrastructure cost calculation to support regional planning are shown in Fig. 11. First, the physical model is compiled taking into account the physical parameters of settlement structures, variations of infrastructure-equipment and settlement development. Second, the cost model is developed based on these physical parameters. It incorporates specific capital costs,

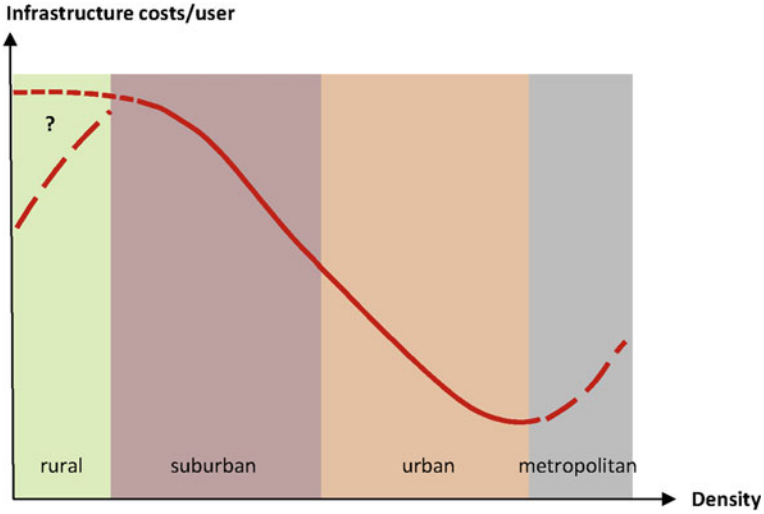

Fig. 10 Correlation between density and infrastructure costs. *Source* IÖR

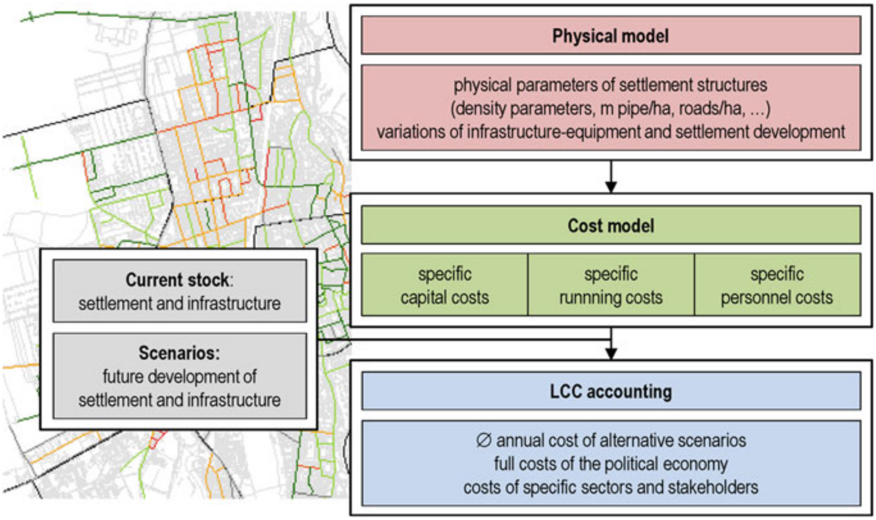

Fig. 11 Regional infrastructure cost calculation. *Source* Schiller (2007), amended

specific running costs and specific personnel costs. Third, life-cycle cost accounting is applied providing average annual costs of alternative scenarios, full costs of political economy, and costs of specific sectors and stakeholders.

By applying this approach, it is possible to calculate the costs that may appear in pursuit of conceivable paths of settlement and infrastructure development. Future development paths can be depicted by means of scenarios. This approach is designed as a tool to talk and serves to foster discussions in the framework of planning processes. For that purpose, local decision makers are actively involved in this participatory scenario process.

The according costs derived by means of LCC analyses are fed into the discussion process as well, and are reflected on in these strategic discussions. Such scenario discussions allow for comprehensive considerations of all available options ranging from green field development to brownfield/infill development as well as alternative infrastructure solutions. Especially in Germany, there are many examples of best practice where adaptation is discussed against the background of demographic changes (Siedentop et al. 2006).

4.4 Adaptation of Infrastructure

Currently, there is a huge and comprehensive change in the demands on water and wastewater systems. Main reasons for this development are related to:

- Increasing prices for energy in Europe, in Germany additionally reinforced due to the nuclear power phase-out.

- Climate change impacts on water run-off, retention and water supply.
- Capacity load problems induced by demographic change, reduction of water consumption, etc.

In this situation, new system alternatives going beyond common technological and planning solutions gain increasing relevance. A trend has been becoming perceivable that in this process, strategic considerations play an important role while taking long-term and life cycle oriented considerations into account.

There are many recent examples for a nexus between water/waste water systems and energy generation based on water (e.g. Makropoulos 2013). Water is utilized for example as kinetic or heat energy, or in the form of containing biomass. Considerations based on LCC also include cost reductions associated with lower energy consumption as well as additional benefits besides operational costs of the alternative. An example is the decision of the Water Board of Lake Constance to utilize the existing slope in water supply pipes to generate electricity by means of turbines. The initially higher investment costs for such pipes will be compensated by the expected energy gains within the life cycle of the facility.

The transformation of existing infrastructure concerning new demands can lead to interventions in existing systems in different intensities ranging from the adaptation of individual components to a complete redirection of the system. Just as much as with new development, the discussion concerning central and decentralized systems is important as well. A transformation of a system's direction can only be managed in the long run, step-by-step. In doing so, LCC considerations can demonstrate their potencies. Therefore, it needs to be considered that transformation costs are not only determined by the development of new infrastructure, but also by changes in the cost structure within the stock of infrastructure. In this context, sunk costs are of eminent relevance. These costs are those financial resources bound in existing (functioning) structure that need to be replaced prematurely due to changed requirements. LCC analyses have to consider these aspects adequately. Due to the heterogeneity of the stock with respect to its condition, building age and remaining service life, small-scale considerations are necessary. This may be realized by combining LCC analyses with spatial analyses of relevant indicators of settlements and infrastructures using geographic information systems (e.g. Schiller 2010).

4.5 Political Economy Considerations: LCC for Strategic Planning

In Europe, life cycle considerations play a role on the strategic level particularly when the definition of fundamental strategies is concerned. This applies to the planning of the maintenance of existing systems as well as to problems of new development. The life cycle approach assists in making future-proven long-term planning decisions, and raises the transparency of the process.

Major planning tasks are associated with the tremendous uncertainties such long-term considerations are confronted with. Correspondingly, the methods are complex while the results are insecure. The results deliver helpful knowledge for strategic planning, which may be taken into consideration for operational planning as well. On the operational planning level, life cycle considerations are rarely used, as technical, functional and hydraulic aspects are focused on. Therefore, the LCC approach is applied during the design phase of water systems, while it plays a minor role in the implementation of the systems.

Further difficulties can be seen in uncertainties concerning the projection of external frame conditions such as the development of prices or of future demand. The latter is becoming a real and ever-increasing problem in the face of the heterogeneous demographic dynamics in Europe. In order to overcome such uncertainties the investment decision process is usually accompanied by sensitivity analyses.

4.5.1 Demography and Infrastructure

New requirements for water and wastewater systems (e.g. increasing energy prices, demographic change), as well as new technological solutions (e.g. higher cleaning performance of small-scale sewage plants) increase the diversity of technically and qualitatively appropriate alternative solutions. Against this background, life cycle considerations are of increasing interest for decision makers, and come to the fore. With raising degrees of freedom in planning, the meaning of life cycle considerations is increasing.

The discussion concerning “cost of sprawl” or “cost of shrinkage” has been also leading to a consolidated application of the LCA in settlement planning rather than infrastructure planning. However, the opportunities to influence the costs of infrastructure through settlement planning are limited and the benefits occur only with enormous delays.

Though there are numerous good examples for application of the LCA in maintenance, as well as new developments, it must be stated that it is by no means common practice. The personal attitude of the decision maker plays a significant role. Moreover, the age of the decision maker is relevant in this context. Many of them are nearing retirement and may therefore only make decisions with positive effects during the time remaining in their respective positions. Experts with vast experience point out that there are differences in Europe, which can be explained through different planning cultures. Forerunners in the application of life cycle considerations in water and wastewater management are countries in Scandinavia and central Europe while the approach is less widespread in southern and eastern Europe.

4.5.2 LCA Versus LCC

Consideration of the LCA in the practice of water and wastewater management in Europe and Germany predominantly relates to LCC. The more holistic perspective of WLC is actually not taken into account. Additionally, in order to draw attention back to the whole LCA, it should be mentioned that as far as LCA is concerned, a practical implementation is not ascertainable in water and wastewater management to the knowledge of the authors, only in the framework of research projects can such an approach be applied (e.g. Ambrose et al. 2009; Gussem et al. 2011; Slagstad and Brattebø 2014). When reviewing relevant literature, it is striking that both on European and global scales, LCAs (often in conjunction with LCC) are conducted in the context of qualitative deficits of water supply and wastewater treatment (usually in the framework of research projects) (e.g. Reddy and Batchelor 2012; International Water and Sanitation Centre 2011, 2012; Reddy et al. 2012; Burr and Fonseca 2013). It seems obvious that a combination of both approaches only receives relatively more importance where environmental and quality standards for water supply and wastewater disposal are not that strict. In this regard, a North-South divide is observable in Europe, but such critical situations occur more in emerging and developing countries outside Europe. These deficits in environmental and quality standards may on the one hand be a result of gaps concerning thresholds and standards that have to be kept. On the other hand, the more relevant reason for these deficits must be seen in the difficulties in implementing existing standards and thresholds into planning practice. Introduction of the LCC management approach may foster qualitative improvement of water and wastewater systems being characterized by such deficits.

4.5.3 Standards, Norms and Regulation

In contexts where quality standards exist, threshold values are determined and receive consideration in infrastructure planning. Moreover, the discussion to extend LCC through environmental aspects is less distinctive. This is comprehensible and leads to the conclusion that quality standards and environmental norms absorb the tasks of an environmentally oriented assessment in case it is ensured that they are adequately considered. It is advisable to concentrate on life cycle costs when the development and implementation of resource efficiency strategies in practice is considered. The situation is to be evaluated differently where no sufficient quality standards and norms exist, where existing regulations are not considered, or where developments aim at the improvement of energetic and emission parameters. In these cases, a combination of LCC and LCA or other methods considering environmental aspects are virtually convincing tools.

5 Conclusions

In order to avoid merely academic discussions and to initiate activities in practice, LCC and LCA management approaches should be embedded in adequate implementation strategies in order to develop its strengths as a management tool.

This chapter discussed challenges and the dynamics of changing requirements forces decision makers to consider new solutions and locate themselves off the beaten paths of planning. Proven routines leave their meaning and have to be questioned. For this purpose, approaches such as process-based modelling in the framework of scenario discussions provide a good solution in which decision makers are actively integrated into the modelling process and can potentially influence it. From methodological perspective, this can be achieved by combining the discussed management approaches of LCC and LCA with participative scenario approaches (Carlsson-Kanyama et al. 2008; Vergragt and Quist 2011).

Settlement and infrastructure planning are still characterized by separate considerations of the various different sectors involved. The water sector is usually managed without taking into account the energy or waste sector though there are huge potentials for combining the according material and energy flows. Such a "silo thinking" as identified in the third European Report on Development (EU 2012) is opposed to integrated (nexus) approaches that could potentially utilize the scarce resources more efficiently. One of the postulations in the report is that optimization is preferable compared to maximization in order to meet the Sustainable Development Goals (SDG) that are yet to be defined and determined precisely. In order to evaluate the achievements concerning the SDG, reliable and practice-oriented methods are necessary. Life cycle management with its various tools such as LCA and LCC provide holistic perspectives that can support the shift towards a more integrated thinking in settlement and infrastructure planning particularly against the background of SDG.

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Chapter 8
Designing Sustainable Wastewater Reuse Systems: Towards an Agroecology of Wastewater Irrigation

Philipp Weckenbrock and Graham Alabaster

1 Introduction: The Nexus of Wastewater Irrigation

Water is one of the major elements on our planet's surface and inextricably linked with life. Of all the earth's water, only 1 % is accessible as groundwater (0.7 %) or surface water (0.3 %) (Gleick 1996). Even today, many regions of the world, in particular parts of subSaharan Africa, south and southeast Asia and Latin America are facing water scarcity (Molden 2007). And in a global context of industrial development, changing dietary patterns, rising incomes and climate change, pressure on these accessible freshwater sources is increasing (UNDP 2006; Bates et al. 2008; Pachauri and Reisinger 2008; McIntyre et al. 2009).

Agriculture is by far the sector with the highest water requirements accounting for approximately 70 % of the global freshwater withdrawals (Rosegrant et al. 2009). However, in a competition about scarce freshwater resources with households and industry, farmers often lose out (World Resources Institute 2000; Jia et al. 2006; Molle and Berkhoff 2006).

While many sources of irrigation water are declining, wastewater availability is more likely to increase. According to the United Nations Population Division, most future population growth is going to take place in urban areas of developing countries, both large and medium-sized cities and the smaller urban centres (UNPD 2007). One of the implications of this growth is increasing volumes of wastewater. Dealing with this wastewater presents planners with a great challenge. Although progress has been made with regard to the Millennium Development Goal (MDG) on providing safe drinking water, progress on the MDG on safe sanitation has been

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lagging behind (Gleick et al. 2009). Even if this MDG should be reached, 1.8 billion people would still be without safe sanitation by 2015 (UNDP 2006; Gleick et al. 2009). While it is already a great challenge to remove it from settlement areas, treatment facilities for this wastewater often do not exist. This means that most of the world's wastewater is released into the environment without any treatment. Obviously, there are great differences in rates of wastewater treatment between countries with different levels of economic development: a recent study estimates that 'high-income countries on average treat 70 % of the generated wastewater, followed by upper-middle-income countries (38 %), lower-middle-income countries (28 %), and low-income countries, where only 8 % of the wastewater generated is treated' (Satoa et al. 2013: 1). The main reason for these low rates of wastewater treatment is the high cost of conventional treatment facilities.

Low wastewater treatment rates imply health and environmental risks and an enormous waste of resources.

> The 'modern' sanitation systems being introduced in many countries in the South are inadequate because they are based on a linear, industrial world-view in which sewage is disposed, 'somewhere' rather than recycled. The system involves unidirectional flows of food and nutrients from farms in the countryside to the city, which are then converted to sewage and dumped, treated or untreated, into rivers or directly into the sea. The lost nutrients are never returned to the land, and instead, combined with soluble synthetic fertilizers running off agricultural land, result in eutrophication and the formation of toxic algal blooms in freshwater and marine environments (Jones et al. 2010: 5).

Box 1: What is wastewater?

Urban wastewater can be one or the combination of the following.

- Domestic effluent consisting of blackwater (excreta, urine and associated sludge) and greywater (kitchen and bathroom wastewater)
- Water from commercial establishments and institutions, including hospitals
- Industrial effluent
- Stormwater and other urban runoff

Normal municipal wastewater consists to 99 % water with only 1 % dissolved solids.

Sources: Mara and Cairncross (1989); van der Hoek (2004)

In this context of ever increasing volumes of wastewater on the one hand and irrigation water scarcity and declining soil fertility on the other, an estimated 200 million farmers worldwide have been using wastewater to irrigate their fields (Raschid-Sally and Jayakody 2008). This practice is thousands of years old and exists in many parts of the world (UNEP and GEC 2004; Raschid-Sally 2010). In spite of the global significance of wastewater irrigation, the topic has remained largely invisible to planners and decision-makers. This is illustrated by the following example of official and unofficial estimates of the area under wastewater irrigation.

In India, the Central Pollution Control Board (CPCB) estimated that only 6,909 ha land is devoted to wastewater farming, while independent studies put this figure at above 100,000 ha (Kurian et al. 2013: 51).

The most widely used estimate for the global area under wastewater irrigation is 20 million hectares (Hussain et al. 2001).[1] There is a range of ways by which wastewater is used for irrigation, direct or diluted, partially treated or raw, etc. The main types of wastewater use are summarized in Box 2.

Box 2: Main types of wastewater use

- **Direct use of untreated urban wastewater** from a sewage outlet is when it is directly disposed of on land where it is used for cultivation.
- **Indirect use of untreated urban wastewater**: water from a river receiving urban wastewater is abstracted by farmers downstream of the urban centre for agriculture. This happens when cities do not have a comprehensive sewage collection network and drainage systems are discharging collected wastewater into rivers.
- **Direct use of treated wastewater**: wastewater has undergone treatment before it is used for agriculture or other irrigation or recycling purposes.

Sources: van der Hoek (2004); Raschid-Sally and Jayakody (2008)

Only recently has wastewater irrigation received wider scientific attention. Most research has come from the field of public health and related sciences with a strong focus on risks (see Fig. 1). The main concerns commonly associated with wastewater irrigation (cf. WHO 2006b; Scheierling et al. 2010; USEPA 2012) are (in descending order).

- Health risks for field workers, consumers of wastewater irrigated produce and people living in proximity of wastewater irrigated areas from microbial infections and chemicals.
- Environmental risks including the contamination of groundwater, open water bodies and soils.
- Agricultural risks for plant and animal health.

Risks of wastewater irrigation must be taken seriously. A wide range of measures to address these risks has been developed (see Sect. 4.1). Besides risks of the practice, the alternatives to the use of wastewater in agriculture must also be

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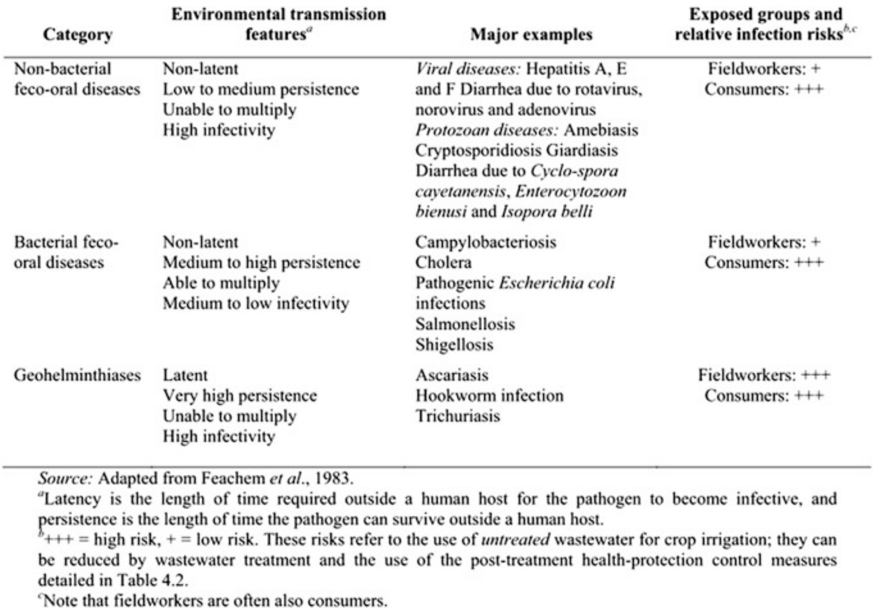
[1] For a discussion of global estimates of the area under wastewater irrigation, see Weckenbrock (2010).



Category	Environmental transmission features[a]	Major examples	Exposed groups and relative infection risks[b,c]
Non-bacterial feco-oral diseases	Non-latent Low to medium persistence Unable to multiply High infectivity	*Viral diseases:* Hepatitis A, E and F Diarrhea due to rotavirus, norovirus and adenovirus *Protozoan diseases:* Amebiasis Cryptosporidiosis Giardiasis Diarrhea due to *Cyclo-spora cayetanensis*, *Enterocytozoon bienusi* and *Isopora belli*	Fieldworkers: + Consumers: +++
Bacterial feco-oral diseases	Non-latent Medium to high persistence Able to multiply Medium to low infectivity	Campylobacteriosis Cholera Pathogenic *Escherichia coli* infections Salmonellosis Shigellosis	Fieldworkers: + Consumers: +++
Geohelminthiases	Latent Very high persistence Unable to multiply High infectivity	Ascariasis Hookworm infection Trichuriasis	Fieldworkers: +++ Consumers: +++

Source: Adapted from Feachem *et al.*, 1983.

[a] Latency is the length of time required outside a human host for the pathogen to become infective, and persistence is the length of time the pathogen can survive outside a human host.

[b] +++ = high risk, + = low risk. These risks refer to the use of *untreated* wastewater for crop irrigation; they can be reduced by wastewater treatment and the use of the post-treatment health-protection control measures detailed in Table 4.2.

[c] Note that fieldworkers are often also consumers.

Fig. 1 Environmental classification of excreta-related diseases important in wastewater-irrigated agriculture. *Source* Scheierling et al. (2010: 24)

considered. At present, much of the world's untreated wastewater is disposed of into open water bodies such as the nearest river. Once this happens, there is little control over what happens to pollutants in this wastewater. Thus, untreated wastewater is linked to potential risks irrespective of whether it is used in agriculture.

What is more—and even though risks of wastewater irrigation continue to be the main focus of scientists, planners and decision-makers—potential benefits of the practice have received more attention in recent years.

Using wastewater for agricultural irrigation allows for addressing simultaneously the challenges of irrigation water scarcity and of unsafe sanitation. Other challenges can be integrated as well: in principle, wastewater reuse also offers possibilities of creating income, contributing to food sovereignty and the creation of renewable energy (through the production of energy crops and biogassification of wastewater sludges). Some additional benefits of the practice are given in Box 3.

Box 3: Potential benefits of wastewater irrigation

If properly managed, wastewater irrigation can have a range of benefits including the following:

- Reliable source of irrigation water for farmers.
- Recycling of nutrients dissolved in the wastewater resulting in higher agricultural yields. This often allows wastewater farmers to stop using mineral fertilizers and thus save money.

- Income creation opportunities (often for lower-income groups).
- Increased food production in proximity to markets and contribution to food sovereignty.
- Production of raw materials for renewable energy.
- 'Land treatment' of wastewater for a fraction of the cost of conventional treatment facilities: filtering out pollutants and thereby reducing the pollution of open water bodies.
- Groundwater recharge.

Source: WHO (2006b); Raschid-Sally and Jayakody (2008); Simmons et al. (2010); USEPA (2012); Mateo-Sagasta et al. (2013).

With the possibility to link different important topics, wastewater irrigation can be seen as a prototype application of the nexus approach (Kurian and Ardakanian 2013; UNU-FLORES 2013).

Almost 100 years ago and in view of this great reuse potential, first efforts were made to manage the risks of wastewater irrigation by developing standards and guidelines. The history of the development of such standards and guidelines is the topic of Sect. 3.

2 Wastewater Reuse Guidelines to Address Health Concerns

Attempts to define quantifiable criteria for irrigation water quality go back to the first half of the twentieth century. The first standard for irrigation water quality from 1918 (for California) effectively prescribed the same quality for irrigation water as for drinking water.[2] However, such strict guidelines were not feasible even in highly developed countries (Havelaar et al. 2001; Fattal et al. 2004). Thus, the standards had to be relaxed. Today, besides local and national standards, such as those of the United States Environmental Protection Agency (USEPA), there are also international standards on irrigation water quality like those published by the World Health Organization (WHO). They are of great relevance for many countries that do not have national guidelines (Ensink 2006).

In 1973, the WHO published their 'Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture'. These first WHO guidelines 'were developed in the absence of good epidemiological studies and borrowed essentially a low-risk approach from the USA' (Carr 2005). After a lengthy process involving several teams of scientists from different institutions, the second edition of the guidelines was released in 1989 (Fattal et al. 2004). Some of the (relaxed) microbiological

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[2] For wastewater used to irrigate vegetable crops eaten uncooked (Havelaar et al. 2001).

standards in this revised edition raised criticism from different sides. Some researchers considered the new guidelines too lenient (Shelef 1991, quoted in Ensink 2006) while others criticized them for being too strict (Faruqui et al. 2004; Ensink 2006).

Some critics pointed out that a strong focus on microbiological risk implies that wastewater has to be treated before it can be used for irrigation. This does not take into account that from a health perspective, it might be more effective to invest scarce financial resources, in a developing country context, into measures like improved water supply or health education (cf. Drechsel et al. 2002; Faruqui et al. 2004). Moreover, the gap between the 'apparently inappropriate target of the WHO standards and existing water quality' (Cornish and Kielen 2004: 1) might lead urban planners and politicians either to condemn the practice of wastewater irrigation or to ignore it (Drechsel et al. 2002; Carr 2005). What is more, strict requirements for wastewater irrigation might lead to the paradoxical situation where highly polluted river water is used instead of better-quality wastewater. Under such circumstances, the health risks for producers and consumers would be increased by adherence to the guidelines (Carr et al. 2004b).

The third edition of the WHO Guidelines from 2006 offers a somewhat new perspective on wastewater irrigation. Although it still has a strong focus on microbiological indicators (and some of the criticism mentioned above still seems valid), it stresses the importance of a holistic approach to risk in accordance with the Stockholm Framework.

> The Stockholm Framework refers to the concept of 'relative risk', which requires that one considers all possible sources of risk and exposure when setting guidelines. These would include risks related to poor water supply, hygiene and sanitation, and other sources of (e.g. post-harvest) food contamination. For example, if contaminated drinking water or lack of toilets is causing high background levels of illness in the population, then a costly treatment of wastewater for crop application is not likely to improve public health, and should not be the priority investment in countries where funds are limited. … Decision-makers are thus encouraged to look at the larger nexus of water-sanitation and health and their interconnections (IWMI 2006: 2).

In other words, there are different entry points for the task of reducing health risks related to wastewater irrigation besides treatment. For instance, improving hygiene at markets can be a better way to protect public health than wastewater treatment (Ensink et al. 2007). Thus, broadening the perspective from the farmer/producer level to include the market and consumer levels is important.

One point for which the 2006 WHO guidelines have been criticized is the prominent role that they attribute to technical wastewater treatment.

> [A]ll different risk reduction scenarios that are presented as a matter of example, include wastewater treatment technology. This seems to imply that municipalities, where untreated wastewater is currently being used, have only two alternatives to protect public health: the removal of farmers from their land, or to turn a blind eye to the practice (Ensink and van der Hoek 2007: 576).

Thus, on the one hand, standards on the quality of irrigation water have continually been modified to take results of new research and a widening of the

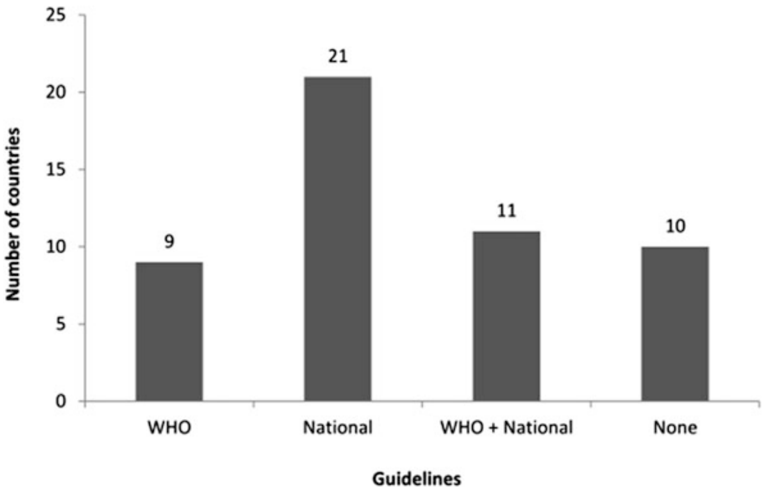

Fig. 2 Guidelines on wastewater use in agriculture in 51 developing countries from Asia, Africa, Latin America and the Caribbean. *Source* Mateo-Sagasta et al. (2013: 64)

perspective on irrigation realities into account. On the other hand, however, there still seems to be scope for a stronger recognition of the beneficial aspects of wastewater irrigation.

As pointed out above, the WHO guidelines are used as a basis for many national guidelines (see Fig. 2). This is illustrated by the example of Latin American countries, most of which have their own national guidelines on wastewater reuse (Jimenez 2008; Mateo-Sagasta et al. 2013). However, these national guidelines do not seem to be widely known even among those interested in this topic (Moscoso Cavallini and Egocheaga Young 2002: 9). What is more, most national guidelines of Latin American countries are based on the 1989 WHO guidelines because the 2006 WHO guidelines are perceived as too complex. Education about the new approach used in this latest edition, including on the Multi-Barrier Approach (see Sect. 4.1) is therefore needed (Mateo-Sagasta et al. 2013).

Confusion about the legal status of wastewater irrigation is illustrated in the case of Brazil, where wastewater use in agriculture is legal on a national level (CNRH 2005). However, an official consultancy for the state government of Sao Paulo, which provides concrete wastewater reuse guidelines explicitly excludes agricultural use of wastewater (SS/SMA/SRHS 2013). Personal communication with one of the authors of this reuse guideline revealed that the exemption of agricultural reuse was based on a lack of awareness about this practice, including its potential benefits.

Besides legal guidance, there are also technical guidelines with standards for wastewater quality for reuse like the ones set by the Brazilian National Standards Organization (ABTN 1997). Often, such guidelines are based on standards adopted from the WHO guidelines (Jimenez 2008).

In principle, therefore, standards and guidelines for the safe use of wastewater in agricultural irrigation exist (see next section and Annex 1). Moreover, there is a range of cheap and simple measures for moving towards the aims set in these guidelines (see next section). These measures must be considered in setting the framework for sustainable wastewater reuse systems.

3 Setting a Framework for Sustainable Wastewater Reuse Systems

3.1 Managing Risks of Wastewater Irrigation

For a long time, recommended risk reduction measures had put great emphasis on wastewater treatment plants, the 2006 WHO guidelines recommend a whole chain of measures, the so-called Multi-Barrier Approach. This approach combines wastewater treatment with measures at the farmer level (e.g. safe irrigation practices), the trader level (e.g. safe handling of produce) and the consumer level (e.g. awareness creation).

Box 4: Examples for health protection measures in a Multi-Barrier Approach

- Wastewater treatment
- Simple sedimentation and/or filtration of wastewater on farms
- Crop restrictions
- Wastewater application techniques that minimize crop contamination (e.g. drip irrigation)
- Use of personal protective equipment for those in direct physical contact with wastewater
- Withholding periods to allow pathogen die-off after the last wastewater application
- Restricted access to wastewater irrigated fields and hydraulic structures
- Hygienic practices at food markets and during food preparation
- Produce washing, disinfection and cooking
- Access to safe drinking-water and sanitation facilities at farms and in local communities
- Medication (e.g. anti-helminthic drugs) and immunization
- Health and hygiene promotion

Source: USEPA (2012); Mateo-Sagasta et al. (2013)

Box 5: Risk management of metals and metalloids

- Identify geographical areas with elevated risks from specific metal sources.
- Perform testing of soil and plant samples to verify the level of the risk from specific metal(s).
- Identify alternative crop varieties of the same desired crop that take up the least metal or convert the toxin to less toxic forms when grown in high-risk areas.
- Develop irrigation, fertilization and residue management strategies that help to minimize metal uptake by plants.
- Recommend crop restrictions, i.e. using other crops that have lower risks of contamination with metals and metalloids and/or pose a lesser risk to human health due to levels of dietary intake.
- Zone the affected area(s) for non-agricultural land use or land rehabilitation

Source: Simmons et al. (2010); (Mateo-Sagasta et al. 2013)

Much concrete advice on low-cost measures for managing health risks of wastewater irrigation has been published in recent years. These recommendations can be used to set the framework for wastewater-irrigated agriculture by reducing health and environmental risks. Examples of publications include the following:

- On-farm practices for the safe use of wastewater in urban and peri-urban horticulture: a training handbook for farmer field schools (Keraita et al. 2012b).
- List of health-protection measures and associated pathogen reductions for wastewater reuse in agriculture (USEPA 2012).
- Measures for dealing with chemicals (Simmons et al. 2010).
- Addressing health risks from farm to fork (Amoah et al. 2011).
- Safe use practices for vegetable production (Keraita et al. 2012a).
- Reduction of vegetable contamination using simple, low-cost reservoirs (Moscoso Cavallini 2013).

While much information is available on health and environmental risks of wastewater irrigation and on measures to reduce them, less has been published on agricultural aspects of the practice. Filling this gap in knowledge can make an important contribution to support setting up new wastewater reuse schemes and improving existing ones. Emphasizing the positive potential of wastewater irrigation for agricultural use (rather than exclusively the potential risks) can serve to motivate local stakeholders to address the issue of wastewater. To achieve this aim, small scale, locally adapted systems must be developed that can be set up at low cost and generate income. Wastewater treatment would then ideally be a side effect of highly productive agricultural systems. In the following, some main agricultural aspects of wastewater irrigation are summarized and a new, agroecological, perspective on the topic is proposed.

3.2 Water Quality Considerations for Agricultural Use of Wastewater

Whether a (waste)water resource is suitable for agricultural irrigation depends on a range of factors concerning crops, soils, climate, agricultural practices, etc. This means that the same quality water might not pose a problem in one context while being unfit for irrigation in another. Hence, while standards (see Annex 2) can give a rough indication of the suitability of a given water resource for irrigation, they cannot replace experimenting in the respective specific context.

In the following, a few of the main irrigation water quality considerations are briefly described.

3.2.1 Salinity

The main concern with regard to water quality from an agricultural point of view are salt concentrations (Ayers and Westcot 1985; Tanji and Kielen 2002). The major chemical elements constituting salinity are sodium, calcium, magnesium, potassium, bicarbonate, sulphate, chloride and nitrate. The most common lump parameters of salinity give concentrations in electrical conductivity (EC) in decisiemens per metre (dS/m) or TDS (total dissolved solids) in milligrams per litre (Tanji and Kielen 2002). The degree of salinity stress in plants depends on several factors.

> Although yield reductions are defined as a function of the average salt concentration in the rootzone, interactions between soil, water and climatic conditions influence the relationship. Exceedingly high air temperatures may cause a reduced salt tolerance. Cultural practices also determine to a certain extent yield reduction resulting from salinity stress. Other plant characteristics (which differ between plant species, varieties of the same species and growth stages during which salinity stress occurs) determine their ability to cope with salinity stress (Tanji and Kielen 2002: 42).

Many crops are most sensitive to salinity in their early growth stages. A strategy for their cultivation is for farmers to use water with lower salt content (or wastewater mixed with such water) for the first crop irrigations (Tanji and Kielen 2002).

The tolerance of plants to levels of contaminants differs significantly between species. Some plants can take up large amounts of salt, as well as heavy metals and other toxic elements (Tanji and Kielen 2002; Simmons et al. 2010). A list of selected salt-tolerant plants is given in Annex 3. Salt tolerance differs furthermore between different varieties of the same species and between different growth stages of the same plant.

3.2.2 Water Infiltration into the Soil

Infiltration of water that is too slow or to fast can represent a major problem for irrigated agriculture. It depends to a large extent on soil characteristics such as the degree of soil compaction, soil structure, organic matter content and the general chemical make-up (Ayers and Westcot 1985). However, the quality of the irrigation water also plays a role for the rate of water infiltration. The most relevant water quality factor with regard to infiltration is the sodium content in relation to calcium and magnesium. Under conditions of sodicity (a high proportion of sodium), the soil's capacity for water infiltration is reduced. The most common indicator used to assess sodicity of water and soils is the Sodium Adsorption Ratio (SAR). It describes the content of sodium in relation to the calcium and magnesium content. For reference values on SAR, see Annex 2.

3.2.3 Toxic Elements

Besides salts, there is a range of other chemical elements that can pose problems for plant growth. The most common phytotoxics in municipal wastewater besides sodium are boron and chloride (Pescod 1992; Bauder et al. 2011). A list with threshold values of phytotoxic elements that may be present in wastewater is given in Annex 2. There are also some emerging issues on antimicrobial drug resistance, related to wastewater, which will need further research.

3.2.4 Nutrients

Nutrient requirements of a plant depend on the growth stage with, for example higher nitrogen demand in early stages of growth than in flowering and fruiting stages (WHO 2006b). Excessive nutrient supply can damage some crops, e.g. by leading to a plant growth that is too fast (cf. Pescod 1992).

3.3 Crops Irrigated with Wastewater

Which crops are grown under wastewater irrigation in an area depends on the respective local context. On the one hand, some restrictions apply to different plants' tolerance to water quality. On the other hand, for many plants, wastewater seems to pose relatively few problems from a phytosanitary point of view as it consists of 99 % water (Raschid-Sally 2010). In fact, studies in India and Pakistan found similar or even higher levels of crop diversity in areas irrigated with wastewater compared to areas irrigated with other water types (Jacobi et al. 2009; Weckenbrock 2010).

The most common crop types under wastewater irrigation are (in declining order) vegetables, cereals and fodder crops (Raschid-Sally and Jayakody 2008).

3.3.1 Vegetables

The fact that vegetables are a main wastewater-irrigated crop type is likely due to the fact that wastewater irrigation usually takes place in close proximity to cities where high demand for fresh produce, proximity to markets and the availability of (waste)water for irrigation represent favourable conditions for their production. Being labour intensive, vegetable production and marketing offer employment opportunities for many people, often from low-income groups (Buechler et al. 2006). The value created per area is high. However, those benefiting from high revenues are not always the same as those who are exposed to the risks of working in close contact with wastewater irrigated soils and crops (Weckenbrock 2010).

With regard to vegetable types, a great variety can be found in wastewater-irrigated plots (compare Table 1).

Table 1 Selected case studies on crops irrigated with (treated and untreated) wastewater

Region	Crops cultivated with wastewater	Source
Brazil, Fortaleza (Ceará)	Bananas, sugarcane	da Costa e Silva et al. (2002)
Brazil, Aquiraz (Ceará)	Watermelon	de Lima Rego et al. (2005)
Ethiopia, Addis Abeba	Vegetables (lettuce, swiss chard, cabbage, spring onion, potato, beat root, etc.).	Bahri et al. (2008)
India, Hubli-Dharwad (Karnataka)	Vegetables, fodder crops, cereals, trees, etc.	Bradford et al. (2003), Hunshal et al. (1997)
India, Hyderabad and Karimnagar (Andhra Pradesh)	Fodder grass, rice, vegetables	Amerasinghe et al. (2009), Kurian et al. (2013)
Iran, Mashad plain	Wheat, barley (also as fodder crops), lettuce	Monem (2013)
Mexico, Mezquital Valley (Hidalgo)	Mainly fodder crops and maize	Siebe (2013)
Morocco, Settat (Chaouia-Ouardigha)	Wheat, maize, fodder crops, potatoes, olives	Larbi (2013)
Pakistan, Faisalabad (Punjab)	Fodder, vegetables, cereals, sugarcane, other crops	Ensink et al. (2004a), Weckenbrock (2010)
Peru, Lima	Vegetables	Moscoso Cavallini (2013)
Peru, Lima	Sweet potatoes, salad, cabbage, tomatoes, onions, potatoes, garlic, bananas, avocados, other crops	Espiritu Limay (2013)
Philippines, Lian (Batangas)	Sugarcane (for biofuel production)	Sandoval et al. (2013)

3.3.2 Cereals

Because of its high irrigation water requirement, the most common cereal grown with wastewater is rice (Raschid-Sally and Jayakody 2008). Other cereals such as wheat, oats, millet, sesame, sorghum and maize are also irrigated with wastewater (Bradford et al. 2002; Weckenbrock 2010; Siebe 2013).

3.3.3 Fodder Crops

Alfalfa, Paragrass (*Urochloa mutica*), Sorghum (*Sorghum* spp.), Persian clover (*Trifolium resupinatum* L.), Lucerne (*Medicago* spp.), Berseem (*Trifolium alexandrinum* L.) are among the fodder crops mentioned in the literature about wastewater irrigation (Buechler et al. 2002; Moscoso Cavallini and Egocheaga Young 2002; Amerasinghe et al. 2009; Weckenbrock 2010).

3.3.4 Energy Crops

The main energy crop cultivated with wastewater in tropical settings is sugarcane (Melfi and Montes 2008; Weckenbrock 2010; Sandoval et al. 2013). In temperate climates, other fast growing plants like willows are being used (Dimitriou and Aronsson 2005).

With their high nutrient requirement and due to the fact that, if used appropriately, they do not pose a risk for human consumption, there is a high potential for the use of energy crops in wastewater irrigated systems even if the water quality is not fit for the production of food crops. In order to be economically viable, the production of energy crops depends on infrastructure in terms of transport and processing as well as power plants for the creation of electricity.

3.3.5 Other Crops

Other crops irrigated with wastewater that have been mentioned in the literature include ornamental plants, timber plants and fruit trees (da Costa e Silva et al. 2002; Moscoso Cavallini and Egocheaga Young 2002; Buechler et al. 2006).

The range of different crops cultivated with wastewater in different countries is illustrated in the examples from case studies listed in Table 1.

In water scarce regions, crops with high water requirements often fetch higher market prices, which make them interesting for wastewater-irrigating farmers. A study in Pakistan, for example, found that farmers using wastewater for irrigation produced crops with higher market values than their non-wastewater-irrigating neighbours (Weckenbrock 2010).

Further examples for reasons why farmers chose specific crops for their wastewater irrigated fields are listed in Hunshal et al. (1997). Some of these reasons are linked to wastewater quality. Positive reasons besides high market demand include good yields, ease of growth and resistance to pests and diseases. Reasons against cultivating crops with wastewater include inferior quality of the produce, vulnerability to pests and diseases and inhibited growth.

3.4 Farming Systems under Wastewater Irrigation

While information on crop types irrigated with wastewater is usually limited to naming the crops, information on farming systems under wastewater irrigation is almost non-existent. A possible reason for this is the fact that most research on wastewater irrigation has been from a health and environmental risk perspective with a much weaker focus on agricultural issues (cf. Carr et al. 2004a; WHO 2006b). Moreover, the variety of different farming systems under use in wastewater-irrigated areas can suggest that there are few specific system requirements for wastewater irrigation agriculture. Like any other agricultural system, the development of a wastewater irrigated agricultural system depends on a wide range of locally-specific technical, environmental, social and economic factors (cf. Moscoso Cavallini and Egocheaga Young 2002; Van der Hoek et al. 2002; Bradford et al. 2003; Ensink et al. 2004b and Kurian et al. 2013).

One obvious example for a factor specific to wastewater-irrigated agriculture is issues related to nutrients. Due to the high content of nutrients, i.e. nitrogen, potassium, phosphorus, zinc, boron and sulphur (WHO 2006b), in wastewater, farmers using this water for irrigation usually reduce or stop the use of mineral fertilizers (Ensink et al. 2003; Raschid-Sally and Jayakody 2008). While this saves them money, higher costs are often caused by increased incidences of pest attacks and weeds that force farmers to use more labour and pesticides (Bradford et al. 2003; Ensink et al. 2003; Kurian et al. 2013). In such cases, increased pesticide use can then become a new source of health and environmental risks. If wastewater irrigation is to make a real positive contribution to the health and environmental situation, such sustainability issues of farming systems must be addressed.

> Farm-based measures such as the use of alternative pesticides or integrated pest management remain the key to risk reduction… Farming practices that reduce runoff, such as the provision of vegetation cover or vegetation buffer strips, can significantly reduce the probability of environmental impacts (Mateo-Sagasta et al. 2013: 31).

Thus, in order to make wastewater irrigation sustainable, the agricultural focus must not only be on crops but—more importantly—on agricultural systems. This is also reflected in a recent report by UNEP and IWMI calling for a shift from ‘water for food’ to ‘water for multifunctional agroecosystems’ (Boelee 2011). In order to plan and design such systems systematically, it makes sense to approach wastewater irrigation from the perspective of ‘an integrative discipline that includes elements from agronomy, ecology, sociology and economics' (Dalgaard et al. 2003: 39). This discipline is the science/practice/movement of sustainable agricultural systems: agroecology. It has so far not been used for the design of sustainable wastewater irrigation systems but offers a great potential in doing so.

4 Towards an Agro-Ecology of Wastewater Irrigation

A relatively young science, agro-ecology has nevertheless been raising hopes for a transition toward sustainable agriculture linked to various fields of sustainable development. Such hopes are expressed in a statement of the United Nation's Special Rapporteur on the right to food.

> Drawing on an extensive review of the scientific literature published in the last five years, the Special Rapporteur identifies agro-ecology as a mode of agricultural development which not only shows strong conceptual connections with the right to food, but has proven results for fast progress in the concretization of this human right for many vulnerable groups in various countries and environments. Moreover, agroecology delivers advantages that are complementary to better known conventional approaches … and it strongly contributes to the broader economic development (de Schutter 2011, p 1).

A worldwide movement, agroecology has a strong basis in Latin America in general and Brazil in particular (Altieri 1999a; EMBRAPA 2006; Holt-Giménez 2006; Wezel et al. 2009; Petersen et al. 2013).

The following sections will introduce the concept of agroecology and outline its possible contribution to the design of sustainable wastewater-irrigated agricultural systems.

4.1 What Is Agroecology? Definitions and Key Principles

One widely quoted definition describes agroecology as 'the science of applying ecological concepts and principles to the design and management of sustainable food systems' (Gliessman 2007: 369). The idea is to learn the design of agricultural systems from nature: 'At the heart of the agroecology strategy is the idea that an agroecosystem should mimic the functioning of local ecosystems thus exhibiting tight nutrient cycling, complex structure and enhanced biodiversity' (Altieri 2002: 8). This means that—unlike in conventional agricultural approaches—the focus is not so much on individual crops but on creating habitats for crops, for instance in polycropping systems. Beside a strong emphasis on cycles (Jones et al. 2010), another focus of agroecology, which is particularly relevant for the topic of wastewater reuse is the detoxification of noxious chemicals (Altieri 1999b). Further agroecological principles are listed below in Fig. 3.

Enhance the recycling of biomass with a view to optimizing organic matter decomposition and nutrient cycling over time.
Strengthen the 'immune system' of agricultural systems through enhancement of functional biodiversity – natural enemies, antagonists, etc.
Provide the most favourable soil conditions for plan growth, particularly by managing organic matter and by enhancing soil biological activity.
Minimize losses of energy, water, nutrients and genetic resources by enhancing conservation and regeneration of soil and water resources and agrobiodiversity.
Diversify species and genetic resources in the agroecosystem over time and space at the field and landscape level.
Enhance beneficial biological interactions and synergies among the components of agrobiodiversity, thereby promoting key ecological processes and services.

Fig. 3 Agro-ecological principles. *Source* Altieri (2012: 7)

Based on these principles, a wide range of agroecological practices have been identified or developed (see Table 2). Many of them are of interest for a sustainable agricultural system based on wastewater irrigation.

However, agroecology is not only a set of agricultural techniques to promote ecological interactions in agricultural systems. It also puts a strong emphasis on the importance of social factors.

> Agroecology is more than merely the promotion of new technologies or practices, but rather a fresh understanding of how to optimize the configuration of biological and technological components of farming systems informed by ecological principles. This necessarily requires a shift in roles among growers and extensionists so that they can actively participate in networks of social learning (Warner 2006: 84).

Such a shift must put farmers in a central role in learning networks (Altieri 2002; Holt-Giménez 2006). This view is not confined to an agroecological perspective. In fact, there is wide agreement about the need for more respect for farmers and for participatory approaches to agricultural development. This recognition ranges from the global report on the state of agriculture (IAASTD 2009) to the literature on wastewater reuse (cf. Faruqui et al. 2004; Clemett and Ensink 2006; Keraita et al. 2007).

A first step towards learning networks is the recognition of innovative ways in which farmers are already using wastewater as a resource.

Table 2 Selected agroecological practices relevant for wastewater irrigation

Practice	Short description	Relevance for wastewater reuse systems (examples)
Crop choice	Use of crop varieties that are resistant to environmental stress and diseases	Selecting plants that are efficient in converting wastewater into produce; selecting plants that can take up high quantities of contaminants (hyperaccumulators*)
Spatial succession of crops	In order to adapt to gradual changes in environmental conditions, different crops are grown in a spatial sequence	Crops that can tolerate and absorb contamination filter the water for crops that are more sensitive
Organic fertilization	Partial or total substitution of mineral fertilizers by fertilizers based on organic matter	Algal biomass from stabilization ponds or other fast-growing plants as slow-release fertilizer
Biological pest control	Control of weeds, pests, and diseases based on introduction of natural enemies, pheromones or 'push' and 'pull' plants**	Ecological and cheap way of dealing with increased pest pressure resulting from high nutrient levels in wastewater
Cover crops	Plants that do not compete with crops used to cover the soil to reduce weed growth, soil erosion and increase soil fertility	Weed pressure on crops resulting from the high nutrient availability in wastewater irrigated areas can be controlled; increased uptake of nutrients from wastewater; reclamation of soil quality
Intercropping	Cultivation of two or more crops on the same field at the same time in order to capture nutrients better and use space more efficiently	Using space more efficiently facilitates the uptake of a wider range and quantity of nutrients from the wastewater. This improves the treatment effect and enhances nutrient recycling rates
Agroforestry	Land-use systems involving trees combined with crops and/or animals on the same unit of land	Efficient use of space with lines of fast-growing tree species such as eucalyptus; fruit on trees do not come into direct contact with the wastewater which lowers the risk of food contamination; deep roots can serve to prevent leeching of nutrients into deeper soil layers and groundwater
Landscape elements	Planting and management of vegetation strips and hedges in fields and at field borders	Habitat for beneficial animals that feed on pest insects; potential for fast biomass production

Source Nair (1991), Vandermeer (1995), Tanji and Kielen (2002), Cook et al. (2007), Dufumier (2010), Scheierling et al. (2010), Simmons et al. (2010), Altieri (2012), Wezel et al. (2013)

[*] In a process called phytoremediation, specific plants can be used to remove pollutants at minimal cost: 'The concentrations of metals accumulated in hyperaccumulator plants may be 100 times greater than those occurring in non-accumulator plants growing on the same substrates' (Simmons et al. 2010: 215)

[**] The push-pull strategy is a dual approach of integrated pest management: 'push' plants between the crops are used to make the protected crops unattractive to pests while 'pull' plants lure them away from the crops (Cook et al. 2007)

4.2 Elements of Agroecological Practices in Existing Wastewater Irrigated Agricultural Systems

Wastewater irrigation often exists without authorities being aware of this. In many cases, farmers have started wastewater reuse schemes on their own initiative and even defended them against attempts by authorities to stop them (Weckenbrock et al. 2011). By engaging in cooperation rather than threatening such initiatives, authorities can build on existing, decentralized bottom-up structures and concentrate their efforts in assisting wastewater-using farmers in making their work safer and more efficient. This could take the latter out of a legal grey area and turn them into partners in the task of reusing wastewater safely and sustainably. The agroecological approach is thus very much about promoting integration between sectors at the local level. This will need collaboration between farmers and their communities, as well as local health and environmental departments and, importantly, the local planners. Champions at the local authority level, perhaps the Mayor, may also support the campaign. A first step that official bodies could undertake would therefore be to find out about wastewater reuse in their municipalities. Existing wastewater reuse schemes would also be a good starting point for determining which crops and techniques are viable in a given context of wastewater-irrigated agriculture. Although this has not yet been a research focus, examples of agroecological practices used in existing wastewater reuse schemes can be found in the literature. The following are examples of interventions with agroecological elements. Compared to highly technical approaches to wastewater treatment, these rely more on living systems and are cheaper. In many cases, these systems were not centrally designed and installed but developed by farmers by trial and error (Table 3).

4.3 Using Agroecology in the Design of Productive Wastewater Reuse Schemes

All wastewater reuse schemes depend on the specific context of each place. The physical context includes factors like climate, soils, irrigation water requirements, availability, quality, etc. The socioeconomic context entails amongst others, the history of landuse, social structure, supply, demand, pricing of agricultural products, land ownership structures and the legal context. Moreover, to be sustainable, an agricultural wastewater reuse scheme must be planned and developed in cooperation between a range of stakeholders including planners, farmers and residents of the respective areas. All this implies that there cannot be one solution for all possible wastewater scenarios.

However, in the task of moving towards sustainable agricultural systems for wastewater reuse, it is possible to learn from existing wastewater irrigation and from agroecological approaches. Such systems can serve to constitute a transition towards or even an alternative to conventional, technical treatment systems.

Table 3 Examples for existing wastewater reuse schemes using agroecological elements

Country	Practice	Source
Egypt	Engineered wetlands for water treatment (at 10 % of the cost of traditional, chemical-intensive wastewater treatment systems), fish farming and agriculture	El-Gamal (2013)
India	Crops that tolerate higher contamination levels (e.g. fodder grass) grown in proximity to the city with more sensitive crops (e.g. rice, vegetables) cultivated further downstream where the contamination levels of wastewater are lower	Amerasinghe et al. (2009), Bradford et al. (2003)
India	Cultivation of cauliflower and beet root in the same wastewater irrigated plots	Hunshal et al. (1997)
India	Beetles as bio-control agents against weeds	Bradford et al. (2002)
India	The East Kolkata wetlands are one of the world's largest integrated systems of wastewater treatment, aquaculture and irrigated agriculture	Fureddy and Ghosh (1984), Ghosh (2005)
Peru	Small treatment ponds for aquaculture (fish production). Effluent is then used for agricultural irrigation	Moscoso Cavallini (2013)
Sweden	Short-rotation willow coppice for low-cost treatment. Biomass used for combined heat and power generation	Dimitriou and Aronsson (2005)

Therefore, rather than doing nothing about a situation in which large volumes of wastewater are disposed of untreated into the environment, it makes more sense to introduce a management approach loop based on agroecological principles. With regards to the need to adapt each system to its specific local context and for a participatory learning and development process is not meant as a fixed model but rather as a basis for discussion (Fig. 4).

5 Conclusions

The huge demographic and social changes that will happen in the next decades will greatly impact society. Urbanization, as one of the most critical changes, in fact the most relevant in the next 50 years, will impact significantly on wastewater generation and the need for increased food production. So far, most of the world's wastewater enters the environment untreated. This does not only constitute risks that are difficult to manage, but also an enormous waste of resources. Wastewater irrigation offers the possibility to link environmental and health protection with food and energy production and income creation. New approaches offer great promise to engage many informal workers in the creation of worthwhile enterprises. So far, there has been a discrepancy between a focus on expensive technical solutions to wastewater treatment from official bodies on the one hand and millions of farmers using wastewater semi-legally or illegally on their fields on the other

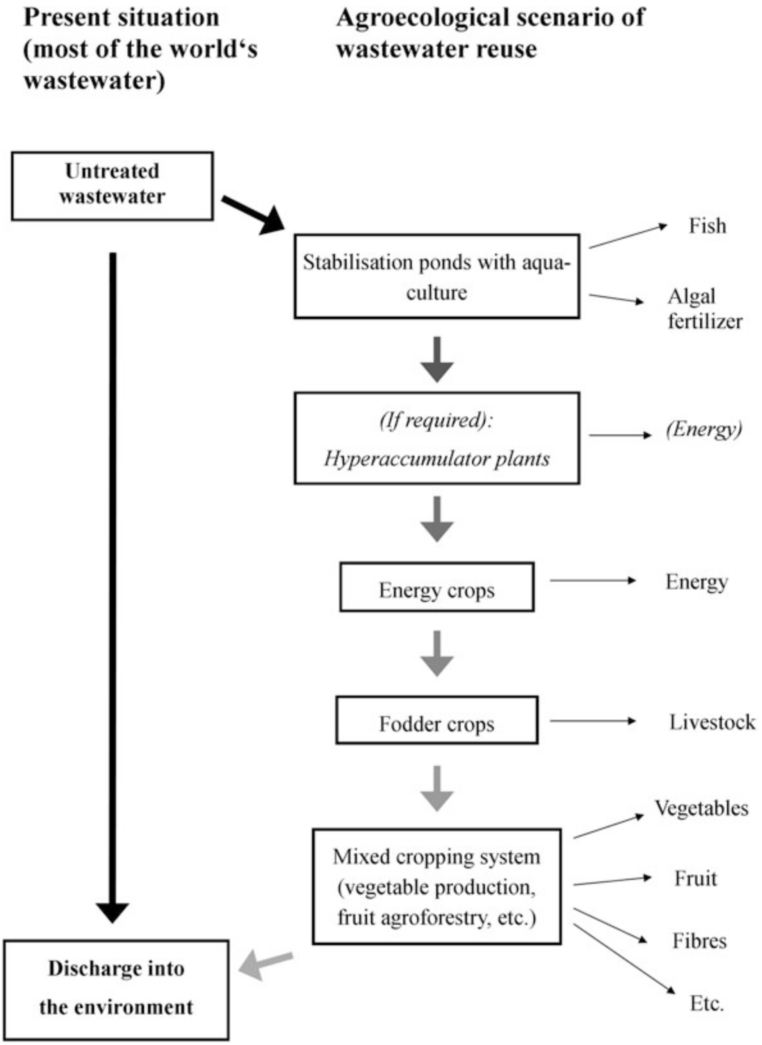

Fig. 4 Possible model for an agroecological wastewater reuse loop for wastewater treatment and nutrient recycling. *Source* Author

hand. Official bodies should look more closely at decentralized, small-scale options. Scientific information on wastewater irrigation has focused mostly on health risks. Applied research on agricultural aspects of wastewater irrigation is scarce. With regard to the multitude of factors that influence the search for sustainable wastewater irrigation systems, there cannot be one solution that fits all possible contexts. However, the discipline of agroecology offers a range of approaches and techniques for designing sustainable wastewater reuse systems. This offers the possibility to put into practice the ‘paradigm shift’ in dealing with wastewater that many experts on the topic call for.

The discussions in this chapter lead us to conclude that research in the following areas could contribute to the design of sustainable agroecological wastewater treatment and production systems. As pointed out in Sect. 2, wastewater-irrigated agriculture remains largely invisible. The fact that few existing schemes have been described limits the knowledge base that can be used for designing new systems. As pointed out, a range of locally specific criteria play a role for any wastewater irrigation agricultural scheme. Therefore, more empirical research on the ground is needed in regions such as South America in general and Brazil in particular for which very little research exists. Concrete agronomic information that is needed includes data on crop types that perform well under wastewater irrigation (adding to information like that given in Annex 3) and on suitable combinations of crops (which does not exist so far, see Sect. 4.4). Because most wastewater-irrigating farmers operate outside of the law or in legal grey areas (see Sect. 3), there should be research on how to best integrate informal wastewater irrigation schemes into partnerships. This is needed for moving from unplanned to planned wastewater use. Land-use planners, particularly in the peri-urban areas of rapidly growing towns and cities needs to develop a rigorous approach to accommodate effective and sustainable reuse schemes.

Annexes

Annex 1 Wastewater Reuse Standards for Health Protection

Health-based targets for wastewater use in agriculture as given in the WHO Guidelines (WHO 2006a)

Exposure scenario	Health-based target (DALY per person per year)	Log_{10} pathogen reduction needed[a]	Number of helminth eggs per litre
Unrestricted irrigation	$\le 10^{-6}$ [a]		
Lettuce		6	≤ 1[b,c]
Onion		7	
Restricted irrigation	$\le 10^{-6}$ [a]		
Highly mechanized		3	≤ 1[b,c]
Labour intensive		4	≤ 1[b,c]

(continued)

(continued)

Exposure scenario	Health-based target (DALY per person per year)	Log_{10} pathogen reduction needed[a]	Number of helminth eggs per litre
Localized (drip) irrigation	$\leq 10^{-6}$ [a]		
High-growing crops		2	No recommendation[d,e]
Low-growing crops		4	≤ 1[c,d]

[a] Rotavirus reduction. The health-based target can be achieved, for unrestricted and localized irrigation, by a 6–7 log unit pathogen reduction (obtained by a combination of wastewater treatment and other health protection measures, including an estimated 3–4 log unit pathogen reduction as a result of the natural die-off rate of pathogens under field conditions and the removal of pathogens from irrigated crops by normal domestic washing and rinsing; see Sect. 4.2.1 for further details); for restricted irrigation, it is achieved by a 2–3 log unit pathogen reduction (Sect. 4.2.2)

[b] When children under 15 are exposed, additional health protection measures should be used (e.g. treatment to ≤0.1 egg per litre, protective equipment such as gloves or shoes/boots or chemotherapy; see Sects. 4.2.1 and 4.2.2 for details)

[c] An arithmetic mean should be determined throughout the irrigation season. The mean value of ≤1 egg per litre should be obtained for at least 90 % of samples in order to allow for the occasional high- value sample (i.e. with >10 eggs per litre). With some wastewater treatment processes (e.g. waste stabilization ponds), the hydraulic retention time can be used as a surrogate to assure compliance with ≤ 1 egg per litre, as explained in Sect. 6.1 in Chap. 5 and Box 5.2

[d] See Sect. 4.2.3

[e] No crops to be picked up from the soil

Source WHO (2006b: 60)

Examples of global water quality standards for non-food crop irrigation

Microbial standards or guidelines by state, country, region	Total coliform per 100 mL	Faecal coliform or *E. coli per* 100 mL
Puglia (S. Italia)	≤10	
California, Italy	≤23	
Australia		≤10
Germany	≤100	≤10
Washington State	≤240	
Florida, Utah, Texas, EPA (Guidelines)		≤200
Arizona, New Mexico, Australia, Victoria, Mexico		≤ 1,000
Austria		≤2,000
Sicily	≤3,000	≤ 1,000
Cyprus		≤3,000
WHO, Greece, Spain		≤10,000

Source USEPA (2012: 3–13)

Annex 2 Wastewater Quality Guidelines for Agriculture

Primary wastewater quality parameters of importance from an agricultural viewpoint

Parameters		Symbol	Unit
Physical			
Total dissolved solids		TDS	mg/l
Electrical conductivity		Ec_w	dS/m[a]
Temperature		T	°C
Colour/turbidity			NTU/JTU[b]
Hardness			mg equiv. $CaCO_3$/l
Sediments			g/l
Chemical			
Acidity/Basicity		pH	
Type and concentration of anions and cations:			
	Calcium	Ca^{++}	me/I[c]
	Magnesium	Mg^{++}	me/I
	Sodium	Na^{+}	me/I
	Carbonate	CO_3^{--}	me/I
	Bicarbonate	HCO_3-	me/I
	Chloride	CI_-	me/I
	Sulphate	SO_4^{-}	me/I
Sodium adsorption ratio		*SAR*	
Boron		B	mg/l[d]
Trace metals			mg/l
Heavy metals			mg/l
Nitrate-Nitrogen		NO_3-N	mg/l
Phosphate Phosphorus		PO_4-P	mg/l
Potassium		K	mg/l

[a] dS/m = deciSiemen/metre in SI Units (equivalent to 1 mmho/cm)
[b] NTU/JTU = Nephelometric Turbidity Units/Jackson Turbidity Units
[c] me/I = milliequivalent per litre
[d] mg/l == milligrams per litre = parts per million (ppm); also, mg/l - 640 × EC in dS/m
Source: Pescod (1992)

WHO water quality standards for irrigation

Parameter		Units	Degree of restriction on use		
			None	Slight to moderate	Severe
Salinity EC_w^a		dS/m	<0.7	0.7-3.0	>3.0
TDS		mg/l	<450	450-2000	>2,000
TSS		mg/l	<50	50-100	>100

(continued)

(continued)

Parameter		Units	Degree of restriction on use		
			None	Slight to moderate	Severe
SAR[b]	0-3	meq/l	>0.7 EC_w	0.7-0.2 EC_w	<0.2 EC_w
SAR	3-6	meq/l	>1.2 EC_w	1.2-0.3 EC_w	<0.3 EC_w
SAR	6-12	meq/l	>1.9 EC_w	1.9-0.5 EC_w	<0.5 EC_w
SAR	12-20	meq/l	>2.9 EC_w	2.9-1.3 EC_w	<1.3 EC_w
SAR	20-40	meq/l	>5.0 EC_w	5.0-2.9 EC_W	<2.9 EC_w
Sodium (Na^+)	Sprinkler irrigation	meq/l	<3	>3	
Sodium (Na^+)	Surface irrigation	meq/l	<3	3-9	>9
Chloride (Cl^-)	Sprinkler irrigation	meq/l	<3	>3	
Chloride (Cl^-)	Surface irrigation	meq/l	<4	4-10	>10
Chlorine (Cl_2)	Total residual	mg/l	<1	1-5	>5
Bicarbonate (HCO_3-)		mg/l	<90	90-500	>500
Boron (B)		mg/l	<0.7	0.7-3.0	>3.0
Hydrogen sulphide (H_2S)		mg/l	<0.5	0.5-2.0	>2.0
Iron (Fe)	Drip irrigation	mg/l	<0.1	0.1-1.5	>1.5
Manganese (Mn)	Drip irrigation	mg/l	<0.1	0.1-1.5	>1.5
Total nitrogen (TN)		mg/l	<5	5-30	>30
pH			Normal range 6.5-8		
Trace elements (see Table A1.2)					

TDS, total dissolved solids; TSS, total suspended solids
Sources: Ayers & Westcot (1985); Pescod (1992); Asano and Levine (1998)
[a] EC_w means electrical conductivity in deciSiemens per metre at 25°C
[b] SAR means sodium adsorption ratio ($[meq/l]^{1/2}$); see section A1.5
Source: WHO (2006b: 178)

USEPA guidelines for the interpretation of water quality for irrigation[1]

			Degree of Restriction on Irrigation		
Potential Irrigation Problem		Units	None	Slight to Moderate	Severe
Salinity *(affects crop water availability)*[2]					
	EC_w	dS/m	<0.7	0.7-3.0	>3.0
	TDS	mg/L	<450	450-2,000	>2,000

(continued)

(continued)

			Degree of Restriction on Irrigation		
Potential Irrigation Problem		Units	None	Slight to Moderate	Severe
Infiltration *(affects infiltration rate of water into the soil; evaluate using ECW and SAR together)*[3]					
SAR	0-3	**and EC_W=**	>0.7	0.7-0.2	<0.2
	3-6		>1.2	1,2-0.3	<03
	6-12		>1.9	1.9-0.5	<0.5
	12-20		>2.9	2.9-1.3	<1.3
	20-40		>5.0	5.0-2.9	<29
Specific Ion Toxicity *(affects sensitive crops)*					
	Sodium (Na)[4]				
	surface irrigation	SAR	<3	3-9	>9
	sprinkler irrigation	meq/l	<3	>3	
	Chloride (CI)[4]				
	surface irrigation	meq/l	<4	4-10	>10
	sprinkler irrigation	meq/l	<3	>3	
	Boron (B)	mg/L	<0.7	0.7-3.0	>3.0
Miscellaneous Effects *(affects susceptible crops)*					
	Nitrate (NO_3-N)	mg/L	<5	5-30	>30
	Bicarbonate (HCO_3)	meq/L	<1.5	1.5-8.5	>8.5
	pH		**Normal Range 6.5-8.4**		

[a] Adapted from FAO (1985)

[b] EC_w means electrical conductivity, a measure of the water salinity, reported in deciSiemens per metre at 25°C (dS/m) or in millimhos per centimetre (mmho/cm); both are equivalent

[c] SAR is the sodium adsorption ratio; at a given SAR, infiltration rate increases as water salinity increases

[d] For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; most annual crops are not sensitive. With overhead sprinkler irrigation and tow humidity (<30 percent), sodium and chloride may be absorbed through the leaves of sensitive crops

Source: USEPA (2012: 3-7)

USEPA recommendations on other toxic elements in irrigation water

Constituent	Maximum Concentrations for Irrigation (mg/L)	Remarks
Aluminium	5.0	Can cause nonproductiveness in acid soils, but soils at pH 5.5 to 8.0 will precipitate the ion and eliminate toxicity
Arsenic	0.10	Toxicity to plants varies widely, ranging from 12 mg/L for Sudan grass to less than 0.05 mg/L for rice

(continued)

(continued)

Constituent	Maximum Concentrations for Irrigation (mg/L)	Remarks
Beryllium	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans
Boron	0.75	Essential to plant growth; sufficient quantities in reclaimed water to correct soil deficiencies. Optimum yields obtained at few-tenths mg/L; toxic to sensitive plants (e.g. citrus) at 1 mg/L. Most grasses are tolerant at 2.0 -10 mg/L
Cadmium	0 01	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L; conservative limits are recommended
Chromium	0.1	Not generally recognized as an essential element; due to lack of toxicity data, conservative limits are recommended
Cobalt	0.05	Toxic to tomatoes at 0.1 mg/L; tends to be inactivated by neutral and alkaline soils
Copper	0.2	Toxic to a number of plants at 0.1 to 1.0 mg/L
Fluoride	1.0	Inactivated by neutral and alkaline soils
Iron	5.0	Not toxic in aerated soils, but can contribute to soil acidification and loss of phosphorus and molybdenum
Lead	5.0	Can inhibit plant cell growth at very high concentrations
Lithium	2.5	Tolerated by most crops up to 5 mg/L; mobile in soil. Toxic to citrus at low doses- recommended limit is 0.075 mg/L
Manganese	0.2	Toxic to a number of crops at few-tenths to few mg/L in acidic soils
Molybdenum	0.01	Nontoxic to plants; can be toxic to livestock if forage is grown in soils with high molybdenum
Nickel	0.2	Toxic to a number of plants at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH
Selenium	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low levels of selenium
Tin, Tungsten, and Titanium	–	Excluded by plants; specific tolerance levels unknown
Vanadium	0.1	Toxic to many plants at relatively low concentrations
Zinc	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at increased pH (6 or above) and in fine-textured or organic soils

Source: USEPA (2012: 3-9)

Annex 3 Selected Crops with High Salt Tolerance

Common name in English	Botanical name
Acacia	*Acacia sp.*
Alkali sacaton	*Sporobolus airoides* Torr.
Asparagus	*Asparagus officinalis* L.
Barley	*Hordeum vulgare* L.
Canola or rapeseed	*Brassica napus* L.
Channel millet	*Enchinochloa turnerana*
Cotton	*Gossypium hirsutum* L.
Date-palm	*Phoenix dactylifera* L.
Eucalyptus	*Eucalyptus sp.*
Guayule	*Parthenium argentatum* A. Gray
Jojoba	*Simmondsia chinensis* (Link) C. K. Schneid
Kallar grass	*Leptochloa fusca*
Kallargrass	*Leptochloa fusca* (L.) Kunth
Leadtree	*Leucaena sp.*
Mesquite	*Prosopis sp.*
Natal plum	*Carissa grandiflora* (E.H. Mey.) A. DC.
Oats	*Avena sativ*a L.
Rhodes grass	*Chloris gayana)*
Rye	*Secale cereale* L.
Salt grasses	*Distichlis spicata*
Tamarugo	*Prosopis tamarugo* Phil.
Wheat, Durum	*Triticum turgidum* L. var. *durum* Desf.
Wheatgrass, tall	*Agropyron elongatum* (Hort) Beauvois

Source: Tanji and Kielen (2002)

There is considerable range of salt tolerance between varieties of the same species. Many different cultivars have been specifically developed to grow under conditions of elevated salinity (cf. Tanji and Kielen 2002). Some plants (halophytes) even respond with higher yields to increased levels of salinity (Goodin et al. 1990).

Annex 4 Policy Priorities on Wastewater Reuse

Priorities depend to some extent on the context for which wastewater reuse is considered. The table below, for instance, relates priorities to the level of economic development of different countries.

Typical wastewater irrigation objectives of countries by level of economic development

Level of economic development	Objective 1: Minimize risk to public health (priorities)		Objective 2: Minimize risk to environment (priority)	Objective 3: Improve livelihoods in Urban Agriculture (priority)	Objective 4: Integrate wastewater into water resources management (status)
	Microbial Risks	Chemical risks			
Low-income countries	Urgent	Low	Low	Urgent	Low
Lower-middle- income countries	High	Emerging	Emerging	High	Incipient
Upper-middle-income countries	High	Urgent	Urgent	High	Evolving
High-income non-OECD countries	High	High	High	Low	Advanced
High-income OECD countries	Low	High	High, with Focus on anthropogenic compounds	Nil	Advanced

Source: Scheierling et al. (2010: 75)

Moreover, as there are many potential stakeholders for wastewater irrigation, it is obvious that there is a wide range of priorities depending on who is asked. Priorities for planners and decision-makers participating in an international workshop on wastewater reuse are summarized in Mateo-Sagasta et al. (2013). Farmers' priorities, too, have been addressed in some publications (c.f. Kauvala 2007; Adjaye-Gbewonyo 2008; Weckenbrock 2010). In the following, the focus is on priorities as perceived by researchers on wastewater irrigation and large organizations like the WHO.

Stepwise approach

A main emphasis of many recent publications, which is also reflected in the latest version of the WHO guidelines for the safe use of wastewater, is on a stepwise approach (WHO 2006b; USEPA 2012). 'It is important always to consider the alternative to this step-wise approach, which may be inaction if standards are set too high and cannot be achieved in a reasonable period of time' (Scheierling et al. 2010: 50).

- Reduction of public health and environmental risks
- Moving from unplanned to planned wastewater reuse
- Gradual, stepwise improvements

- The whole progress can take a long time. In order to plan this process, a strategic plan should be developed (Scheierling et al. 2010):
- Multi-barrier approach (Faruqui et al. 2004; WHO 2006b; Scheierling et al. 2010; USEPA 2012)
- From an end-of-pipe to a source approach (Bahri 2009)
- Reduction of environmental contamination through source separation and moving towards separate treatment of industrial effluent (Buechler et al. 2006; Bahri 2009; Scheierling et al. 2010; Kurian et al. 2013)

Opening up the perspective and aiming at integrated approaches

- Using a multisectoral approach involving various governmental agencies and institutions work on issues related to wastewater reuse (Buechler et al. 2006; Scheierling et al. 2010; Kurian and Ardakanian 2013)
- Move from a focus on wastewater regulation and treatment towards one in which treatment and non-treatment options are combined to reduce health risks (Buechler et al. 2006; Bahri 2009)
- Multi-purpose approach based on the perception of wastewater as a valuable resource (c.f. Pearce 2008; USEPA 2012). Some authors even call for a paradigm shift in wastewater treatment and reuse (Bahri 2009; Scheierling et al. 2010)

Promoting stakeholder participation and social acceptance

- Involve all stakeholders from the start in water reuse operations and ensure multi-stakeholder platforms to facilitate dialogue, participatory technology development, innovation uptake and social learning (Bahri 2009)
- Particular focus on practitioners, especially wastewater using farmers (Buechler et al. 2006; Adjaye-Gbewonyo 2008; Scheierling et al. 2010)
- Involvement of private sector institutions (Scheierling et al. 2010)
- Awareness creation from farm to fork (Bahri 2009)

Annex 5 Organizational Stakeholders in Wastewater Reuse (Focus on Brazil)

In general, the following stakeholders are typically involved in the management of wastewater reuse schemes (Mateo-Sagasta et al. 2013):

- Ministries of Agriculture, Water Resources, Health, the Environment, Energy and Development
- Research institutions and universities
- Non-governmental institutions and organizations
- Farmers' groups
- Consumers

- Municipalities and local water management institutions
- Water operators

Important organizations on a supra-national level:

- WHO (WHO 2002, 2006a)
- Pan American Health Organization (PAHO)
- FAO (FAO 1997, 2008a, 2008b)
- UNEP (UNEP and GEC 2004)
- UNDP (UNDP 2006)
- UN-Water (http://www.unwater.org/)
- UN-Water Activity Information System (UNW-AIS) is UN-Water's online platform to present and share information (http://www.ais.unwater.org/ais/course/view.php?id=6)
- IWMI (IWMI 2003, 2006) http://www.iwmi.cgiar.org/health/wastew/
- RUAF foundation has carried out much research on wastewater irrigation (see their list of online material at www.ruaf.org/taxonomy/term/33?page=9)
- Swiss Federal Institute of Aquatic Science and Technology (Eawag): Swiss research institute that has carried out research on wastewater reuse http://www.eawag.ch/index
- Sandec is the Department of Water and Sanitation in Developing Countries at Eawag (http://www.sandec.ch/index_EN)

National level: Brazil

In Brazil, according to Mierzwa (2004), there were no examples of planned wastewater reuse schemes outside some research projects. However, there are some organizations with experience in technical aspects of wastewater reuse in agriculture.

- Agência Nacional de Águas (ANA): Brazilian national water agency has initiated a research centre on wastewater reuse (http://www2.ana.gov.br/Paginas/projetos/Reuso.aspx). http://www2.ana.gov.br/Paginas/default.aspx
- Associação Brasileira de Engenharia Sanitária e Ambiental (ABES): non-profit organization with an engineering approach and subsections in all States of Brazil. Has conducted research on wastewater reuse. http://www.abes-dn.org.br/
- ABES-Franca have organized a workshop on wastewater reuse in 2012: http://www.abesfranca.com.br/eventos/W_RE_09.pdf

Sub-national level: Sao Paulo State (Brazil)

- University of Sao Paulo (USP):
- Centro Internacional de Referência em Reúso de Água (CIRRA): The International Reference Center on Water Reuse has worked on wastewater reuse and offers a platform with information on wastewater reuse. http://www.usp.br/cirra/
- Departamento de Engenharia Hidráulica e Sanitária
- Companhia de Saneamento Básico do Estado de São Paulo S.A (SABESP) http://site.sabesp.com.br/site/: large Brazilian waste management company. Owned by Sao Paulo State

- Centro de Vigilância Sanitária (CVS): Institution of the Health Secretary of the State of Sao Paulo responsible for sanitation issues. http://www.cvs.saude.sp.gov.br/

Small farmers' movements

Local peasant organizations exist in many regions of Latin America. Usually, they can only be identified in their respective area. However, there are some peasant organizations and movements that are in touch with many smaller organizations. They include the following:

- Via campesina: international peasant movement. They are in contact with many local peasant organizations. http://viacampesina.org/en/
- Movimiento Campesino a Campesino: large movement of farmer-promoters, mainly active in Latin America. http://www.foodfirst.org/backgrounders/campesino
- Movimento dos Pequenos Agricultores (MPA): national peasant movement in Brazil http://www.mpabrasil.org.br/

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Chapter 9
Visualization of Water Services in Africa: Data Applications for Nexus Governance

Theresa Mannschatz, Manfred F. Buchroithner
and Stephan Hülsmann

1 Introduction

Africa receives the third largest amount of global annual precipitation, which builds up the African water resources (Curmi et al. 2013). Still, at the continental level, Africa's renewable water resources only represent around 9 % of the world's total freshwater resources, making it the second driest continent (UNEP 2010). Moreover, in Africa the water resources are spatially unequally distributed. In combination with varying population density, this results in wide differences in water availability and poses challenges for water supplies. Both extremes (arid and humid regions) face numerous water-related problems. (Semi)-arid regions have to deal with droughts, poor water quality, soil salinity, low agricultural production and limited water supply. In contrast, humid regions are confronted with floods, biological risks (e.g. malaria, cholera), soil erosion and landslides. 'Water services' is defined by FAO Water as 'the activity of providing users with water deliveries as well as it can define the company itself who provide the service' (FAO 2014). Water services comprise regulating services (sanitation, flood protection, erosion

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control), cultural services (tourism, cultural heritage values, infrastructure), provisioning services (vegetation growth, transportation, irrigation, hydropower), and supporting services (groundwater recharge, fishing, support to biodiversity, soil conservation) (Renault et al. 2009). Future water demand (not only) in Africa is expected to increase due to a growing population and food demand. This problem is intensified by global change processes including climate change, ineffective water management and economic globalization (Curmi et al. 2013).

Successfully coping with water-related problems and handling future water demands depend on effective water resources management. The management requires data about the actual and future state of the environment (including water resources) and socio-economics. The data assessment and management requires an integrated approach where spatial data is a key for further systems analysis and water management (Molina et al. 2014). Data requirements and challenges for integrated data analysis increase further when water management is addressed considering its close interrelation with soil and land-use management and waste management (Lal 2013, 2014). In spite of the associated challenges, adopting a nexus approach to the management of water, soil and waste (WSW Nexus) is increasingly recognized as a means to increase resource use efficiency and overall sustainability (Kurian and Ardakanian 2014), introductory chapter of this volume). The WSW Nexus represents the resources perspective to the Water, Energy and Food Security Nexus (Hoff 2011), promoting synergies between sectors.

While data availability is an issue, at least equally important is the question of how to make use of the data in a way that enables decision-makers to bridge from good science to good practice. Since pure data are meaningless without context and analysis with respect to a relevant question, an appropriate visualization technique is needed to support water management and decision-makers. Nowadays, data availability is continuously growing in many parts of the world due to fast technological developments (e.g. high-resolution remote sensing). For this reason, 'big data', as a synonym for very large and complex data sets becomes an issue, as it is so complex that it is difficult to process and analyse solely by looking at innumerable tables and figures. Data visualization that integrates complex information content is therefore mandatory for understanding and filtering of data significance for a specific application (e.g. water management) (Molina et al. 2014). The still largely lacking data visualization with the aim of decision support might be due to the high expertise and technical knowledge requirements for visualization workflow (Kwakkel et al. 2014). Recently, however, several (quite) easy to use software tools have become available that can be used by researchers to disseminate their research results in an adequate manner to support decision-makers.

This chapter aims to present the general workflow from data to visualization supported by examples, paying special attention to water-related problems and solutions in Africa. In order to support ease of access, also concerning costs, mainly no cost or open source visualization tools are presented. As one specific example, relevant in an African context, Water Point Mapping (WPM) is introduced.

2 General Workflow from Data to Modern (State-of-the-Art) Visualization

This section describes the general workflow that transforms data to visualization (Fig. 1). While examples mainly draw on water-related problems and variables, the focus is on basic principles, applicable to any visualization of environmental data. Basis of any visualization is the availability of data, which should be collected according to a defined sampling design. Data can be ground based (traditional sampling) or quasi-continuous based on various technologies. Data sampling design and data collection approaches (traditional and quasi-continuous) presented here are applicable to data-rich (Sect. 2.1.1) as well as to data-poor (Sect. 2.1.2) environments.

2.1 *Data Availability*

On a global view, regions can be grouped according to the availability of data into data-rich and data-poor environments. The data availability of a certain region is related to the country's history, climatic conditions, geographic location and development stage, which includes infrastructure, financial as well as socio-economic background. As a measure for general data availability might serve the

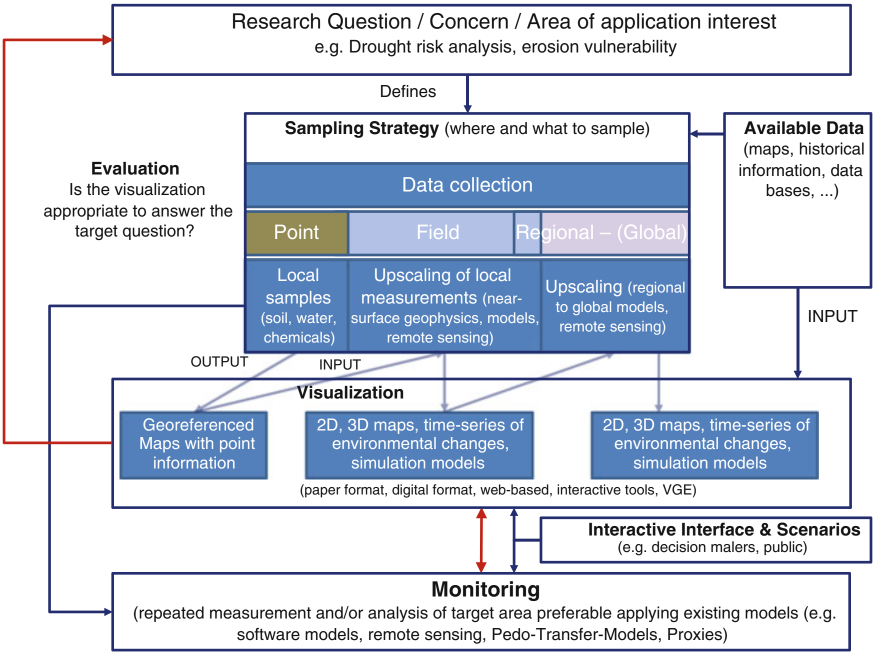

Fig. 1 General workflow from the research question via data up to visualization

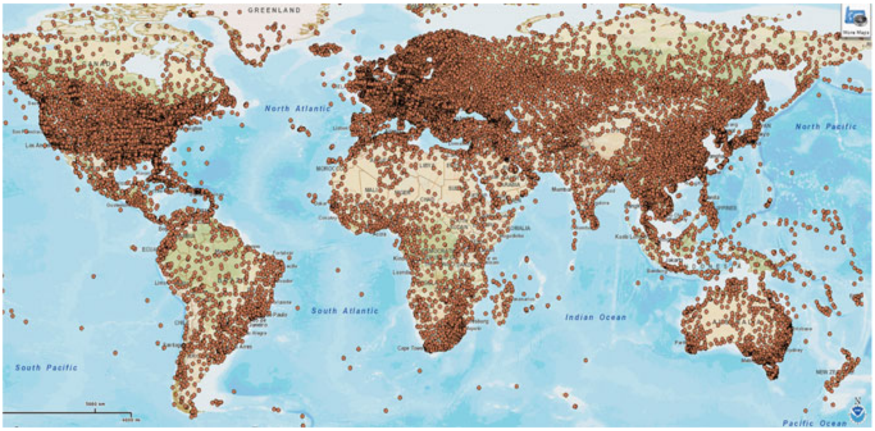

Fig. 2 Global distribution of climate stations (*brown dots*) that deliver varying number of weather variables. *Source* DOC/NOAA/NESDIS/NCDC, http://www.climate.gov/

global distribution of climate stations as shown in Fig. 2, demonstrating a huge variability at a global scale and data-scarce conditions in wide areas of Africa and South America. What adds to the number of climate stations is the data complexity (quality, number of measured variables) delivered by them. Stations in data-rich environments deliver a large number of weather variables (e.g. dew point, global radiation), while in data-poor environments; delivery is typically limited to basic weather data (e.g. temperature and precipitation). Later on in this chapter, we discuss a case study of Tanzania to highlight challenges in data-poor environments.

2.1.1 Data-Rich Environments

Data-rich regions generally have a long history of data collection, well-developed data collection infrastructure (dense sampling network, standardized sampling approaches, sophisticated instrumentation) along with a high degree of data reliability. In these regions, data repeated measurements (e.g. weather and water measurement stations) over longer periods are commonly carried out. Additionally, large number of economic projects for water management (e.g. reservoirs, water extraction wells) or agriculture (e.g. precision farming, erosion control) has led to extensive data surveys. Scientific projects contribute to the data availability to some degree through data collection, development of methods and instruments that improve data assessment. For these reasons, a large number of detailed maps and databases are available in data-rich regions that are frequently updated. In some regions (e.g. USA), data assessed by public financed institutions is openly accessible to the public.[1] Nevertheless, even under data-rich conditions, there may be

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[1] For more information, see https://www.data.gov/ or http://project-open-data.github.io/.

constraints for studying environmental and socio-economic related processes—particularly in consideration of global change processes. Such analyses require long-term data collections of the processes and phenomena under consideration. While the existing data collection infrastructure of weather stations allows for the analysis of long-term trends, respective data of ecological or socio-economic processes are not easily available over longer periods. Further development of state-of-the-art knowledge about processes might make it important to gather new data with the objective of densifying the measurement network, to account for process heterogeneity, or to incorporate innovative technologies (innovative instrumentation, methods) into the data measurement. The densification of a measurement network acknowledges the existing data, which is in contrast to data-poor environments.

2.1.2 Data-Poor Environments

Data-poor environments generally lack infrastructure, financial support, have difficult climate conditions (very cold, very dry) or are located in remote areas (low population density). An example for such a data-poor environment is the Sahara region, which is dry, low population and remote in relation to infrastructure. Basic weather data assessment has a long history and is relatively simple (e.g. temperature, precipitation) compared to other data assessments (e.g. vegetation, soil). Considering the low number of climate stations as indicator for data availability of that region, we can assume that availability of other data that are more difficult to measure will be much lower (Fig. 2). Lacking financial background, data-poor environments offer low measurement infrastructure such as low instrumentation, low measurement standardization and low number of qualified people for measurements. All factors together lead to low data reliability and low-resolution of final data products such as soil, vegetation or geological maps. This data scarcity hinders effective management of resources, performing risk analyses and analyses of actual and future environmental and socio-economic development. Data-poor regions require focusing on effective sampling design (Sect. 2.2) together with the usage of affordable, but reliable data sources and technologies such as remote sensing (Sect. 2.3.3). The use of proxies (which need to be verified under data-rich conditions) becomes particularly important and is discussed in Sect. 2.3.1.

2.2 Sampling Design

The design of any sampling strategy needs to be defined according to the sampling purpose, research questions and the visualization objective. Water service-related research questions, which need to be solved might be formulated as: Which is the level of drought risk, erosion proneness and related soil fertility, or water quality in a specific region? What are the consequences of land-use changes for a specific water service? The assessment of environmental as well as social data requires the data to be measured in conjunction to their geographic location. One should be aware that it is of importance, for the successful solving of the stated research question, to decide early about the appropriate data dimension to be covered by the sampling approach (Wang et al. 2012). The dimensions comprise 1D (point data), 2D (surfaces or depth information) or 3D (surfaces and depth information). For decision-makers, the sampling design needs to be defensible under public and scientific criticism. It needs to be taken into account that all approaches are related to uncertainties (Molina et al. 2014). For this reason, the data quality and uncertainties need to be documented and reported prior to further usage that canalize in visualization.

A comprehensive summary of important technologies for spatial measurements that are useful in hydrology is given by Molina et al. (2014). For further information about sampling and analysis of environmental data (multivariate geostatistics), please refer to Chiles and Delfiner (2012), Mateu and Muller (2012) and Wackernagel (2003).

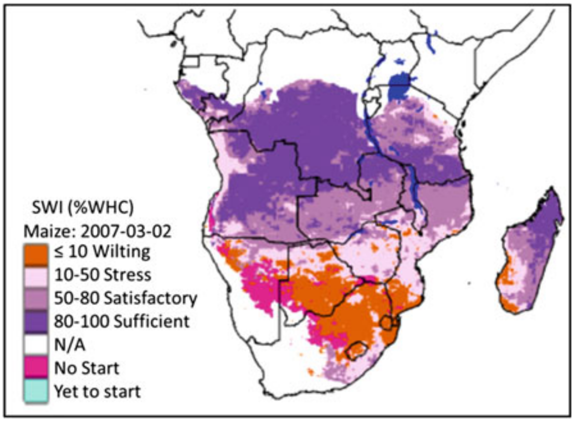
2.3 Data Assessment Adequate for Data-Poor Environments

Visualization is always based on any kind of data. In water services context, data comes not only from environmental assessments, but also from socio-economic sources. In general, collected data can be stored in databases that are then available to the stakeholders, such as researchers, students, decision-makers and the public. Data sources for defining a sampling design that is adequate for data-sparse regions, such as Africa, will briefly be summarized in the next sections.

2.3.1 Proxies—As Data Substitutes

The assessment and monitoring of system changes (e.g. water supply infrastructure, climate change) related to water services might be based on specific indicators and proxies. A proxy is a simplification of reality that aims to substitute real data by an estimation value that should, qualitatively or quantitatively, represent such real data. They are applied to overcome data scarcity in data-poor environments or when time-and-cost-consuming data surveys are not feasible. Since proxies are estimations, they possess a varying degree of uncertainty, unless the proxy is verified by real data measurement analysis. Proxies can potentially guide and support decision-makers by making them aware of the system conditions. This might lead to improved resource management, risk assessment and allocation of specific support. Proxies can be applied for qualitative estimations that are based on simple observations (e.g. colour), and quantitative estimations that are based on mathematical relationships (e.g. empirical, mathematical transfer functions). For instance, soil colour describes qualitatively or quantitatively the carbon content (level of black colour), iron content (level of reddishness) or a specific soil type (colour along soil

Fig. 3 Soil–water index of South and Central Africa, which shows the level of soil–water in the root zone. *Source* Melesse et al. (2007)



profile). The water colour of a sample can be a proxy of the pollution level or sediment content, which then might be a proxy for soil erosion.

A second proxy type is often called index. Indices are mathematically derived values that are calculated from several available data. Indices are single numbers that represent a more complex reality, which makes them useful for decision-makers. Another common feature of indices is that the data used for their calculation is generally easier to collect than the target data. Many indices that represent this relationship are based on remote sensing. This is especially true for data-poor environments as more satellites become available making satellite images more affordable. Remote sensing indices are based on their spectral bands related to the physical properties of the target value. An example is the vegetation index that is a proxy for vegetation density and leaf area index, which is a proxy for biomass production, photosynthesis, CO_2 uptake, water interception, plant height, root development, plant health and others. A vegetation index is therefore useful for agriculture management, hydrological analysis and climate change predictions. Similarly, the wetness index and soil–water index are used as proxies for soil–water content, which influences plant growth and infiltration capacity (flood protection) and can be used for drought prediction (Melesse et al. 2007). The Food and Agriculture Organization (FAO) applies the FAO-Agriculture Stress Index System (ASIS) that facilitates the establishment of risk transfer tools such as crop insurance.[2] Another example is water index (Fig. 3; Leblanc et al. 2011) or soil aridity index (Costantini and L'Abate 2009).

There are also socio-economic indices that integrate different data sources to derive one single value representative of the social and economic conditions, which can indicate where development or governmental support is required. The different indicators are mathematically combined where different weights are allocated to each data input variable. The level of allocated weights for each input parameter

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[2] For more information, see https://www.agriskmanagementforum.org.

needs to be defined (e.g. based on a principle component analysis, score), stated and defended. The weights reflect their influential importance for the process or condition an index represents. For example an index of economic resources of a specific area might be calculated from different weighted data as, for instance, number of companies, unemployment, income, expenses and ownership.

2.3.2 Point Data—Knowing and Verifying Environmental Parameters

For water-related issues, data is needed that informs about socio-economics (water use and quality, income, health status), near-surface characteristics (soils, vadose zone), subsurface characteristics (saturated zone), climate and land cover (vegetation, urban areas). Questionnaires, interviews and information obtained from media and press can be used to assess socio-economic aspects such as water use, water quality, population density, location of urban areas and political (policy), as well as economic relationships. The mapping of objects and resources, such as the position of a specific tree, river, lake, groundwater well or climate station, is useful to create maps. Those maps can support environmental planning, decision-making, as well as the verification of system modelling results or remote sensing image analysis.

On discrete locations, environmental qualitative (e.g. concentration levels high/low) and quantitative data (e.g. concrete concentration values) can be collected as single samples. The data collection in developing countries can be supported by freely available software tools such as the ‘Water Point Mapper’, which was designed to collect data easily based on spreadsheets from maps generated without an internet connection or extensive GIS knowledge[3] (see Sect. 2.6.1). Samples for quantitative investigations applicable in environmental risk assessments are collectable from surface and subsurface water, soils, rocks, air, plants or humans. Conventional sampling methods are time- and cost-consuming, because sampling generally has to be carried out at a large number of locations. However, point samples along with their corresponding laboratory analysis still provide the most reliable source of information about the environment. This point information is connectable to remotely sensed data visualizations, which is crucial for interpretation of its image features (Sect. 2.3.3). Additionally, simple proxies (e.g. water colour) or measurements (e.g. temperature, pH) can be applied to derive further data (e.g. water pollution, eutrophication) through the application of known transfer functions.

Recent technological development in the mobile phone sector opens the potential for using phones as mobile sensors. There already exists several software projects that offer freely usable (some are even open source) software tools that allow for partly automatic (e.g. geographic position) or manually entered (e.g. name of a lake, water quality) data collection. OpenDataKit is an example of an open

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[3] For more information, visit WaterAid at http://www.waterpointmapper.org.

source software solution that was explicitly developed to support decision-makers in developing countries.[4] As one potential application for using mobile phones or other GPS devices, WPM is discussed in Sect. 2.6.3.

2.3.3 Quasi-continuous Data

Several technologies for quasi-continuous measurements of environmental properties exist. The methods are suitable for earth (near-) surface measurements (2D–3D–4D) such as characterization of topography, vegetation, soil and surface or subsurface water bodies. Some of the selected methods can account for depth (3D) or temporal information (4D) through time-lapse measurements (time series). Technologies that have the potential for being applicable in regions where limited data is still an issue are mainly geophysical methods (Hartemink et al. 2008) such as:

- **Near-surface hydrogeophysical methods**, which are applied for quasi-continuous local to large-scale measurements of the surface and subsurface. Their purpose is the characterization, mapping and monitoring of soils, geological features and groundwater processes (Binley et al. 2010). The medium to large-scale quasi-continuous mapping is not obtainable with traditional point-based field measurement approaches. Geophysical methods additionally are helpful in assessing water quality and monitoring of underground contamination movements (Binley et al. 2010). However, geophysical measurements generally require an adequate number of field samples to verify and to assign real soil/underground property values to the geophysical data. This verification process is historically called ground truthing in remote sensing, but nowadays transferable to general geophysical measurements (Hargrave 2009). Methods comprise: *Electromagnetic induction* (*EMI*), *Seismic methodology, Geoelectrics* (Fig. 4), *Ground Penetrating Radar* (*GPR*). The physical variables measured by geophysical methods such as electrical conductivity can be produced by different combinations of underground material properties (equifinality). Equifinality in context of geophysical soil mapping means that different combinations of material compositions (water, salt and clay content) cause similar measurement values/results. For instance, areas with high clay content have high electrical conductivities similar to areas with high water content. Due to the equifinality of the geophysical measurement results, the data and image interpretation should be carried out in combination with auxiliary methods (models of physical relationship between geophysical data and hydrological property) or ground truthing (e.g. water sample) (van Dam 2012; Binley et al. 2010). An extensive review of hydrogeophysical methods, their advantages and limitations is provided by Reynolds (2011), Rubin and Hubbard (2005), Knödel et al. (2005) and Binley et al. (2010).

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[4] For more information, visit http://opendatakit.org/.

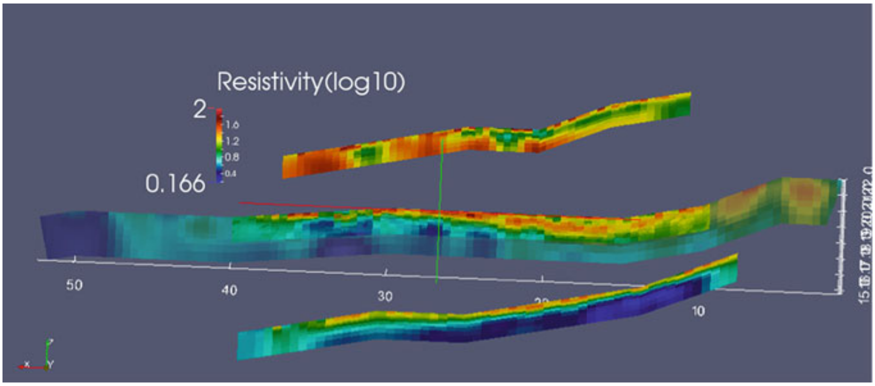


Fig. 4 Geoelectrical profile measurements visualized in spatial relationship context (x-y-z axis). The resistivity (colour-coded) is shown in relation to depth (x axis) and profile length (y axis), which allows a (pseudo)-3D interpretation of the sub-surface

- **Remote sensing and ground-based spectroscopy** is widely applied to continuously measure and record the reflected or emitted radiation from the earth surface (CCMEO 2014). A comprehensive summary of state-of-the-art remote sensing technologies and methods is given by the Canada Centre for Mapping and Earth Observation (CCMEO 2014), NASA (http://nasa.gov) and Melesse et al. (2007). Mainly three types of remote sensing technologies are available: multispectral (visible-near- (vis-NIR) to mid-infrared (vis-MIR)), radar and hyperspectral remote sensing (CCMEO 2014). In general, hydrology remote sensing is applied for mapping and monitoring of watersheds (e.g. flooding areas, river banks, wetlands) and hydrological features [e.g. land cover classification, impervious areas, topography, precipitation, spectral indices (wetness index, vegetation index)] (Melesse et al. 2007). The measurement can be carried out ground- (e.g. vis-NIR spectroscopy), air- or space-based (CCMEO 2014). All remote sensing images require image pre-processing prior to visualization and further usage (CCMEO 2014). All above-presented technologies might be applied for upscaling of point measurements to larger scales. This can be done by assigning point measurements to larger clusters (e.g. soil type) obtained by classification of remote sensing images or geophysical measurement results. Methods comprise: *multispectral remote sensing* (mostly using vis-NIR spectral range), *Radar* (Radio Detection and Ranging)*, LiDAR* (Light Detection and Ranging) (independent from cloud coverage measurement of precipitation [e.g. tropical rain measurement mission (TRMM)], heights [such as topography, vegetation height) and water depth (CCMEO 2014)], *thermal remote sensing* (measures the temperature of the earth surface making it useful for hydrology in terms of mapping and monitoring of water resources), ground-based and airborne *vis-NIR spectroscopy and hyperspectral remote sensing. Vis-NIR spectroscopy and hyperspectral remote sensing* are used to characterize in the field chemical and physical properties of soils (Stenberg et al. 2010; Viscarra Rossel et al. 2010), contaminations

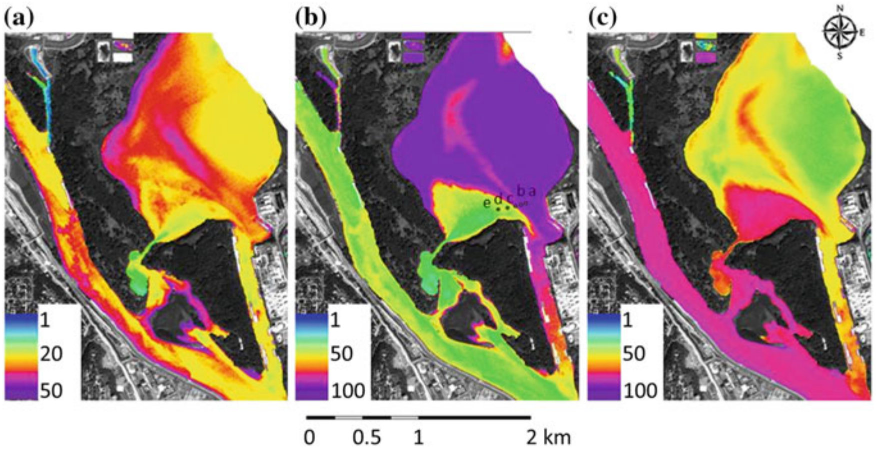


Fig. 5 Hyperspectral remote sensing measurement of water quality, **a** turbidity, **b** chlorophyll and **c** ratio non-volatile suspended solids and total suspended solids of a lake connected to the Mississippi River. *Source* Olmanson et al. (2013)

(Shi et al. 2014), vegetation (Kokaly et al. 2009), minerals (Viscarra Rossel et al. 2009; Van der Meer et al. 2012), erosion (Vrieling 2006), or water quality [Ji et al. 2010; Olmanson et al. 2013 (Fig. 5)], and is helpful for ground truthing.

2.4 *Monitoring*

Environmental monitoring means the systematic collection of point data of water quantity and quality variables according to a defined sampling strategy and a (more or less) defined schedule, usually with the aim to document trends in the availability and/or quality of environmental resources or ecosystem health in general. Ground-based monitoring can be complemented and to some extent preplaced by quasi-continuous data as outlined above. The general concern for any monitoring programme is to assure that accurate and reliable data are routinely collected and updated.

Nexus governance—or any management of environmental resources relies on such reliable and sustained monitoring programmes with an ‘adequate’ spatial and temporal resolution and coverage. The definition of an adequate spatial and temporal resolution is far from trivial and depends on the monitored resource as well as on the specific environment—and ultimately on available resources to perform the monitoring. For example soil properties of a specific region may not change much for many years under ‘normal’ conditions and under less exploitative land-use (e.g. forestry). However, plot-scale, single extreme events, which may cause heavy erosion, can have a big impact. Water quantity and quality is generally much more variable than soil properties both on a temporal (seasonally, but also concerning annual variability) and on a spatial scale (depending on land-use, geology, etc.).

Visualized in a meaningful manner, monitoring data enable the posing of relevant questions and initiate relevant management strategies, channelling resources and setting incentives. Such questions and the respective measures relate to spatial comparisons (e.g. bad water quality in one region compared to others) and/or temporal developments (e.g. water quality is deteriorating/improving/constant) and the underlying data have to enable such analysis and visualization.

Monitoring of water services can be used to define proxies (e.g. drought index, vegetation index) to establish models and empirical relationships (transfer functions) that are applicable for monitoring. For example an empirical relationship model was established that relates field measured water body volume to remotely sensed water body extensions (Liebe et al. 2005). This mathematical model can then be applied to water volume monitoring of water bodies solely based on mapping of water body extensions in future remote sensing images. The monitoring data could feed connected models that in real-time update the connected maps (e.g. of water usage). Continuous data input on water usage can be provided by mobile phone applications by (and for) different users such as the public, experts or government members. In Africa, the number of mobile phone subscriptions has increased over the last few years. Previous data measurements and maps can be used as basis for additional research surveys, as for example the choice of locations for interviews or supplementary data sampling. Therefore, the application of spatial sampling methods is crucial for monitoring, since they build the basis for designing monitoring networks (e.g. definition of additional sampling locations) (Wang et al. 2013).

2.5 Circumventing the Science Policy Divide in Data-Poor Conditions

For decision-makers it is important to communicate explicitly their concerns and needs about environmental and socio-economic issues to scientists or other experts. It is of importance to identify which scales and processes need to be considered. The identification and communication of the needs is a type of feedback loop where the needs have to be adjusted to state-of-the-art knowledge. For example research results become available revealing that small-scale land-use changes can have an impact on large-scale water quality, which might not have been assumed in the past. Therefore, the choice of considered processes (biophysical and socio-economic) and scale depends on the stated research question. For instance, river water usage has implications on regional scale (e.g. irrigation, soil salinization) as well as on a larger scale (reducing downstream water supply for population and agriculture). Processes and their feedback are therefore scale dependent. Thus, the question arises as to how we can overcome the scale issue—particularly in data-poor environments.

First, each environmental and socio-economic analysis (e.g. risk analysis) as well as predictions needs to be based on data. Since different kinds of processes have to be considered, it is advantageous or even mandatory to work with a transdisciplinary or nexus approach that integrates area/sector specific knowledge and methods. Second, it is important to identify the boundary conditions in terms of which data are needed, which data are available and what we can do with it. This allows us to select appropriate methods and highlight where new data needs to be assessed.

In data-poor environments, large amounts of data should be gathered from proxies and transfer functions that rely on fast and cost-effective data assessment methods, such as remote sensing. This data can be analysed and interpreted by scientists and governmental bodies. Therefore, remote sensing image availability should be supported by the government, external institutions or image suppliers. Another option might be ‘rapid’ near-surface geophysics such as spectroscopy and EMI. The EMI instrument is light and carried above the earth surface, which gives insights into the soil’s physical and chemical composition (e.g. used for farming). However, data from remote sensing or geophysics require some kind of ground truthing. Therefore, a sampling design is required that cost-effectively allows for the extraction of required ground-based point information. The assessment of land-use changes, for instance, requires an image classification where each class represents a different land use. Each land use possesses a specific reflectance that is used for the classification. Expert knowledge or ground-based information is needed to allocate each class to a specific land-use.

Since those instruments and many methods are relatively cheap, but may still be difficult to afford in developing countries, it might be advantageous to implement a sharing system for instruments, laboratory facilities, expert knowledge and databases, which could be supported by capacity development. Sharing of knowledge, tools and recommendations about standardized methods could be done via internet. Direct face-to-face consultations will be important, however, and cannot be replaced by online tools. The public should be included in all steps, since it is another valuable source for data collection (e.g. mobile phone). In addition, decisions from decision-makers might be more acceptable and understood if public involvement is considered from the outset. Modelling as a means of process understanding, managing and prediction should be supported by experts/organizations through capacity development. Software tools that are applicable and easy to use in data-poor environments should be provided together with adequate documentation.

2.6 *Making Use of Data: Data Integration and Visualization for Decision-Making*

Data that was assessed (see Sect. 2.3) need to be statistically prepared, investigated as well as analyzed using some form of visualization technique. Visualization makes data accessible and understandable to any stakeholder (e.g. researchers, decision-maker or the public). The importance of data visualization for decision-makers that allows for understanding of complex data and relationships from diverse sources/disciplines is well known (Kwakkel et al. 2014).

Innumerous publications about visualization techniques for scientific data are available (e.g. Bonneau et al. 2006; Mirkin 2011; Dzemyda et al. 2013). Kelleher and Wagener (2011) summarize in a short communication ten general guidelines for good practices for scientific data visualization along with references to related key literature. The ten guidelines are:

1. ‘Create the simplest graph that conveys the information you want to convey;
2. Consider the type of encoding object and attribute used to create a plot;
3. Focus on visualizing patterns or on visualizing details depending on the purpose of the plot;
4. Select meaningful axis ranges;
5. Data transformations and carefully chosen graph aspect ratios can be used to emphasize rates of change for time series data;
6. Plot overlapping points in a way that density differences become apparent in scatter plots;
7. Use lines when connecting sequential data in time series plots;
8. Aggregate larger datasets in meaningful ways;
9. Keep axis ranges as similar as possible to compare variables;
10. Select an appropriate colour scheme based on the type of data.’

In order to inform decision-makers best, the selection of visualization method should be guided by the general workflow (Fig. 1) to assure it clearly meets the purpose of the visualization. The type of visualization should be chosen in a way that it is able to answer questions of interest. Water-related questions might be: What happens if a water usage policy will be changed? Which are the water-related implications on agriculture for future climate change predictions? For instance, if one wants to answer the latter question, then a map could show a (interactive) time series of a drought risk index and the expected agricultural yield /productivity in a colour-coded format.

2.6.1 Geospatial Visualization

If we consider the visualization of water services, data is mostly related to a geographic position.

Data integration that makes data usable for visualization is not a trial issue. The problem arises of how to derive continuous maps from point data. Various methods and approaches exist to upscale point information collected from an actually continuous feature (e.g. land use) to continuous map visualizations. Those methods include interpolation, geostatistics (kriging) or the creation of homogeneous map units based on image classifications of meso- and large-scale measurement results (see Sect. 2.3.3). The basis is a simplification of reality assuming that single point information represents a larger scale unit. As an example, water samples are taken from different locations of a lake and averaged to a mean value that afterwards is used to represent the water quality of that single lake. In sequence, based on remote sensing, lakes with similar characteristics are assigned to the same water quality value. Another example is the creation of a soil map that is based on measurements with electromagnetics (EMI). Different homogeneous soil units are assigned to several point soil samples and soil profile descriptions that then represent each of the electromagnetic soil units. The degree of spatial resolution depends in this case on the number of homogenous soil units and number of soil point samples. This upscaling approach should additionally be supported by experts and further knowledge of the investigation area.

Nowadays, paper maps are still in use due to their handiness, independence from technology and comprehensibility. Today's maps come as interactive, web-based high-resolution tools such as Google Earth, GeoCommons (geocommons.org) or OpenStreetMap (openstreetmap.org) whose content can freely be extended through community input. These maps are based on remote sensing images in RGB (photography) visualization. Topographic or land cover type information is represented by natural colour shadings (e.g. forest corresponds to dark green areas) as we know from ordinary photography. However, natural colour shading is equivocal where, for example a dark green area might correspond to forests or grasslands. These digital interactive maps are only partly usable for decision-makers, unless earth surface features are explicitly indicated and interpreted by cartographic symbols. The symbols are applied to highlight specific earth surface features such as urban areas, forests, water bodies or soil types using specific colour shadings, symbols, or text features and corresponding map legend. The identification of cartographical features is based on image classifications (e.g. classification of land use or soil type) with expert knowledge and supplementary information (e.g. paper maps, ground truthing).

In a fast changing world with complex global interactions and an increase in environmental and social influential factors (e.g. development of chemicals, technologies, cross-bordering land and resource uses) it is challenging to understand fully these developments and their interactions. Coping with those challenges requires more sophisticated visualization tools. The visualization tools need to be more flexible and extendible to make it possible to understand the interconnectedness (nexus) of global change processes as well as their feedback mechanisms. Kwakkel et al. (2014) give a good overview of selected software tools for geospatial data and networks visualization. In the next sections, we will briefly present various software tools that can partly be found in Kwakkel et al. (2014).

2D Visualization

Geoinformation systems (GIS) are used to collect systematically and visualize data interactively from various sources linking them not only with a geographic reference system, but also with additional information (e.g. soil type, water type) (O'Looney 2001). In general, map information is coded by symbols and/or colours. For example topographic maps generally colour flat areas in green and mountainous areas in brownish shades, whereas line features might represent streets or rivers. The digital character of the map allows overlying several user-defined adjustable data layers, where the user can seamlessly zoom in and out. The quality and degree of detail depends on the number of input data as well as on their accuracy that regulates the map resolution and information content.

Data sources can be point information (e.g. different water or soil samples) as well as spatially continuous data such as remote sensing images, other existing digital maps (geological maps) or static modelling results (e.g. mean groundwater levels). In particular, for developing countries such as most of the countries in Africa, it should be an interesting option to make use of well-developed open source GIS applications (e.g. GRASSGIS, Quantum GIS, SAGA GIS). However, since the system is generally static or semi-dynamic through manually switching on and off different maps/layers/data, process understanding within GIS is limited and prediction about the future is not possible.

Taking into account the general characteristics and purposes of a GIS map drawn by O'Looney (2001), in the context of water services:

- Mapping allows data integration from diverse sources (surveys, censuses, spaceborne imagery, etc.) as well as from different disciplines (social, economic, environmental data). Maps enable systems analysis across borders and across disciplines: socio-economic boundaries (e.g. state) to ecohydrological boundaries (e.g. watershed). Data can be effectively integrated and managed within GIS.
- Maps are powerful visualization tools that, if well prepared (e.g. clear symbols), are understandable by all stakeholders including parts of the population that might have no or limited access to education (e.g. analphabetism). Application of visual tools is particularly important in developing countries.
- Visualization of water-poverty relationships and characteristics, such as the distances between water supply sources as well as the general water supply infrastructure are easily includable in a GIS system (Toure et al. 2012).
- Land-use conflicts can be mitigated or anticipated through identification of areas with high conflict potential (e.g. high water resources concurrence), it is especially advantageous if the groups of interest are included in the land managing process (Brown and Raymond 2014).
- Since maps highlight where water services are lacking, specific resource (e.g. irrigation water distribution) and support material allocation can be planned and executed more cost-effectively taking into account local requirements and conditions (Gerlach and Franceys 2010; Wellens et al. 2013), which is advantageous to unspecific universal distribution programmes.
- Digital (GIS) maps have the advantage that they can be extended or updated with additional data (e.g. inclusion of new features or improvement of spatial resolution) as soon as it becomes available. This assures the map significance over long periods.
- GIS maps are printable or distributable in any number and at any scale. However, the scale depends on the data resolution and quality, thus on map purpose and related data survey costs. For instance, a coarse map resolution might be sufficient to locate water supply infrastructure, but might be insufficient to

support decision-making related to flood protection, where a finer scale is required to account for soil or vegetation heterogeneity (e.g. needed for estimation of water infiltration capacity).

A large number of further visualization options is available for ‘realistic world’ representations. An example of an abstract symbolic map showing relationships are cartograms with a gridded surface. Each grid cell area is resized according to their value (e.g. high number of water resources equal to large grid field area size), where all grid cell areas are resized relative to each other. The method was developed and publicized in the Worldmapper project (Sasi Group and Newman 2014).

3D–4D Visualization

The increasing needs of spatial understanding have led to the development of 3D data visualizations (e.g. volumetric models, discrete models and continuous models) (Lin et al. 2013). The number of software tools that create [e.g. Paraview (paraview.org)] and display [Google Earth (Google), Layerscape (Microsoft Research), World Wind (NASA), Skyline (http://skylineglobe.com)] 3D data and objects are increasing. These tools can illustrate three-dimensional geological features (e.g. groundwater systems), topography, urban structures as well as heights of natural land cover features (e.g. forest height). The illustration is often supported by a remote sensing natural colour (RGB) image overlay. Some emerging web-based spatial visualizations include data analysis results such as areas of global risk maps or interactive statistical graphs (Fig. 8).

To get better insights into feedback systems (cause-effect relations) of varying processes as well as between compartments, more dimensional time series (4D) visualization tools are required. The understanding of feedback loops is important for decision-makers, since each action seldom causes only desired responses, but also undesired side effects. For instance, the extraction of river water for agriculture purposes might increase yields and local income, but unsustainable water use can decrease water availability downstream, which leads to an increase in drought risk, decrease of yields and increase in hunger. Thus, the knowledge of feedback loops is needed to choose appropriate decisions and to adjust them effectively. A visualization that aims at a full system interaction representation needs to be supported by model simulations and prediction (Kwakkel et al. 2014). Models enable the simulation of complex relationships and processes based on mathematical equations as well as on data of different sources. The integration of these data along with known mathematical relationships allows us to give predictions about future system behaviour under specified conditions. For instance, Fig. 6, shows the usage of remote sensing data as input for a hydrological modeling framework (LIS—Land Information System) that might simulate the actual water balance and future water availability changes due to climate change (e.g. decrease of precipitation). Milewski et al. (2009) described an approach to use remote sensing data as input for a hydrological model to estimate run-off and recharge in an arid environment. With

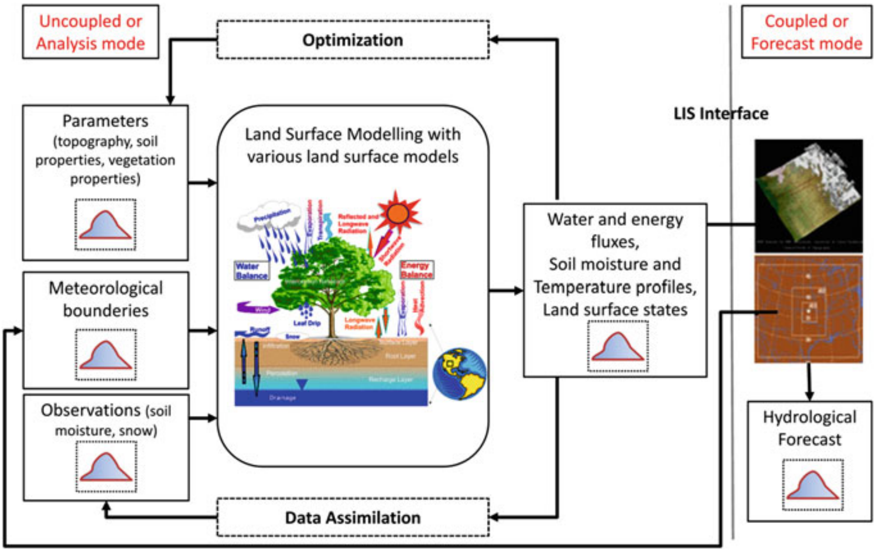


Fig. 6 Land Information System (*LIS*) by NASA Goddard Space Flight Center, integration of remote sensing data into a modelling framework. *Source* Modified from http://lis.gsfc.nasa.gov/

the help of remote sensing data products (such as classification maps of land use, vegetation properties and urban areas), the model simulates the water balance of a specific area. Influential factors to the water balance such as land use changes and the resultant impact on water availability can be investigated. Based on the observed system, behaviour scenarios about future water availability (e.g. in dependency on the predicted land-use changes) can be analyzed. The visualized model results can support decision-makers with choices related to water management policies. Several recent projects [e.g. ARIES (University of Vermont et al. 2013), CESM (UCAR and NCAR 2013)] follow the visualization workflow as depicted in Fig. 1 in order to inform and support decision-makers.

Most simulation models provide visualization of the modelled results, but these images are often very simple. For example, for flood protection purposes, a time series of water flows in a river system is shown in a large number of water flow maps, where each of the maps represents a discrete snapshot. Interactive map representations of water flow time-series that colourfully highlight potential discharge regions on the map are easier to understand and have a much higher chance to be considered by decision-makers during the decision process than convential non-interactive maps. In the case of drought risk analysis, an interactive time series of drought indices can highlight where and when the risk for drought is highest. Additionally, time series of river flow maps can reveal where water might be lost from the system (e.g. through withdrawal from the river system for irrigation).

This basis of the dynamic illustration of fluxes (e.g. water flow) is either time series of measured data or time-dependent modelling results. Freely available tools that allow for visualizing dynamic fluxes are for instance Worldwide Telescope together with Layerscape (Microsoft Research 2013), Paraview (Fig. 7), and GeoZui4D (http://vislab-ccom.unh.edu/GeoZui4D/). These tools allow for the creation of more or less interactive 3D movies that illustrate fluxes (4D as exemplified in Fig. 7).

Modern geospatial visualization techniques for system understanding that is appropriate for decision-makers should make use of the completely automatic infrastructure that goes the complete distance from data to interactive visualization. Therefore, such a framework should allow that the included model is fed by data that can be continuously added manually or automatically by sensors or mobile phone data. The model should then automatically, with very low supervision and user inspection, simulate the processes of interest. The complete workflow from data to visualization can be represented by virtual geographic environments (VGE). VGE are computer- and often web-based geographic information systems (Lin et al. 2013). As a further development of geographic information systems (GIS), VGE generally comprises four components: data, modelling and simulation, interactivity, and a collaborative component (Lin et al. 2013). This platform is designed to provide to the users a systematic analysis of processes with a real world experience feeling (Lin et al. 2013). The VGE approach considers the proposed workflow from data to visualization shown in Fig. 1. The data is stored in geographic databases and is connected to the modelling component of the VGE system. The several types of data products (geospatial images, tables, structural objects) need to be jointly stored and transformed for integrative use. This is often needed to meet the data format requirements of the applied model or to visualize the model products making them available through the internet [e.g. by GIS, GeoServer (geoserver.org)]. This integrated and modular VGE system allows additionally for the simulation and

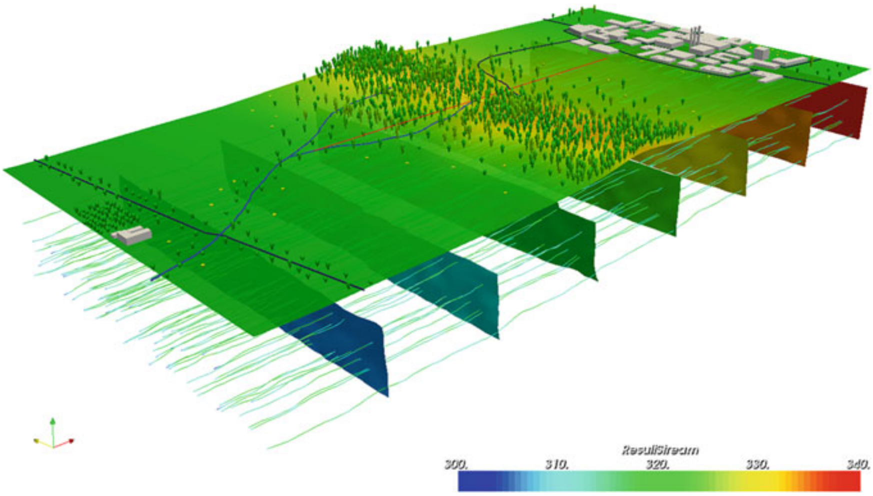


Fig. 7 3D–4D visualization of GRASS GIS voxels of groundwater flow with Paraview. *Source* GRASS GIS http://grass.osgeo.org/screenshots/3D/ (screenshot: Sören Gebbert)

interpretation of scenarios (Lin et al. 2013). Scenario modelling is helpful for decision-makers, researchers and the public in order to understand consequences coming from global change processes (e.g. impact of land use or water management changes). A user-friendly web-based simulation and visualization tool is usable for education purposes, because the public can explore the interconnection between the past and future as well as their influential factors (e.g. water availability and water usage for agriculture). In addition, experiencing this vivid geographic virtual reality is easier than attempting to understand the numerous tables and graphs that aim to explain the same issue (Lin et al. 2013).

2.6.2 Non-geospatial Visualization

Non-spatially related data visualization is used to provide insights into data relationships, making them accessible for decision-makers or the public. This is often statistical information about number of people with access to water in the form of histograms. Feedback relationships might be shown based on a scatter plot between the variables, such as number of industrial plants and water quality in a specific region or soil salinization in relation to irrigation and time of the year. Being aware of such statistical relationships (backed up by further evidence for causal relationships), decision-makers are able to act and to adjust support and policy measures. Looking at the irrigation example, decision-makers can give recommendations to the farmers about adjustments to their irrigation type in order to minimize soil salinization.

Traditional visualization methods comprise tables, graphs, histograms, treemaps, voronoi maps, symbol maps, bar charts, dendrograms, contour plots, parallel coordinates, boxplots, scatterplots, colour-encoded maps (choropleth maps), correlation matrix and calendar charts. Correlation matrix plots as shown in Fig. 8a are useful to illustrate the relationships between variables and therefore are a way of illustrating potential feedback systems. A straight line represents a high correlation known for conductivity and water salinity. That mathematical relationship can be used to predict water quality guiding decision-makers in water quality management related issues (Kumar and Sinha 2010). Two other examples of time series representations are shown in Fig. 8b and c. A streamgraph is a type of stacked graph that shows the time-dependent development of certain variables based on their relative area change (Fig. 8b). The area size of each colour-coded stack represents the magnitude of the variables, such as the development of conductivity, pH or other measures of water quality. The calendar chart, compared to the streamgraph, has the advantage that colour coding is used to highlight days of special events (Fig. 8c). This makes it easier to see patterns quickly that reveal and relate, for instance, the history of drought occurrence to wild fires. This knowledge might be helpful in drought and fire prediction. Several open source tools for data mining, analysis and visualization [e.g. Orange (http://orange.biolab.si), R (www.r-project.org), StatNet (http://statnet.org/), PySal (https://geodacenter.asu.edu/)] are available, typically with an active user community providing support. Being open source, these tools should be particularly useful for developing countries.

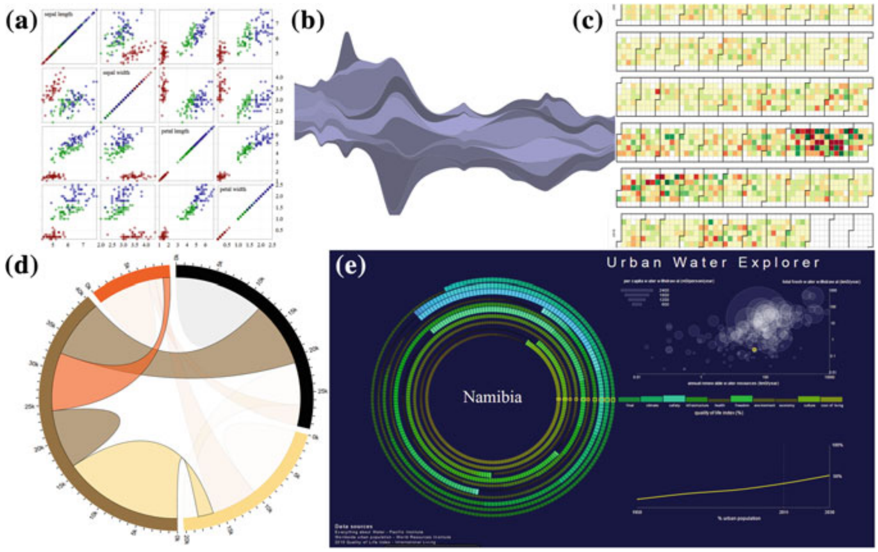


Fig. 8 Examples of interactive visualization: **a** correlation matrix that visualizes relationships between variables (e.g. air temperature and soil salinization). *Source* Edgar Anderson, **b** streamgraph showing a time series of variable development based on relative area change (e.g. water quality variables: conductivity, pH, etc.). *Source* Lee Byron and Martin Wattenberg, **c** calendar chart showing colour-coded soil moisture at a certain day. *Source* Rick Wicklin and Robert Allison, **d** chord diagram showing relationships between different groups of entities (e.g. political relationships). *Source* Martin Krzywinski, and **e** interactive tool 'Urban Water Explorer' that illustrates water resources, quality of life index and urban population. *Source* Jan Willem Tulp, http://www.visualizing.org/visualizations/urban-water-explorer; all illustrations created using D3.js library, images obtained from https://github.com/mbostock/d3/wiki/Gallery

Nowadays, traditional data plotting methods become interactive and web-based, examples are given in Fig. 8 (e.g. with D3.js open source tool). The interactivity and visually accessible/catchy design makes them increasingly interesting for education and decision-makers for understanding the relationships of processes and temporal dependent changes. Networks, interactive or not, are adequate visualization techniques for illustrating any kind of water service relationships (e.g. network of water suppliers). Useful open source tools to create several types of networks are D3.js (Fig. 8) and Gephi. The 'Urban Water Explorer' shows how these tools can be used to inform the public interactively through combination of several visualization tools and statistics (Fig. 8e). The 'Urban Water Explorer' presents statistics about the amount of annual renewable water sources, quality of life index and urban population of each country.

For public education purposes, infographics can be a powerful conceptual illustration method of complex environmental, socio-economic or political issue. Infographics combine visual and textual components that make it easier to transport the desired statement of a specific issue by the editor to the target group through limiting the space of interpretation.

2.6.3 The Case of Water Point Mapping in Tanzania

One specific target of the Millennium Development Goals (MDGs) defined by the United Nations (UN 2001) addresses access to safe drinking water and basic sanitation, which is still problematic in many developing countries (Giné-Garriga et al. 2013). Adequate evaluation of the status of public access to safe water needs accessible, accurate and reliable data for mapping based on comprehensive (in spatial and temporal terms) and reliable, yet cost-effective and easily implementable monitoring.

WPM is a planning and monitoring approach for identification of water infrastructure (e.g. location of wells) as well as data collection about the functionality and status of water sources (e.g. water quality) (Nyitambe 2014). WPM is defined by Nyitambe (2014) as a system that 'is an integration of hardware, software, methodologies, data, processes and users dedicated to collecting, storing, processing and analysing water-related information and giving feedback for public use'. The data collection can be carried out with varying methods and technologies ranging from simple spreadsheet to GIS-based visualizations. It was originally designed and promoted by WaterAid in Malawi in 2002, although in recent years, it has been carried out in different African countries [e.g. Tanzania (Nyitambe 2014)] by a number of stakeholders (WaterAid, SNV, Ingeniería Sin Fronteras—ApD, Concern, etc.) (WaterAid and ODI 2005). The approach is now being promoted by a growing number of organizations and governments, e.g. the Ministry of Water in Tanzania, see http://wpm.maji.go.tz/. Over the years, it has evolved to cater to the needs of new environmental and political situations and reflect differences in complex and changing national water sectors (Welle 2010).

WPM should be seen as one component and placed into context of Integrated Water Resources Management (IWRM) or in an even wider nexus context. Regarding an improved water management, Barry et al. (2009) as well as Muller (2009) give *comme il faut* examples from Africa (Mali and South Africa). Sivakumar (2011) requests the setting up of national drought policies for the countries concerned. FAO, in 2012, suggested an information system on water and agriculture that could be the basis of such nexus index.

A comprehensive and yet concise account of modern integrated river basin management, e.g. by means of digital models and decision support systems, is given by Hassing et al. (2013). Striking positive examples of successful (and in some cases also less successful) water governance in India and China are given by GWP (2013). The findings reported represent the lessons learned and may well be applied to Africa, too.

Gan et al. (2013) have been assessing drought, climate and hydrological conditions in Africa based on the application of remotely sensed geospatial data and various models. Best practice examples from Namibia and South Africa on presently successful integrated water management are given by Ibisch et al. (2013). Following the suggestions made by Tsegai and Ardakanian (2013) about the global capacity development in the water sector, at the beginning of the twenty-first century, Tanzania started activities for a nationwide WPM initiative (Welle 2006).

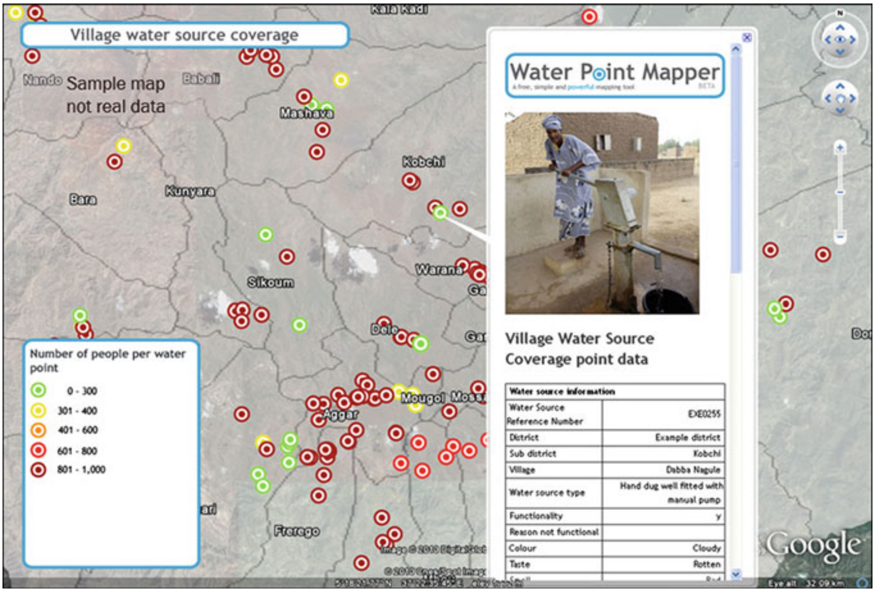
Water points (WP) are discrete locations of water supply sources (e.g. wells, springs) of diverse uses for which data (e.g. GPS location, photography, number of people to supply) is collected (Welle 2005). Because of the allocation of geographic information to the WP, the collected data can be visualized based on maps or statistical graphs. This helps to visualize the spatial distribution of water supply coverage (water points per population) and can thereby be used to highlight unequal water distribution issues quickly, as well as regions that are disconnected to the water supply infrastructure (Giné-Garriga et al. 2013). The information collected provides insights into water quality levels (e.g. biological quality) and management-related aspects (e.g. households' water accessibility, status of WP functionality) of water points (Giné-Garriga et al. 2013).

According to Nyitambe (2014), WPM is useful for:

- Infrastructure improvement planning to support water supply coverage,
- Identification of regions where basic water services are lacking and to support them with needed resources,
- Monitoring and planning of water sectorial investments,
- Assessment and monitoring of progress and performance of water supply.

The biggest challenge and the bottleneck of the whole system is routine data acquisition, data quality and, even more so, data updating (Giné-Garriga et al. 2013). For any ongoing monitoring tool, this represents the biggest problem, and unfortunately, there is no simple answer. Every country's water sector is different and each presents its own challenges. A major one is the continuous updating of the information about non-functioning and water-losing water points, which can help save water by quick-response repair. This goes along the lines of what Ardakanian and Bernhardt (2011) are postulating in their paper about water loss reduction in Africa.

Technological developments such as remote sensing (Sect. 2.3.3) or mobile phone availability along with specific software applications for (e.g. OpenDataKit) improvement of data quality, scalability as well as data availability for monitoring purposes (Sect. 2.4) is growing quickly. Hence, it has been proposed (Feurer et al. 2008) to use geocoded ultra-high resolution satellite images as an appropriate substitute. This type of imagery has the big advantage that due to their pictorial nature, it is easily understandable by non-expert decision-makers and politicians. As another example, WPM mapping can be supported by the software tool 'Water Point Mapper', which accelerates and simplifies the manual data collection at each water point location. The data collection is still manually done by filling out a digital spreadsheet. The spreadsheet data can then automatically be visualized with Google Earth (offline) by the software tool (waterpointmapper.org) (Fig. 9). Google Earth maps can be made accessible to the public by connecting the offline Google Earth maps to web-based Google maps service, which is addable to any internet page by using the Google web widget. However, the aspect of covering the maintenance costs of technological-based systems on one side and of giving incentives to the individuals in charge of keeping the system working and—most of all—the data up-to-date must not be underestimated and treated with appropriate



Village Water Source Coverage point data

Water source information	
Water Source Reference Number	EXE0255
District	Example district
Sub district	Kobchi
Village	Dabba Nagule
Water source type	Hand dug well fitted with manual pump
Functionality	y
Reason not functional	
Colour	Cloudy
Taste	Rotten

Fig. 9 Water Point Mapper produced map of village water source coverage. *Source* WaterAid http://www.waterpointmapper.org

priority. Here, capacity building for water resources management in the best sense of the word (cf. Ardakanian and Liebe 2012) can be materialized (cf. also Gan et al. 2013).

Collected data from varying sources can be managed and presented in a user-friendly format by a GIS system (Sect. 2.6.1). The data might be integrated within a VGE framework to account for the need for future system response predictions.

3 Conclusion

In many developing countries such as main parts of Africa, data scarcity is an issue. Considering their financial as well as personal limitations, cost-effective data assimilation methods should be applied. Additionally, smart technologies that allow the public to participate in the data acquisition process should be taken advantage of. These technologies include, for example the use of mobile phone services such as within the WPM process.

In this chapter, we elaborated on the general workflow from data to visualization of water services in the context of informing decision-makers about the status and development of water services, thereby enabling them to implement good and adequate water governance. The examples provided focus in particular on water management in Africa. Since any modelling and visualization is only as good as the underlying data, it is crucial that the user of such a map, graph or table, is aware of the data source, quality and the filtering and transformation procedures applied to the data (Kwakkel et al. 2014).

Another approach to deal with data scarcity is to make use of proxies, based on simpler-accessible data. Quasi-continuous data from remote sensing is often used as proxies for the environment as well as socio-economic aspects. This information can be transferred into data format that is usable for instance in models for predictions, risk analysis or resource management. For some basic purposes, paper maps might be sufficient to inform decision-makers as well as the public. However, in a complex and changing world, more sophisticated tools for data assimilation and especially visualization should be considered. Virtual Geographic Environment (VGE) systems might be a good tool that is interactive enough to cope with future challenges of water scarcity. Various web-based visualization tools have become available lately and can be helpful for understanding and sharing of data, and results from mapping and modelling. Those tools often allow for the inclusion of and interaction with the population that improves their acceptance of decision-makers' actions.

The choice of visualization type has a strong influence on the Viewer and needs to be carefully selected (Kwakkel et al. 2014). This is especially true because the same data can produce different types of visualizations that in turn present and transfer different information to the viewer. In the case of WPM, this means, for example that a histogram can reveal statistics of a certain area but is often generalizing, which means that geographic differences in water service access might be extraordinarily high in one part and extraordinarily low in another part of that area. For this reason, geospatial maps are needed to combine the statistics and the spatial distribution of water access.

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Chapter 10
Policy Is Policy and Science Is Science: Shall the Twain Ever Meet?

Mathew Kurian and Reza Ardakanian

1 Introduction

The comparative advantage of the United Nations University (UNU) system lies in its ability to design, execute and mainstream research outputs within the policy domain. Given that the UNU is accountable to member states, there is a more than obvious connection to the needs of member states in developing and emerging economies. Sustainability is an important focus of the UNU system as the world seeks to respond to global changes posed by increased economic activity. Three key global changes that have been highlighted in recent international discussions relate to demographic change, urbanization and climate change (Chap. 3).

1. Economic development is making the differences in income and employment, disaggregated by gender, age and ethnicity more stark especially in relation to discussions pertaining to people's access to environmental resources.
2. The process of urbanization is making the disparities between rural and urban regions more stark while highlighting the inter-dependencies between them in terms of energy and resource flows.
3. Increased frequency, intensity and duration of climate events such as floods and droughts is making it imperative to devise mechanisms by which data on temperature and rainfall can be harnessed to improve systems for forecasting, monitoring and rapid response especially as they relate to public services such as water supply, wastewater and irrigation.

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The nexus approach to management of environmental resources has highlighted the challenges of ‘integrated management’. The nexus approach offers alternative pathways for discussing integration challenges using more nuanced perspectives such as trade-offs and synergies. However, the discussion remains focused on the biophysical domain—resource flows, linked cycles, modelling, waste, water and soil management. The chapters in this book highlight an important facet of the nexus, which so far has remained largely overlooked by the debate: the institutional domain. Chapters 2 and 3 highlight the issue of efficiency and resource recovery, which is an important consideration in addition to those of trade-offs and synergies that were alluded to earlier. Would we be better off by referring to ‘resource optimization’, which may or may not be the result of increased ‘system efficiency’? The chapters in this volume call attention to a broader perspective on systems—air, water and soil. This broader perspective must encompass social and political systems, as well as the expression of the intersection of these systems with the biophysical domain in the form of ecosystem services (Chap. 5). From a nexus perspective, we should also consider whether optimizing the use of budgetary resources will result in optimal use of biophysical resources such as water, waste and soil or vice versa.

Chapter 3 points out that the Poverty-Environment (P-E) nexus is robust. It is this assumption that shapes public interventions for management of environmental resources. What we know for sure is that scale is an important determinant of the outcomes of the P-E nexus. At larger scales of analysis, the impacts of soil erosion for example, may be less intensive than at the level of a farm or plot. This difference in outcomes can be an important influence on how public programmes are targeted, such as using a sector-wide approach assuming that the PE nexus is strong or a budget-support approach that assumes the relationship is weak (Dasgupta et al. 2005).

The discussion about the role of public financing of infrastructure projects is something that has been overlooked by discussions on management of environmental resources. The nexus approach makes it imperative that we discuss the role of higher order institutions (*understood as rules*) and their influence on resource management decisions at multiple levels (Ostrom 2009). For example, what role can central transfers, taxes and tariffs have on distribution of benefits and costs of infrastructure projects covering sectors such as irrigation, wastewater or hydropower? Linda Veiga, in Chap. 4, points out that while the overall benefits of decentralization appear positive, the actual distribution of benefits and costs of infrastructure projects under decentralized regimes may depend on demography (*population size and age*). This issue is highlighted by the example of European experience with costing and tariffs of wastewater projects (Chap. 7). The implications of this analysis suggests that peri-urban regions composed of small/secondary towns could be candidates for policy and programmatic attention of strategic infrastructure investments since they are currently experiencing the fastest rates of demographic change, but without the matching infrastructure coverage that is required to keep pace with demand for services. (UN-Habitat 2013).

2 Think Tank Function of UNU

We began this volume by posing two questions: (1) Why does good science not always equate with good policy? and (2) Why does good policy not always equate with what is politically expedient? These may be characterized as think tank questions. Robust think tanks incubate policy relevant questions without necessarily offering definitive advice on one or more options. They can perform this function by: (a) identifying cases of programme implementation success and failure, (b) understanding the spatial and temporal context for explanations of success and failure that incorporate both biophysical and institutional perspectives, (c) consolidating data, information from multiple sources in support of scientific analysis, (d) exploring technologies that permit real time, continuous monitoring or validation of scientific analysis and (e) translating knowledge gained from analytical work into policy relevant advice on available options together with an explanation of trade-offs and synergies involved under different scenarios. To be able to perform this function effectively, think tanks usually distinguish between science concerns (e.g. scale, boundary conditions or feedback loops) from policy concerns (poverty reduction, equity, efficiency).

The introductory chapter of this volume hypothesized that the nexus approach can advance integrated management of environmental resources by identifying through trial and error factors that lie at the intersection of: (a) spatial dynamics of material fluxes, (b) socio-ecological differences in resource use and (c) rules that guide allocation of public finances. This hypothesis is based on the assumption that there are no blueprint solutions to challenges of environmental resource management. This perspective also suggests that there is heterogeneity both within biophysical domains (e.g. forests, watersheds) and institutional domains (e.g. public sector agencies, water user associations). Finally, administrative culture and individual discretion can play a role at multiple levels of governance with implications for public interventions (e.g. levels of accountability) and environmental outcomes (e.g. levels of soil erosion).

2.1 Co-provision: Rudiments of an Analytical Framework

The nexus approach to management of environmental resources can be advanced if the science-policy divide is bridged. For this to occur, three considerations must be addressed: (a) scale, (b) boundary conditions and (c) feedback loops. Conventional discussions on integrated management of environmental resources have focused either only on water and underplayed the links with soil and waste resources. Second, the issue of governance has only made a superficial reference to issues of trade-offs. Nevertheless, there is a vast amount of literature on the commons and collective action that engages with concepts of accountability, autonomy and institutions (*understood as rules*). The concept of co-provision is pertinent to discussions surrounding relationships between human behaviour (e.g. land use, payments for services, crop or technology choices) and conditions of environmental resources (water, soil or waste). This is especially because the concept of co-provision emphasizes the following issues:

- Accountability in fiscal relations involving multiple levels of government that influences decisions on infrastructure design and incentives for undertaking maintenance.
- Climate-induced risks posed by variability in climatic, soil and groundwater conditions that influence *system* performance in terms of biophysical processes (e.g. material flows) or infrastructure operation (e.g. of dams or wastewater plants).
- Exercise of discretion by public officials in enforcement of rules at different levels of government.
- Uncertainty in factor and product markets that influence incentives for cooperation in management of common pool resources.
- Heterogeneous social relations that offer opportunities for local leadership to emerge to enforce natural resources management rules effectively.

2.2 Adaptive Management: Coming to Terms with Policy and Implementation in Support of the Nexus

1. **Sustainability of infrastructure investments**: Chap. 6 in this volume uses several case studies to demonstrate the importance of incorporating life-cycle costs in planning for infrastructure projects. However, as Reddy and Kurian point out, despite the apparent benefits of employing life-cycle cost approaches, planners are reluctant to use them in their planning procedures and processes. Both Linda Veiga and Mario Suardi in their chapters (4 and 5) point out that by compromising the sustainability of infrastructure projects, a number of other problems can arise. These include a potential increase in public debt by local governments and inability to meet the service delivery needs of poorer segments of the population.
2. **Incentive structures**: Greater autonomy of local governments to decide on policy design and implementation may allow for greater innovation in incentive structures. Mario Suardi argues in Chap. 5 that results-based financing is a promising approach that allows local governments to innovate with use of financing instruments such as payment for environmental services and cash on demand to target services at poorer segments of the population. He also emphasizes the importance of 'alignment of rules' at different levels of government. Adaptive management is essentially the ability of resource management regimes to devise effective resource management strategies that respond to environmental events/shocks and changes in human behaviour. From an

implementation perspective, this could imply improving quality of human resources within the public sector, innovation in training methods that include skills in participatory techniques and trans-disciplinary research, better assignment of functions within administrative departments at different levels of government and partnerships with private/community-based service providers with access to appropriate technology and financial resources.

3. **Feedback loops**: The chapter by Weckenbrock and Alabaster demonstrates how well- meaning water quality standards at international and national levels may have limited impact in promoting safe use of domestic wastewater. An alternative approach that Chap. 8 proposes is to base policy prescriptions on a characterization of agro-ecological systems. Such a perspective views environmental resources as offering multiple benefits. With minimal retrofitting of technical design, multiple benefits can be unlocked that have implications for agricultural productivity and safe sanitation. Such an approach also emphasizes that there are no universal blueprints; instead, evidence-based options could be made available for decision-makers to choose from with advice on the necessary calibration that may be required to address local conditions (see also Chap. 2). Safe use of wastewater is a good example to demonstrate the importance of feedback loops between: regulatory action/policy, human behaviour and policy outcomes in terms of both environmental sustainability and public health.

3 Data Visualization and Management of Environmental Risks: Example of Drought

Drought is a consequence of a natural decrease in the amount of rainfall received over a prolonged period usually a season or more in length. It originates from a deficiency of precipitation over an extended period, usually a season or more resulting in a water shortage for some activity, group or environmental sector. Droughts are one of the most common disasters, which can undermine livelihoods and well-being. They can cause decline in crop yields resulting in reduction in income for farmers, which will increase market prices of products. Changing climate and weather systems pose serious risks to agriculture, livestock and rural water supplies through increased variability in frequency, intensity and duration of droughts and high temperatures.

The adverse impacts of droughts on regional economies and local livelihoods in developing countries can be mitigated through improving the evidence base at the disposal of public agencies that facilitate drought forecasting, monitoring and rapid response. Building capacity for drought risk forecasting, monitoring and rapid response was identified as a priority at UNU-FLORES regional consultation on Water Point Mapping held during 25–26 February 2014 in Dar es Salaam, Tanzania. In this connection, it was recognized that data availability was an important constraint: data poor regions usually lack reliable, disaggregated and continuous data on biophysical and institutional parameters. Further, it was acknowledged that pure data is meaningless without providing a context and analysis with respect to a relevant policy objective. However, recent technological developments with regard to remote sensing and massive enhancements in computing power could make it possible to exploit the benefits of data visualization to support evidence-based decision-making for management of environmental risks in data poor environments (Mannschatz et al. in this volume).

3.1 The Nexus Observatory at United Nations University: Advancement of Hybrid Approaches

UNU-FLORES has initiated discussions with Department of Geosciences, Institute of Cartography to identify elements of a PhD level research programme on *data visualization and management of environmental resources.* Based on a request for technical assistance from the Ministry of Water, Government of Tanzania, the CDG unit has begun working closely with the Institute of Cartography to develop methodologies, build capacity of local training institutes and publish a nexus-planning manual. Three online courses that further the nexus approach will be hosted on the Blended Learning Platform of the Nexus Observatory. The courses to be introduced in 2015 are as follows: (a) Green Economy and the Life-Cycle Cost Approach, (b) Financing Public Services and Environmental Sustainability and (c) Rethinking Infrastructure Design for Multi-Use Water Services.

Overarching Questions Guiding Research, Teaching and Policy Advocacy at UNU-FLORES

- How can the *classificatory*[1] function of a UNU observatory enhance the applicability of the nexus approach to management of environmental resources?
- How can data visualization approaches strengthen feedback loops to support greater accountability and autonomy of decision-making processes and norms within a multi-level governance framework?
- How can the establishment of regional nexus observatory networks facilitate innovations in trans-disciplinary research methods that advance the think tank function of UNU?

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[1] Classification of data, knowledge and information according to theme and programme in a way that addresses nexus challenges relating to: (a) boundary conditions, (b) scale conditions, (c) feedback mechanisms, (d) hybrid research methods and (e) innovations in didactic approaches to training and capacity development.

4 Expected Outcomes for Science and Policy

4.1 The Nexus Observatory

The scientific and policy-oriented activities that advance the nexus approach to management of environmental resources will constitute important outcomes of the research project. The UNU-FLORES nexus observatory will play an important role as an incubator of policy relevant research questions and help identify triggers for policy and institutional reform in developing and emerging economies (Kurian and Meyer, forthcoming). In addition, the classificatory function of the observatory will serve to generate knowledge that clarifies the role of the following factors in management of environmental resources: (1) trade-offs, (2) synergies, (3) processes of intersection and interaction covering both biophysical and institutional domains, (4) trans-disciplinary research methods that capture the outcomes of adopting a nexus approach to management of environmental resources and (5) regional/programmatic context of a specific development intervention. Data visualization techniques that can effectively address the challenges of data availability and reliability in developing and emerging country contexts can prove useful in advancing the nexus approach to management of environmental resources as outlined below (see Table 1).

Table 1 The classificatory function of an observatory: an indicative list

Science concerns	Policy concerns	Nexus concerns	Governance concerns
Sustainability of Water Sources	Irrigation services/pro-poor, life-cycle costs of infrastructure projects, drought forecasting, monitoring and response, data availability and reliability	Multiple uses/ boundary conditions, material and energy flows and fluxes	Pricing/subsidies, poverty/feedback loops/data visualization
Contamination of Water Sources	Water supply/livestock services/life-cycle costs of infrastructure projects, drought forecasting, monitoring and response, data availability and reliability	Soil-water nexus, hydro-geology, remote sensing	Pricing/subsidies, poverty/feedback loops/data visualization
	Wastewater treatment/ life-cycle costs of infrastructure projects, drought forecasting, monitoring and response, data availability and reliability	Recycle and reuse	Pricing/subsidies, human behaviour/ poverty/feedback loops/data visualization

4.2 Policy Domain: Nexus Observatory Classificatory Scheme

Expected Outcomes

1. Knowledge transfer: Through regional consultations and biannual Dresden Nexus Conference
2. Field testing/piloting: Based on requests from member states
3. Policy/programme management triggers: Based on data visualization of resource use trends
4. Incubation of policy-relevant research questions: Through proposal writing workshops
5. Good practice guidelines: Through publication of policy briefs

Sub-fields for Component 1: Functionality of linked databases/regional consultations

(a) *Mapping results*: Organizational jurisdictional overlaps/knowledge and information gaps
(b) *Planning clinic*: Vision of institutional reform
(c) *Knowledge dissemination*: Reform framework

Sub-fields for Component 2: Functionality of field testing alternative approaches and methods

(a) *Mapping results*: Approaches to planning and methods for monitoring and evaluation
(b) *Planning clinic*: Action plan, sequencing strategy, risks and assumptions, monitoring framework
(c) *Knowledge dissemination*: Reform elements

Sub-fields for Component 3: Functionality of regional consultations

(a) *National level*: Guidelines, directives, legal and institutional arrangements
(b) *Provincial level:* Action plan, sequencing strategy, risks and assumptions, monitoring framework
(c) *Local government level:* Action plan, sequencing strategy, risks and assumptions, monitoring framework

Sub-fields for Component 4: Functionality of capacity development databases

(a) *National level:* Mapping and gap analysis based on policies, programmes and projects by theme and organization
(b) *Regional level:* Mapping and gap analysis based on policies, programmes and projects by theme and region
(c) *International level:* Analysis of trends at national and regional levels

Sub-fields for Component 5: Functionality of national/regional databases

(a) *National level*: Trend analysis emerging from sector specific or pilot projects in emerging and developing countries

(b) *Regional level*: Establishment of a *nexus index* that can potentially inform decisions on allocation of financial and/or human resources by governments/donors at different scales: Regional, national and provincial for integrated management of environmental resources

(c) *International level*: Donor harmonization, cross-fertilization across regions/countries, institutional arrangements for establishment and maintenance of a global nexus index

4.3 Science Domain: Nexus Observatory Classificatory Scheme

Expected Outcomes

1. **Boundary conditions**: Specified to determine applicability of research outputs
2. **Scale conditions**: Specified to determine applicability of research outputs
3. **Intersections**: Critical nodes at intersection of biophysical, institutional and socio-economic domains that impact upon management of environmental resources identified
4. **Interactions**: Biophysical and institutional processes that impact upon management of environmental resources mapped
5. **Feedback loops**: Mechanisms that transmit the effects of policy/programme interventions on human behaviour and their consequences for resource use strengthened

Sub-fields for Component 1: Specification of boundary conditions

(a) *Projects and programmes*: Analysis of success and failure of policy, programmes and projects, exploring both backward and forward linkages in an institutional and biophysical context; clarifying boundary conditions both spatially and temporally

(b) *Linked databases*: Analysis of backend data from universities and UN agencies relevant to water resources, systems and flux, waste management and soils

(c) *Process documentation*: Analysis of regional consultations that generates important insights relating to needs assessments, gap analysis and overlaps in a cost-effective manner

(d) *Citizen observatories*: Employ private data sets based on information from GIS, mobile and open source computing applications

(e) *Data visualization*: Employ suitable modelling techniques for data rich and poor environments

Sub-fields for Component 2: Specification of scale conditions

(a) *Projects and programmes*: Analysis of success and failure of policy, programmes and projects, exploring both backward and forward linkages in an institutional and biophysical context; clarifying boundary conditions both spatially and temporally
(b) *Linked databases*: Analysis of backend data from government ministries, UNU, universities and UN agencies that is relevant to water resources, systems and flux, waste management and soils
(c) *Process documentation*: Analysis of regional consultations that generates important insights related to needs assessments, gap analysis and overlaps in a cost-effective manner
(d) *Citizen observatories*: Employ private data sets based on information from GIS, mobile and open source computing applications
(e) *Data visualization*: Employ suitable modelling/remote sensing techniques for data rich and poor environments

Sub-fields for Component 3: Intersections

(a) *Biophysical processes*: Employ suitable modelling/remote sensing techniques for data rich and poor environments
(b) *Financing processes*: Understanding of norms for allocation of funds, functions and functionaries and transfers, taxes and tariffs
(c) *Socio-economic processes:* Understanding of demographics, income, ethnic, gender and resource use attributes of users of environmental resources

Sub-fields for Component 4: Interactions

(a) *Donor level*: Understanding of donor policies, projects and programmes
(b) *National level*: Understanding of legal framework, policies and programmes
(c) *Provincial level*: Understanding of management strategies, directives and guidelines
(d) *Local government level*: Understanding of equity norms, coordination norms and allocation norms

Sub-fields for Component 5: Feedback loops

(a) *Interventions*: Policy, programme and financing structures
(b) *Environmental resource*: Trends in use of water, waste and soil resources
(c) *Human-Environment interaction*: (1) Data proxies for environmental resource flows and fluxes, soil quality and waste characteristics and economic effects of waste, (2) Data proxies for socio-economic attributes relating to income, employment, demography, gender and/or ethnicity, and (3) Data proxies for dimensions of environmental resource use: consumption, price, volumes, cropping intensity, farming techniques
(d) *Programme*: Assumptions, risks, outcomes and impact
(e) *Project*: Assumptions, risks, outputs and outcomes

(f) *Implementation mechanisms*: Reporting norms, processes that link changes in interventions to human behaviour and outcomes in terms of achievement of policy objectives
(g) *Nexus index*: Explore how indices can help design policy relevant research related to management of environmental resources

Expected Impact If adequate attention is paid to creating robust linkages between the science and policy domains, then the Nexus Observatory could result in enhanced capacity for evidence-based decision-making. Strengthen capacity for drought risk forecasting, monitoring and rapid response in peri-urban regions of Africa, Asia and South America covering sectors such as irrigation, water supply and wastewater. Mainstream use of remote sensing and data visualization techniques within government ministries and departments to facilitate sustainability of water sources and prevent their contamination through appropriate wastewater management/treatment interventions. Evidence-based decision-making facilitated by nexus observatory through partnerships for data, information and knowledge sharing involving public and private sectors and community groups in Asia, Africa and South America.

5 Conclusions

The chapters contained in this volume address important issues at the intersection of science and policy. These concerns strike at the heart of the UNU system in its role as a think tank of the United Nations system. Sustainability is a key concern of the UNU system given the magnitude of global changes that are currently underway in developing and emerging economies. This volume is an attempt to outline key elements of transdisciplinary approaches for management of environmental resources considering global processes of demographic and climate change and urbanization. This volume, by drawing upon the combined expertise of professionals from multiple disciplines and use of case studies from both the developed and developing world attempts to forge trans-disciplinary perspectives on management of environmental resources: water, soil and waste.

This book addresses important lacunae in current debates on the nexus approach. First, the book attempts to relate the debate on Water-Energy-Food (WEF) nexus to the debate on nexus of water, soil and waste resources. Second, the book distinguishes between the policy and science questions that can shape discussions of key nexus concepts of trade-offs, synergies and equity. Third, the chapters in this volume highlight some of the contradictions inherent in discussions of concepts such as equity and efficiency that are very often shaped by disciplinary biases or blind spots. Fourth, this volume is emphatic that analysis of the nexus approach to management of environmental resources will be incomplete without an integrated view of the biophysical and institutional domains. Finally, this chapter proposes a rudimentary framework for integrated analysis of biophysical and institutional perspectives in the hope that such a project will clarify the poverty-environment nexus.

This chapter discusses ongoing initiatives at UNU-FLORES to advance the nexus approach to management of environmental resources through establishing an observatory. The role of data visualization in management of environment risks such as droughts is discussed through an example from Africa. The benefits of the classificatory function of an observatory are outlined for design of policy relevant research, teaching and policy advocacy initiatives at the United Nations University. This collection of papers besides serving to benchmark the evolution of the nexus concept at UNU-FLORES also highlights points of intersection where the science-policy divide can be effectively bridged. By documenting cases where synergies are possible and discussing the nature of trade-offs that are necessary to support them the nexus observatory can become a barometer of the role of UNU-FLORES in advancing transdisciplinary approaches to management of environmental resources-water, soil and waste.

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