INDICATORS FOR MEASURING THE SUSTAINABILITY OF URBAN WATER SYSTEMS - A LIFE CYCLE APPROACH

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ABSTRACT

Infrastructure for the provision of drinking water and the treatment of wastewater and stormwater, is essential for an urban society. In this project methods are developed which measure and assess the sustainability of urban water systems. A first set of environmental sustainability indicators (ESIs) was constructed, covering technical and environmental aspects, with a division within traditional water resources and process boundaries. The ESIs were applied in case studies in Göteborg, Sweden and King William's Town, South Africa. The ESIs demonstrated that the urban water system in Göteborg has moved towards environmental sustainability, but that recycling of nutrients to agriculture remains a major concern. The situation in King's Williams Town was quite different due to an increasing population and an increasing pressure on water resources. One of the findings from the case studies was that a more rational procedure for the selection of ESIs is required. Further, consideration of system boundary extensions is essential for the provision of a relevant assessment. At this point an iterative ESI selection procedure based on life cycle assessment (LCA) was developed.

The strength of LCA was demonstrated in two studies comparing technical options. First, LCA was used to compare projected wastewater systems with increased recycling of plant nutrients. Urine separation in combination with existing large-scale treatment was demonstrated to be a promising option that improves the opportunities for recycling of nutrients. Thereby water emissions are lowered, as well as energy use since the production of mineral fertilisers can be decreased. The benefits of separation systems were first revealed when the system boundaries were expanded to include fertiliser production. LCA combined with a cost analysis provided an assessment of four sewage sludge options. It was shown that incineration and agricultural use have respectively economic and environmental restrictions. The development of relatively low cost phosphorus recovery technologies has the potential to reconcile the environmental and economic aspects of sustainability.

Finally, the iterative procedure for ESI selection was applied and evaluated in a cooperative study with Stockholm Water to ensure indicator user interaction. A number of assessment tools (including LCA) were used as an input to rank technical options for handling sludge in a multi criteria analysis and led to the selection of indicators that reflect the economic, environmental and social aspects of sustainability for wastewater and sludge handling systems.

Keywords: Life cycle assessment, LCA, sustainable development, sewage sludge, indicators, urban water systems, environmental systems analysis, decision-making, wastewater systems

LIST OF APPENDED PAPERS:

I. Lundin, M., Molander, S., and Morrison, G. M., 1999. A set of indicators for the assessment of temporal variations in the sustainability of sanitary systems, Water Science and Technology, 39, 5, 235-242.

II. Lundin, M., Bengtsson, M. and Molander, S., 2000. Life cycle assessment of wastewater systems - Influence of system boundaries and scale on calculated environmental loads, Environmental Science and Technology, 34, 180-186.

III. Lundin, M. and Morrison, G. M., 2002. A life cycle assessment based procedure for the development of environmental sustainability indicators for urban water systems, Urban Water, 4, 2, 145-152.

IV. Lundin, M., Olofsson, M., Pettersson, G. J. and Zetterlund, H. 2002. Environmental and economic assessment of sewage sludge handling options, submitted to Resources, Conservation and Recycling.

V. Palme, U., Lundin, M., Tillman, A.-M. and Molander, S., 2002. A procedure for constructing sustainability indicators for wastewater systems – researchers and indicator users in a cooperative case study, manuscript.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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Margareta Lundin

ABBREVIATIONS AND TERMS

Abbreviations

BOD	Biological Oxygen Demand
CO_2	Carbon dioxide
EEA	European Environment Agency
ESA	Environmental Systems Analysis
ESI	Environmental Sustainability Indicator
EU	European Union
Eurostat	European Statistical Office
GDP	Gross Domestic Product
GRI	Global Reporting Initiative
IISD	International Institute for Sustainable Development
ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MCA	Multi-Criteria Analysis
METRON	Metropolitan Areas and Sustainable Use of Water
MISTRA	The Foundation for Strategic Environmental Research
N	Nitrogen
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
OEDC	Organisation for Economic Co-operation and Development
P	Phosphorus
PSR	Pressure State Response
S	Sulphur
SDR	Sustainable Development Record
SI	Sustainable Development Indicators
SEI	Socio-Ecological Indicator
SEPA	Swedish Environmental Protection Agency
SPI	Sustainable Process Index

SWARD	Sustainable Water Industry Asset Resource Decisions
UN	United Nations
UNCSD	United Nations Commission on Sustainable Development
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
WCED	World Commission on Environment and Development (also known as the Brundtland Commission)
WWF	World Wildlife Fund
WWTP	Wastewater treatment plant

Terms

Benchmark: serves as a standard by which others may be measured or judged or a point of reference from which measurements may be made

Bio-Con: process for separate sludge incineration with phosphorus recovery

Cambi-Krepro: process for sludge fractionation by hydrolysis and acidification for phosphorus recovery

DPSIR: SI framework used by the EEA and others into categories of Driving force, Pressure, State, Impact and Response

Ecological footprint: the area that would be required to support a defined human population and material standard

Effectiveness: the extent to which objectives are achieved

Efficiency: the extent to which resources are utilised optimally to produce outputs (goods or services)

Environmental impact: effects on the environment and human health from environmental pressures

Environmental pressure: emissions, wastes, energy and material uses that human activities put on the environment

Environmental sustainability: long-term maintenance of ecosystem components and functions for future generations (here taken synonymously with ecological sustainability)

Environmental sustainability indicators: pieces of information that aim to measure and assess progress towards environmental sustainability

EPS (Environmental Priority Strategies in product design): weighting method used in LCIA

ET-long (Environmental Themes): weighting method used in LCIA

Emergy: measurement of the accumulated energy inputs required for producing a product calculated as solar energy (the concept originates from Dr H. T. Odum)

Exergy: concept used to aggregate energies of different quality

Framework: conceptual model used to identify and organise indicators *e.g.* the pressure-state-response framework

Goals: usually qualitative targets indicating a general direction

Human Development Index: index calculated from three statistics; average of life expectancy, educational attainment and an adjusted GDP per capita

Indicator selection criteria: desirable characteristics that indicators should fulfil; *e.g.* validity (relevance, sensitivity, appropriateness, representativeness), feasibility (cost-effectiveness, measurability, data availability), interpretability (understandability, data comparability)

Life cycle assessment (LCA): analytical tool for modelling the environmental impacts associated with a product or a service over its life cycle "from cradle to grave"

Life cycle impact assessment LCIA): phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.

Life cycle inventory (LCI): phase of LCA involving the compilation of inputs and outputs, for a given product system throughout its life cycle

Life cycle thinking: conceptual idea behind LCA that reflects the consideration of cradle-to-grave implications of any action

MARTES: model for district heating systems with production of heat, steam and electricity

Multi-criteria analysis (MCA): analytical tool that assists the decision-maker in identifying trade-offs between different criteria and finding the 'best solution'

Performance indicators: parameters describing the level of achievement in respect to one or a set of reference values

PICABUE: methodological procedure for the development of SIs

Pressure-State- Response (PSR): model used by the OEDC and others to classify indicators into environment pressures, environment conditions and indicators of societal responses

Socio-Ecological Indicators (SEI): term used by the Natural Step foundation and others for indicators that are based on a specified framework for sustainability and focus early in the causal chain

Sustainable Development: defined in the Brundtland report as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" Sustainable Development and sustainability are here taken synonymously although they can mean different things

Sustainability Indicators (SIs): pieces of information that aim to measure and assess progress towards Sustainable Development

Targets: represent a specific value to be achieved

Tools: operational methods providing information for assessments

1 INTRODUCTION

Infrastructure for the provision of potable drinking water and the treatment of wastewater and stormwater is essential for an urban society. The urban water system is as necessary for economic development as it is for human health. During this century global water use has increased by more than double the population increase. Consequently, all aspects of sustainability - economic, environmental, health, and social – are critical considerations in upgrading or constructing new urban water systems. However, there is a lack of methods for assessing aspects of sustainability of these systems. This research sets out to describe and develop different methods that can be used for assessing the sustainability of urban water systems in order to provide adequate information to decision-makers and operators in the water sector.

1.1 Measuring progress towards Sustainable Development

Increasing global population and excessive consumption in wealthy countries result in the over-exploitation of resources and increased pollution. Concerned over environmental effects, inequality between countries, and the fate of future generations, the World Commission on Environment and Development called for Sustainable Development (WCED, 1987). Their publication, also known as the Brundtland report defines Sustainable Development, as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Subsequently, several attempts to define the concept of Sustainable Development and formulate sustainability principles have been made. One definition that focuses more on environmental degradation defines Sustainable Development as “improving the quality of life while living within the carrying capacity of supporting ecosystems” (IUCN/UNEP/WWF, 1991). According to the Brundtland report the concept of Sustainable Development implies limitations imposed by the present state of technology and social organisations, on environmental resources and by the ability of the biosphere to absorb the effect of human activities (WCED, 1987).

The Brundtland report also called for new ways to measure and assess progress towards Sustainable Development. This was further endorsed in the action document Agenda 21 (UN, 1992). Sustainability indicators (SIs) are tools that aim at making the concept measurable by quantifying trends in society and try to address the key question: Are we, or are we not, moving towards sustainability? The aim of SIs is to guide decision-makers at various levels so they can contribute to the development of society towards sustainability.

Recently, many SI projects have been initiated to describe the three pillars of Sustainable Development; economic, social and environmental dimensions. The majority of these have been proposed for use at an international, regional or other administrative level. SIs have also been used to describe the sustainability of specific sectors, but until recently few projects have used SIs to assess the Sustainable Development of companies or organisations. The approach to assess sustainability at the corporate level has often commenced with measurements of environmental performance, although the interest in measuring social performance has increased (Ranganathan, 1998). Most corporate performance indicators are developed on a company basis and most companies typically measure and report performance at the facility or company scale, thereby ignoring the environmental impacts or benefits from upstream and downstream activities, involving suppliers, consumers and waste management. The next step for sustainability measurement at a corporate level is to pay greater attention to the total supply chain.

1.2 Sustainable urban water systems

Economic growth and increasing food needs are two main threats to future water supply through increased pollution and excessive consumption of water. Water shortage and pollution are a public health problem, limit economic and agricultural development, and harm ecosystems. The challenge for sustainable urban water systems is to satisfy varied demands in different regions of the world. In many areas the main requirement is access to healthy water and a reasonable level of sanitation. In the industrial world, environmental concerns have grown, focusing on the quality of groundwater, the recycling of nutrients and the reduction of environmental effects.

Conventional, large-scale urban water systems in the industrial world were primarily designed to protect the health and safety of citizens and in these respects they function well. The systems provide a reliable service at a low operational cost, although the urban water system has difficulties to meet the challenges of an increasing population and the requirements of a cyclic use of plant nutrients. Phosphorus and nitrogen are of primary interest. Phosphorus is essential for plant growth and cannot be substituted. Concentrated reserves of phosphorus are limited, especially phosphate rock with low cadmium content (Steen, 1998). Nitrogen is not a limited resource but the production of nitrogenous fertiliser demands significant quantities of energy and provides gaseous emissions including CO_2, NO_x and N_2O (UNEP, 1996).

The history of urban water systems and particularly wastewater management tells us that efforts have been made to solve one problem at a time (Kärrman, 2000), which has often led to unexpected effects. This includes solving the sanitation problem in cities through the installation of sewers to remove wastewater, thereby causing eutrophication in rivers and lakes, or the construction of end-of-pipe measures in order to reduce emissions causing increasing resource requirements. Some of the problems that urban water systems need to face are an increasing water use, an increasing pressure on resources, an ageing infrastructure and a mixing of different water qualities that contaminate sludge and complicate the recycling of plant nutrients.

1.3 Life cycle assessment

In order to avoid shifting of problem focus and to find strategies to improve existing infrastructure and develop new systems, without only solving one problem at a time, system-wide methods are required. Life cycle assessment (LCA) is one of the most comprehensive tools used to assess the environmental load of a product or service. The whole chain of activities required for production is taken into consideration. Both emissions of potentially harmful substances from these activities and their consumption of natural resources are analysed. In this way, different technical systems, providing the same product or service, can be followed and compared with regard to their impacts on the environment. Since LCA can include the total supply chain and in principle, all environmental interventions it is an important tool in the assessment of environmental sustainability and can therefore provide a systematic basis for selecting SIs at a corporate level. One advantage with LCA is the well-described, international standardised structure (ISO 14040, 1997). Life cycle thinking is the conceptual idea behind LCA that reflects the consideration of the total supply chain. Such a systems perspective is valid not only for the environmental dimension but also for social and economic dimensions.

1.4 Aims and objectives

The aim of this thesis is to develop methods for measuring and assessing the sustainability of urban water systems. Two assessment tools and their use in corporate decision-making have been investigated, LCA and SIs. More specifically, the objectives include the following:

1. Review the main SI frameworks, demonstrating their advantages and limitations in the preparation of SIs for urban water systems.
2. Evaluate the environmental sustainability of alternative wastewater and sludge handling technologies using LCA.
3. Present selected environmental SIs and use them to assess the environmental sustainability of urban water systems over time in both a developed and an undeveloped region.
4. Develop, apply and evaluate a method/procedure based on LCA methodology and case studies for preparing SIs for assessing the sustainability of urban water systems.

The focus is on the environmental dimension of sustainability but this thesis also includes some considerations regarding SIs covering social and economic dimensions.

1.5 The appended papers

The thesis is based on five papers. Figure 1.1 shows how the papers are related to each other. A literature review was conducted to identify the state of the art for SIs and sustainable urban water systems (presented in chapter 2). Based on literature studies and discussions with representatives from the water sector a first set of environmental sustainability indicators (ESIs) was proposed (Lundin, 1997). In paper I, the majority of the proposed ESIs were tested in a case study of Göteborg and it was demonstrated that the selected indicators were useful for evaluating the environmental sustainability of an urban water system over time. The study showed that the urban water system in Göteborg has moved towards a more sustainable status in several respects, the systems are more efficient in terms of energy and chemicals and more effective in terms of higher treatment performance, but recycling of nutrients to agriculture remains a major concern.

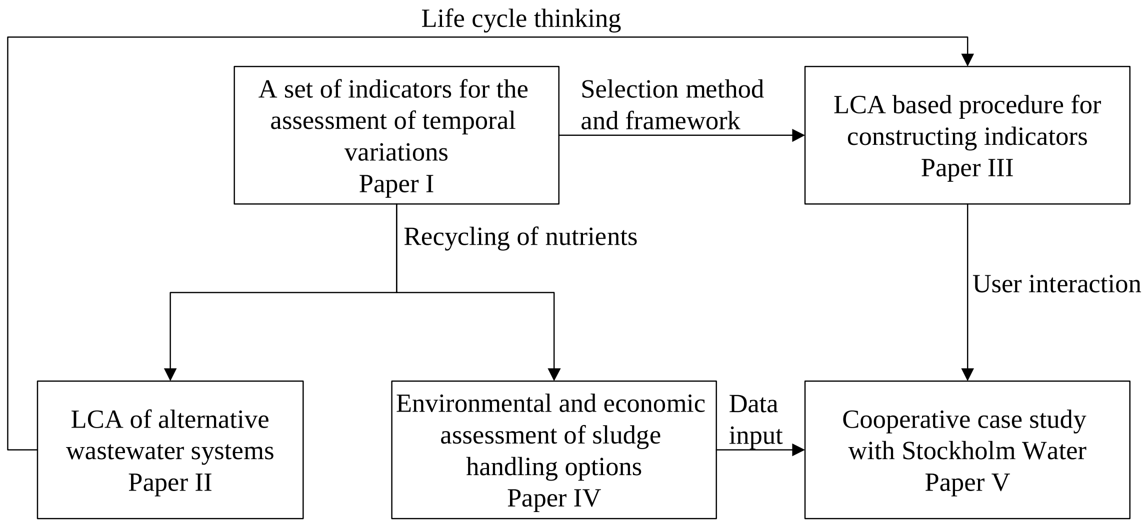

Figure 1-1 Structure of the research presented in the five papers.

Two ways to increase nutrient recycling from wastewater systems were evaluated using LCA methodology. In paper II, LCA was used to compare the environmental loads from separation wastewater systems with conventional solutions. It was concluded that some of the most important environmental advantages of separation systems are found only when models of wastewater systems are expanded to also include potential effects on the production of agricultural fertilisers. In paper IV the environmental and economic consequences of four recycling and disposal options for municipal sewage sludge were assessed. The interaction with the energy system was investigated using an energy system model. This study showed that application of sludge to agriculture had the lowest cost but was the least preferable option from an environmental point of view. Co-incineration had the best energy balance but without recovery of phosphorus. In the Bio-Con and Cambi-KREPRO processes both energy and phosphorus could be recovered at relatively low cost.

Based on the ESI and LCA case studies, a more formalised method for SI identification was proposed in paper III, which presents an iterative procedure for constructing ESIs based on LCA methodology. The importance of careful selection of system boundaries and the involvement of indicator users in the selection process was emphasised.

To evaluate and further develop the iterative procedure presented in paper III, a case study was performed in cooperation with the Stockholm Water Company (paper V). Participants from the company were involved in the study from the outset. Results from the economic and environmental assessment of sewage sludge options (paper IV) were used together with other tools to provide decision support for SIs selection through a multi-criteria analysis. The cooperative process combined the knowledge of researchers and practitioners and led to the development of quantitative and qualitative SIs representing environmental, social and economic aspects.

2 SUSTAINABILITY INDICATORS – STATE OF THE ART

After a decade of research and activities in the field of SIs, the number of publications on SIs is extensive; at least for SIs on the international and national scale. In this section an overview of different approaches for developing SIs is presented. The focus is on the different models or frameworks employed in the SIs field and on the selection processes. Finally, selected SIs concerning water resources and projects related to urban water management are discussed.

2.1 Definitions, functions and presentation

An indicator is usually defined as a piece of information which has a wider significance than its immediate meaning (Bakkes *et al.*, 1994). If an indicator relates to a criterion, an objective or a target, it may be referred to as a performance indicator. If several indicators are combined, then that is an index, while a set of indicators represents a larger issue (Bakkes *et al.*, 1994). Headline indicators are a small set of key indicators, often selected from a larger set, which represent main issues and decrease the information content.

An indicator is useful if it is of fundamental interest in decision-making, simplifies or summarises important properties, visualises phenomena of interest and quantifies, measures and communicates relevant information (Gallopín, 1997). An indicator can be either qualitative or quantitative, although in practice the latter is more useful. Further relevant functions of indicators are (Gallopín, 1997):

- to assess conditions and trends (sometimes in relation to goals and targets);
- to provide information for spatial comparisons;
- to provide early warning information;
- to anticipate future conditions and trends.

Economic indicators, such as the gross domestic product (GDP), have been used since the 1950's and in the 1970's the first social and environmental indicators were suggested and presented by the OECD (Verbruggen and Kuik, 1991; OECD, 1998). Since the advent of the concept of Sustainable Development, a variety of SIs have been proposed for different aspects. Traditional indicators of economy have been modified to include environmental aspects, one example being the Index of Sustainable Economic Welfare (Daly and Cobb, 1989). Social indicators have been linked to environmental or economic aspects, an example is the Human Development Index, published annually by the United Nations in their Human Development Report (UNDP, 1996). Environmental indicators have expanded from the assessment of environmental state to include environmental pressure and the driving forces behind these pressures (OECD, 1998).

As important as the selection of good SIs is their presentation. An indicator is information relevant to a particular issue of concern. The added value of an indicator over a raw data set is that the indicator is presented in a way which represents the broader significance or implications of the data. If the indicators are difficult to understand it follows that they may be difficult to use. The choice and design of SIs should be based on the purpose of the use of information and an understanding of information needs of different target groups. Different sets of SIs may thus be tailored for different groups.

Braat (1991) distinguished three types of target groups; professionals, policy-makers and the general public. Figure 2.1 illustrates the relationship between relative condensation of information and different target groups. According to Braat (1991), scientists are most interested in raw data that can be analysed statistically. Policy-makers prefer data which are related to policy objectives and reference values, while the general public prefer simple index of information. So for each purpose, presentation should reflect meaning for the particular target group.

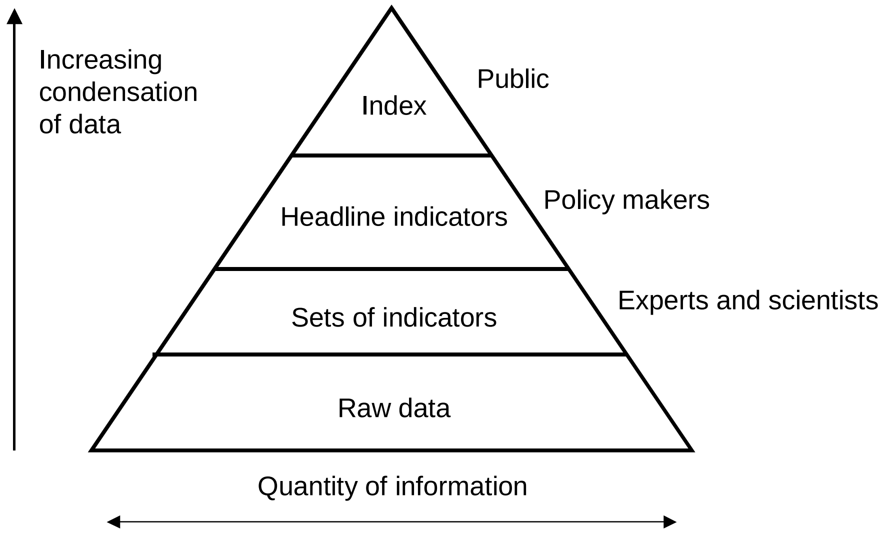

Figure 2-1 The information pyramid (Braat, 1991)

2.2 Frameworks for sustainability indicators selection

Several different approaches have been used to identify, develop and communicate aspects of Sustainable Development through available SIs. In line with this variety of approaches, several frameworks have been adopted. A framework can be viewed as a structure that can be used to select relevant SIs by identifying information need for the stated purpose. A framework can also aid the process of structuring information during reporting and communication. An extensive comparison of frameworks has been reported previously (Hardi *et al*, 1997; Hodge, 1997). In the following, a selection of frameworks representing different models for SIs is presented. The focus is on physical measures and the environmental dimension of Sustainable Development.

2.2.1 Sustainable Development Records

One approach to the determination of environmental performance in both physical and monetary units is Sustainable Development Records (SDR). SDR has been established in several Swedish municipalities and companies (Nilsson and Bergström, 1995). The SDR model emphasises the link between generated services and used resources (social, material and financial). It consists of four parts that form the basis for SIs. The 'operation' is the organisation under study, delivering 'services', which represent the purpose of the operation. These services require flows of resources (throughputs) from a 'resource base'. Three types of SDR indicators (effectiveness, thrift and margin) are formed as relationships between these parts (Table 2.1)

The model has been used to develop a set of SIs, which was used to assess the sustainability of different wastewater systems (Nilsson and Bergström, 1995). The set is presented in Table 2.1.

Table 2-1 Sustainable Development Record indicators proposed for wastewater systems (Nilsson and Bergström, 1995)

Type of SDR indicator	SDR ratio	Numerator	Denominator
Effectiveness	Sewage treatment quality	Acceptable samples	All samples
	P and BOD		
	Recycling of phosphorus	Phosphorus to farmland	Phosphorus to sewage system
Thrift	Sewage water	No of people	Sewage water produced
	Financial	No of people	Depreciation of assets
	Energy	No of people	Energy used
	Labour	No of people	Labour used
	Chemical	Phosphorus	Chemical used
Margin	Phosphorus	Actual purification	Sanitation standard
	BOD	Actual purification	Sanitation standard
	Chemicals	Value of sludge	Cost of chemicals

The SDR model has been criticised (Carlson, 1997) for not providing an explicit description of sustainability and for essentially being a bookkeeping system for material and energy flows. Several of the indicators are difficult to categorise and sometimes overlap. As an example, three indicators are suggested for phosphorus reduction. The extent to which an indicator measures effectiveness or thrift is not obvious. The margin indicator is in theory a SI, but in practice it is difficult to apply since the total resource base is not known by companies and hard to define. Still, the idea of linking an effective service with the efficient use of resources is relevant at a company level.

2.2.2 Pressure-State-Response and similar frameworks

Several organisations have used frameworks based on the Pressure-State-Response (PSR) framework (Figure 2.2) which was developed by the OECD. Pressure indicators describe environmental pressures from human activities, which influence the environment through emissions and the use of natural resources. State refers to the state of the environment, the quality or quantities of natural resources, and provides an overview of the situation in the environment. Response describes the extent to which society is responding to environmental changes and concerns.

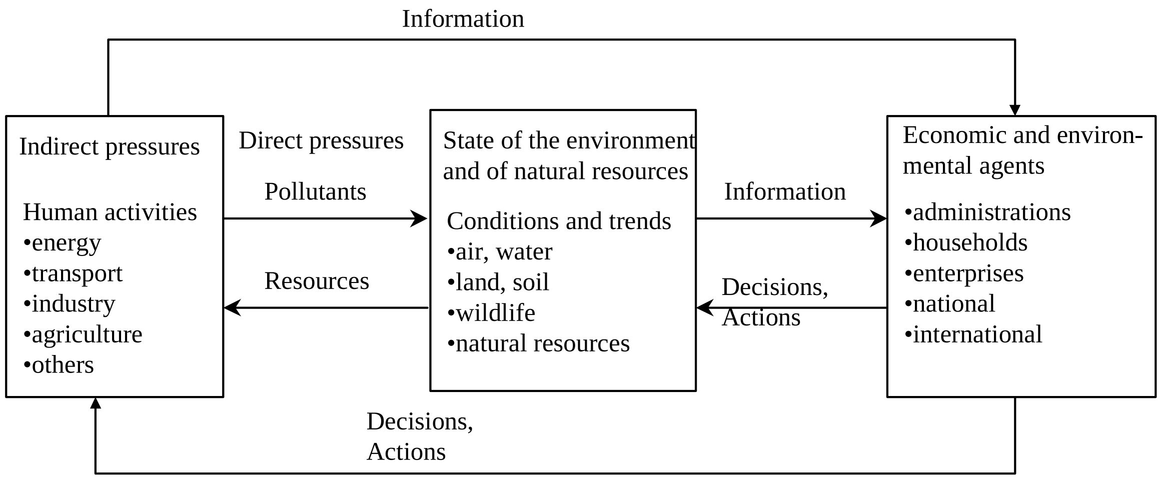

Figure 2-2 The Pressure-State-Response framework (OECD, 1998)

It is generally accepted that a universal set of indicators does not exist for the PSR framework and that the appropriate set should be tailored to the needs of the users. This has led to a core set of environmental indicators (approximately 40 different indicators) that covers the issues of climate change, ozone depletion, air quality, waste, water quality, water resources, forest resources, fish resources and biodiversity. Some examples of indicators related to water quality and resources are presented in Table 2.2.

Table 2-2 OECD indicators related to water quality and resources and their place in the PSR framework (OECD, 1998).

Set of indicators	Selected indicators	Place in framework
Water quality	Oxygen and nitrate content in selected rivers	S
	Sewerage connection rates	R
	Public expenditure on wastewater treatment	R
Water resources	Withdrawal of freshwater	P
	Intensity of use for irrigation, households and industry	P
	Prices for public water supply	R

The core set is supplemented with sets of sectoral indicators to help improve the integration of environmental concerns into sector related decision-making. These are limited to a specific sector and are not restricted to environmental indicators, but also concern linkages between the environment and the economy. They may include environmental indicators, economic indicators and selected social indicators. So far, the

OECD has developed sector related indicators for energy, transport and agriculture (OECD, 1998; OEDC, 2000).

The PSR model may be useful for describing causes of environmental problems and for communicating an understanding of the linkages between emissions and impacts. However, it is less useful in describing the economic and social dimensions of Sustainable Development and also there is a lack of selection procedure which relates to Sustainable Development. There may also be confusion over the placement of certain indicators in a specific category, *e.g.* a response indicator can also be a pressure indicator. The indicators may be useful for authorities at a national level, but need to be linked to regional goals and complemented with indicators at a lower level (sector, company, individual). On the other hand, the framework is well accepted and many organisations have proposed frameworks based on this model.

A modified PSR framework has been adopted by the European Environmental Agency (EEA) and the European Statistical Office (Eurostat, 1997) to include Driving forces and Impacts (Figure 2.3). Driving forces include economic development, population, education and life style, while Impacts includes health-related aspects and biological effects. EEA regularly publishes an indicator report on the state of the environment in Europe 'Environmental signals' and has also started to develop sector related indicators (EEA, 2000; EEA, 2001; EEA, 2002). Since the number of reported indicators is (too) large, EEA has proposed a set of eleven headline indicators aimed at decision-makers and the general public. The modification makes the framework more complicated, but also more flexible.

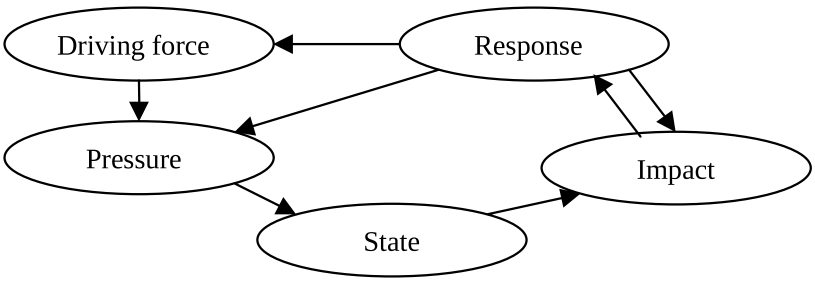

Figure 2-3 The DPSIR framework used by the EEA (Eurostat, 1997)

The Swedish EPA has also used the DPSIR model to monitor fifteen national environmental objectives (Government Bill, 1997/98:145). The goals that directly affect the urban water system and the proposed indicators are presented in Table 2.3. A number of interim targets have been defined and adopted for each environmental objective resulting in 159 indicators. The monitoring proposal has been criticised due to its extensive character and an assessment is now under way to reduce the complexity and create more easily acceptable information.

Table 2-3 Swedish national environmental objectives and proposed indicators related to urban water systems, categorised in the DPSIR model (SEPA, 1999).

National environmental objectives	Driving force and Pressure indicators	State and Impact indicators	Response indicators
Oceans in balance No eutrophication	Emissions of N Exploitation of coastal zones Agricultural production	Areas with algal blooming Oxygen limited areas Concentration of N and P	Development of coastal wastewater treatment
Living lakes and watercourses	Emissions of P from different sources Use of fertiliser	No of eutrophic lakes No of acid lakes	Development of wastewater treatment
Groundwater of high quality	Total water use Loads of N and S Use of pesticides	Concentration of nitrate and chloride	No of protected water sources No of protected gravel pits
Fertile agricultural landscape	Nutrient balance in agricultural land Area of organic grown food		
Toxic free environment	Use of certain chemicals Emissions of persistent organic substances and metals	Metal content in fish and plants	Collection of mercury and cadmium

2.2.3 Frameworks that link societal activities and the environment

Approaches such as Socio-Ecological Indicators (Holmberg, 1995) or the aggregated Ecological Footprint (Wackernagel and Rees, 1996), have focused on the physical influence of society on nature and attempt to link human activities to the environment.

Holmberg (1995) defines Socio-Ecological Indicators (SEIs) as indicators that focus early in the causal chain and are based on four principles for sustainability, defined by this research group. SEIs are directed towards societal causes rather than towards environmental effects. The first three principles deal with the societal use of material from the lithosphere, emissions of compounds produced in society and the long-term productivity of ecosystems (Holmberg, 1995). The fourth deals with an effective and fair resource use with respect to meeting human needs. SEIs have been formulated for various geographical levels: regional, national and global, and have also been proposed for some organisations (Carlson, 1997). SEIs are usually formulated as a ratio between an environmental pressure and a reference value based on sustainability; all in line with the four stated principles. SEIs should, according to their definition, place emphasis on societal activities (Driving forces or Pressures in the DPSIR framework) if they are to be operational in policy situations.

Table 2.4 gives examples of SEIs related to urban water systems. They include both indicators of Pressure and State (P and S in the PSR model) as well as Efficiency (E), the latter being defined as benefit per resource input. These indicators are important and might be useful for large geographical areas, national or larger. However, for selected municipalities or water companies, data maybe scarce and the approach will not provide an assessment of environmental sustainability.

Table 2-4 Socio-Ecological Indicators related to urban water systems (modified from (Holmberg, 1995; Azar et al., 1996).

Principle 1 and 2	Mining of phosphorus compared to natural flows (P) Accumulation of cadmium compared to natural content in soils (S) Anthropogenic flows of nitrogen compared to natural flows (P) Production of persistent substances (P)
Principle 3	Transformation of land (P) Area of wetlands (S) Nutrient balance in soils (S) Maximum sustainable yield (MSY)* Non-renewable water use / Total freshwater use (P)
Principle 4	Amount of nitrogen which ends up in the food/total nitrogen given (E) Recycling of P/ total input (E) Percentage of population with access to potable water and sanitation (S)

*MSY refers to the maximal yield that can be achieved by harvesting a population at the same time as a stationary population size is maintained

A now famous index of sustainability is the Ecological Footprint (Wackernagel and Rees, 1996). This index is based on the idea that one can assess sustainability in terms of the area required to produce ecosystem services for a person or a country. Calculations are made for five major categories; food, housing, transportation, consumer goods and services. In theory, all the land and water area required to produce all goods consumed and to assimilate all generated waste should be included.

Another area-based index is the Sustainable Process Index (SPI) that focuses on process technologies. The total area required to produce raw materials, process energy, provide installations and area required for the staff and to accumulate products and by-products is calculated and compared to available area (Narodoslawsky and Krotscheck, 1995; Krotscheck and Narodoslawsky, 1996; Narodoslawsky and Krotscheck, 2000).

Single aggregated indices may be satisfactory for the communication of changes in Sustainable Development or to indicate targets, but are unlikely to identify changes that are required to promote Sustainable Development at the local level. The use of area as a basic unit (instead of money) is an interesting approach since area is a limited resource. However, the calculations of the Ecological Footprint and the SPI involve a number of simplifying assumptions necessary to reach a single number.

2.2.4 Balanced lists or theme framework

A third type of framework tries to balance different considerations of Sustainable Development by compiling comprehensive lists of indicators. This framework together with the PSR model dominates the SI literature and is often applied for political use. It is usual to include the generally accepted dimensions of Sustainable Development;

social, economic and environmental dimensions, although, sometimes additional components such as institutional or cultural aspects are considered.

In 1995, the United Nations Commission on Sustainable Development (UNCSD) developed a first list of 134 SIs, which were intended for use by countries in their decision-making process and to enable international comparisons. Initially, they used a modified PSR model by substituting the concept of Pressure for Driving forces and expanding it to include not only environmental but also social, economic and institutional issues, following the relevant chapters in Agenda 21 (UNCSD, 1996). Approximately 20 of the SIs deal with water and wastewater issues (Table 2.5).

Between 1996 and 1999 the SIs were tested in 22 countries, of which eight were European. One outcome of this process was that the framework was found to be inappropriate for economic and social indicators and that the list of SIs was too long. In Europe, several of the SIs were already in use, some were not relevant and alternative SIs were added. As a result, UNCSD revised the framework to focus on policy issues and main themes related to Sustainable Development. Further the number of SIs was reduced to a list of 58 from which each country can choose SIs appropriate to their specific conditions (UNCSD, 2001).

Table 2-5 UNCSD indicators related to urban water systems placed in the Driving force–State–Response model (UNCSD, 1996).

Category	Driving force indicators	State indicators	Response indicators
Social indicators	Rate of growth of urban population	Access to safe drinking water and basic sanitation	Infrastructure expenditure per capita
Economic indicators	Annual energy consumption	Share of renewable energy Intensity of material use	Environmental protection expenditures as a percent of GDP
Environ-mental indicators	Annual withdrawal of freshwater / annually available volume Domestic water consumption Population growth in coastal areas Releases of N and P Use of fertilisers Use of agricultural pesticides Irrigated portion of arable land	Groundwater reserves Concentration of faecal coliforms in freshwater BOD in water bodies Algae index	Wastewater treatment coverage Expenditure on waste management Waste recycling and reuse Municipal waste disposal Number of chemicals banned or severely restricted

2.2.5 Systems analytical framework

A completely different approach to preparing SIs is through the use of a systems analytical framework (Bossel, 1997; Bossel, 1999). In this approach SIs are chosen for their ability to provide answers to a set of questions concerning the viability of a sub-system and its rate of change, as well as how it contributes to the overall system or goals that are desirable for society. Otherwise, according to Bossel (1997), there is a risk that the SIs reflect the specific expertise of the designers and are detailed in some areas while sparse in other important areas. Sustainability assessments can hence be reduced to finding which basic needs or orientors (Table 2.6) are not sustainable, why this may be the case and then finding solutions.

Table 2-6 Basic system needs or orientors for viable system performance (Bossel, 1997).

Basic orientors	Subsystem performance	Contribution to total system
Existence	Is the system viable? Can it exist?	Does subsystem contribute to existence and viability of total system?
Psychological needs	Is it compatible with psychological needs and culture?	Does it contribute to the psychological well-being of people?
Effectiveness	Is it effective and efficient?	Does it contribute to the effective and efficient operation of the total system?
Freedom of action	Does it have the necessary freedom to respond and react as needed?	Does it contribute to the freedom of action of the total system?
Security	Is it secure, safe, and stable?	Does it contribute to the security, safety, and stability of the total system?
Adaptability	Can it adapt to new challenges?	Does it contribute to the flexibility and adaptability of the total system?
Coexistence	Is it compatible with interacting subsystems?	Does it contribute to the compatibility of the total systems with its partner systems?

Bossel (1997) attempted to include all aspects of sustainability and suggested a system of over 200 SIs set to answer the questions in presented in Table 2.6. The large number of SIs makes them difficult to grasp and several would be very difficult to collect data for. Nonetheless, the approach is interesting in that it starts by addressing the question of human needs and how different sectors can contribute to Sustainable Development.

For an urban water system the question of sub-system performance could be addressed as well as how it can contribute to the overall efficiency in terms of surrounding systems including energy, food production, human well-being and urban beauty. System ideas are central to the concept of sustainability since a holistic, long-term perspective needs to be considered.

2.3 Sustainability indicator selection process

Compared to the issue of SI frameworks, literature on the SI selection process is limited. Two distinctive approaches dominate the field. With the top-down approach, experts and researchers define the framework and the set of SIs. This is the common approach and includes the frameworks presented in section 2.2. The SIs may be applied and modified to fit a local situation but the end users have no major say in defining them. The bottom-up, participatory approach has often been used in sustainability assessment projects in municipalities (exemplified by Sustainable Seattle, which follows).

2.3.1 Sustainable Seattle

The Sustainable Seattle project is often referred to as an early grassroots effort in the selection of local SIs. Sustainable Seattle has been praised for the participatory approach adopted, although it has also been criticised for having had minimal effect on policy (Levett, 1998). In 1991, 15 volunteers started to develop the first SIs. Soon, around 150 citizens from different sectors of society contributed to the process of developing SIs. After initial brainstorming, groups met to develop, review, debate, form consensus and revise proposed SIs. Initially, 99 SIs were suggested and in 1993 the first set of 20 SIs which met a set of criteria and for which data could be obtained was published. Four important criteria were recognised (Sustainable Seattle, 1993). SIs were selected if they:

- were fundamental to long-term economic, social and environmental health
- could be understood and accepted by the community
- had interest and appeal for use by local media
- were statistically measurable.

In 1998 a second report including 40 SIs was published (Sustainable Seattle, 1998).

2.3.2 Bellagio principles

The selection process is considered so critical that in 1996 an international meeting was held in Italy, which resulted in the Bellagio principles (Hardi and Zdan, 1997). These principles aim to serve as guidelines for the whole assessment process including the choice and design of SIs, their interpretation and the communication of results. The ten principles deal with four aspects of assessing progress towards sustainability.

- Principle 1 deals with establishing a vision of Sustainable Development and clear goals that provide a practical definition of that vision in terms of meaning for the decision-making unit in question.
- Principles 2 to 5 deal with the need to have a sense of the overall system with a practical focus on current priority issues; holistic perspective, essential elements, adequate scope.
- Principles 6 to 8 deal with key issues of the process of assessment; openness, effective communication and broad participation.
- Principles 9 and 10 deal with the necessity for establishing a continuing capacity for assessment.

The Bellagio guidelines are often referred to in the SI literature but their usefulness still needs to be demonstrated in defined case studies.

2.3.3 PICABUE

Mitchell *et al.* (1995) presented a participatory approach to SI selection at a city level. The PICABUE method includes the following steps (Mitchell, 1996):

- Specification of the purpose of the SIs and their user group
- Specification of the definitions and principles of Sustainable Development
- Selection of local and global issues of concern
- Matching of SIs characteristics to the purpose and the users of the SIs
- Evaluation of the SIs against desirable characteristics.

The method does not specifically include an SI framework but the authors state that the SIs should be selected to include important issues and a set of sustainability principles. The PICABUE method is an attempt to develop SIs in a more rational way than the approach of Sustainable Seattle. The method has been implemented by several organisations including the Stockholm City Council, the EU BEQUEST research network and the Sustainable Futures Society (USA), and has been used as a consensus building tool (personal communication Mitchell 2002).

2.4 Sustainability indicators and urban water systems

Within the water sector, indicators are being developed and used in several countries. A major objective of water utilities is to improve the quality of the service, while keeping down costs. Most indicators have been used for monitoring these objectives. Environmental aspects are also recognised as being important. Performance or sustainability indicators are now being developed and used in international and national indicator projects. (Balkema *et al.,* 2002) presents an overview of sustainability assessment methods and currently used SIs.

The METRON (Metropolitan Areas and Sustainable Use of Water) research project was undertaken on the premise of identifying strategies, policies and tools for the sustainable management of water (supply and use) for European metropolitan areas. The objective was to bring forward data and problem contexts from a number of cities in order to develop a "rich" understanding of issues at stake and their socio-economic dimension as an input to policy design at the local and EU levels. Within METRON a set of SIs has been proposed to assess sustainability issues of water use (Kallis and Coccossis, 2000). The SIs are based on a modified SDR model (see 2.2.1). The selection process includes:

1. A description of the water system
2. Definition of sustainability goals
3. Compilation of a first broad list of SIs
4. Case studies to identify degree of data
5. Selection of key SIs.

The SIs have been used for investigating the current state of water systems in five European cities. Table 2.7 summarises the main sustainability policy issues and key SIs identified in the METRON project. A limitation is that the METRON project only includes the system for drinking water supply, ignoring the wastewater system and its impact on environmental sustainability.

Table 2-7 SIs proposed in the METRON project for the assessment of policies for urban water use (Kallis and Coccossis, 2000).

Policy issue	Sustainability goal	SI
Service	All population connected	Service coverage, %
	Acceptable quality	Acceptable samples, %
	Adequate customer service	Service effectiveness
Cost of water	Affordable	Cost of water
	Fully priced	Recovery from charges, %
Raw water quality	Public health risks monitored	Samples at the tap, %
	Non-deteriorating quality	Quality deterioration risk
Environmental impacts	Foreseen, regulated and controlled	Environmental flow regulation
Delivery efficiency	Low and non-increasing losses	Un-accounted for water, %
Conservation	Non-increasing per capita water use	Per capita water use, l/cap/day
Supply security	Demand within limits of existing resources	Resource capacity, %

Sustainable Urban Water Management is a six-year research program initiated in 1999 by the Swedish Foundation for Strategic Environmental Research (MISTRA). The purpose is to improve knowledge of sustainable water and wastewater management. Within the program there is a systems analytical project that aims to develop a tool-box to assess and integrate environmental, health, economic, social and technical sustainability criteria into decision-making processes for the water industry in Sweden. Within each criterion SIs have been proposed and the project provides a priority list of the most important criteria and SIs (Hellström *et al.*, 2000).

With a similar aim, the SWARD (Sustainable Water Industry Asset Resources Decisions) project in the UK has developed a guidebook that enables the UK water industry to assess the relative sustainability of water asset development. The guidebook outlines seven component phases in the decision-making process including the selection of appropriate criteria and SIs (Ashley *et al.*, 2002). A set of generic criteria with example indicators are suggested with the intention to aid water service providers in the selection of more specific criteria for evaluating the contribution to relative sustainability of different (technical) options (Foxon *et al.*, 2002).

The “six-cities group” (Göteborg, Malmö, Copenhagen, Stockholm, Oslo and Helsinki) has, since 1995, co-operated to develop performance indicators, to be used as a benchmarking tool and allow comparisons between the participating cities. The selected indicators cover; customer satisfaction, economy, availability, organisation/staff, quality and environmental aspects (Larsson *et al.*, 1997). Within the six-city project, emphasis has been placed on indicator definition and the comparability between the cities. One conclusion is that the results from the indicators should be compared with care. Differences in organisation structure, population density and topography are all factors that influence the result.

Indicators have also been used by organisations in their communication with the external audience. Environmental reports that concentrate on legal requirements are required annually by the authorities in several countries. In addition, an organisation may choose to distribute environmental reports to a wider public. The Stockholm Water Company has published such voluntarily environmental reports since 1996. The latest reports include a short presentation of the company, its activities and services and identified significant environmental aspects (Stockholm Water, 2002). The company's environmental and quality policy is presented together with a set of objectives and selected environmental targets (Table 2.8). The objectives are accompanied by fact sheets with indicators that show to what degree the targets are reached. The results are presented annually and compared to historical data.

Table 2-8 Objectives and targets for Stockholm Water (Stockholm Water, 2002)

Objectives:	Selected targets
1. Satisfied and environment-conscious customers	At least 50% of users never throw substances and objects down the drain.
2. Ecologically sustainable and resource efficient operation	Transport systems must be made more efficient and there must be a change over to renewable fuels.
	The use of chemicals that are harmful to the environment and human health, especially chlorine, must be reduced.
3. Clean, healthy drinking water	The company must take measures to ensure that Lake Mälaren and Lake Bornsjön remain sustainable water sources.
4. An efficient distribution system	Leakage must not exceed an average of 25 litres per minute per km on a rolling 5-year average basis.
5. Reduced pollutant input into the sewer system	The sludge standards laid down in legislation and the Sludge Agreement must be met.
6. Treated wastewater that does not strain nature's carrying capacity	Limit values of BOD, P and N must not be exceeded.
7. Healthier lakes and archipelago	The knowledge of the function of receiving waters must constantly improve.
8. Development through regional, national and international activities	The company will help, by means of knowledge transfer and exchanges of experience, to build up effective and efficient water and sewerage operations in the Baltic Sea drainage basin.

2.5 Conclusion on sustainability indicators

This chapter has reviewed some of the on-going development of SIs with particular focus on the water sector. The presentation is selective and the examples are chosen to illustrate the various frameworks and approaches being used to identify SIs. The different frameworks presented in section 2.2 are based on different perceptions of Sustainable Development. Even though an adequate framework is often emphasised as important for the selection of SIs there is no superior framework, but each needs to be adjusted to the application of the SIs.

The frameworks and processes presented have contributed to the assessment of sustainability but their usefulness at a corporate level and for assessing the sustainability of urban water systems is limited. At a corporate level, the approach to assess Sustainable Development has focused on measuring environmental performance, without a specific procedure towards SI selection. The indicators are generally developed on a company basis and typically measure and report environmental performance at the facility or company scale, thereby ignoring the environmental impacts of their products. The next step for future sustainability measurement, at least at a corporate level, is to develop adequate procedures and frameworks for SI selection, using a life cycle perspective on all aspects of Sustainable Development.

3 LCA OF URBAN WATER SYSTEMS

3.1 Previous studies

A variety of methods have been used to assess urban water systems, mainly from an environmental point of view, including mass flow and substance flow analyses (Dalemo *et al*., 1997; Sonesson *et al*., 2000; Bringezu, 1998; Reckerzugl and Bringezu, 1998), environmental impact assessment (Gardiner, 1996; Arce and Gúllon, 2000; Kärrman, 2000), exergy, emergy and energy analyses (Hellström and Kärrman, 1997; Björklund *et al*., 2001). One of the most comprehensive methods is LCA and there are an increasing number of LCA studies for drinking water and wastewater systems, treatment processes or components such as pipes or chemicals. In table 3.1 a selection of some LCA-studies on wastewater and sludge handling systems is presented.

Table 3-1 Selected LCA studies of wastewater and sludge handling systems.

	Purpose of study	System boundaries	Includes construction?
1	Compare options for the disposal of sanitary waste	WC to disposal or incineration	No
2,3	Compare conventional systems with separation systems	A wastewater system incl. energy supply and avoided fertiliser production	Yes
4	Compare conventional system with urine separation	From households to treatment and final disposal or spreading	No
5	Compare sludge processes and disposal (more or less centralised)	A WWTP incl. sludge treatment	No
6	Compare small-scale WWTPs	Construction, operation and demolition of a WWTP	Yes
7,8	Compare conventional sludge handling options	From sludge generation to final disposal incl. incineration, landfill, energy recovery	No
9,10	Compare new sludge handling options	From sludge generation to final disposal incl. surrounding systems	No
11	Compare sludge reuse strategies	From sludge separation to application on agricultural land	No
12	Compare conventional treatment methods	A WWTP incl. sludge treatment	Yes
13	Compare conventional treatment methods	From receiving chamber to effluent	No
14	Evaluate the consequences of changing existing wastewater systems	A wastewater system incl. drinking water, district heating and fertiliser production	Yes

1 Ashley et al., 1997
2 Bengtsson et al., 1997,
3 Paper II
4 Dalemo et al., 1997
5 Dennison et al., 1998
6 Emmerson et al., 1995
7 Friedrich, 2001
8 Johnsen and Pretlove, 1999
9 Houillon, 2001
10 Houillon and Jolliet, 2002
11 Neumayr et al., 1997
12 Ødegaard, 1995
13 Roeleveld et al., 1997
14 Tillman et al., 1998

As the table shows, most studies are made on the level of a wastewater treatment plant (WWTP) or processes within the plants. There are also a number of studies that deal with the handling of sewage sludge after the WWTP. Since different LCA studies on urban water systems have used different assumptions concerning functional and geographical boundaries, inventory parameters, functional units and impact assessment methods (LCIA) it is difficult to draw any general conclusions. Often scientific publications are based on more detailed reports that are not publicly available or even confidential and the degree of transparency is often limited. However, a similarity between most of the LCA studies on wastewater systems is that energy is an important issue (*e.g.* Friedrich, 2001; Houillon, 2001, Neumayr *et al.*, 1997; Tillman *et al.*, 1998; Johnsen and Pretlove, 1999; Suh and Rousseaux, 2002), as are the emissions of nutrients and heavy metals (Friedrich, 2001; Houillon, 2001). Most authors agree that it is difficult to evaluate health and environmental effects for heavy metals, while certain metals as most significant.

3.2 LCA of alternative wastewater systems (Paper II)

In recent years and following the increasing interest for sustainable wastewater systems, several studies of the environmental performance of alternative systems that enable nutrient recovery have been carried out (Tillman *et al.*, 1998; Sonesson *et al.*, 2000). In the case study presented in paper II, LCA methodology was used to compare the environmental loads from wastewater systems with different technical solutions of different scales. The project has also been presented in detail in a technical report (Bengtsson *et al.*, 1997). The study compared proposed conventional wastewater systems with separation systems; one in which urine is handled separately and one in which black water is treated in a liquid composting process. The boundaries of the wastewater system model were expanded to include the avoided production of agricultural fertilisers through the recovery of nutrients from the wastewater.

It was found that the two separation systems, outperformed the conventional systems through lower emissions to water and a more efficient recycling of nutrients to agriculture, especially of nitrogen, but also of phosphorus. This implies that the use of such systems could significantly reduce the need for, and hence the production of, fertilisers and thus reduce the overall use of energy and phosphate minerals. Furthermore, large economies of scale could be gained both for the operation and for the construction phase. The combination of large-scale wastewater treatment and urine separation was found to be advantageous.

These findings are in agreement with other studies on separation systems. The Swedish substance-flow simulation model (ORWARE) has been developed for modelling different systems for handling organic waste (Dalemo *et al*., 1997). The ORWARE model has been used to assess the environmental consequences of different systems of handling biodegradable waste and sewage including one system in which urine is handled separately using urine separation toilets (Sonesson *et al.*, 2000). The results were evaluated using methodology from LCA. Urine separation was found to have great advantages in its low impact on the environment.

Gujer (1996) did not use a standardised LCA but a life cycle approach to compare urine separation and compost toilets with conventional technology and included important aspects such as pollutant loading, electricity consumption and energy use, material and chemical requirement. Urine separation proved to have merits over conventional technology.

An extensive LCA study of alternative wastewater systems was carried out by Tillman *et al.* (1998). The assessment focused on the consequences of a change in the existing wastewater systems in two Swedish municipalities, and included an analysis of the environmental load of both the construction and the operation of the systems. Two alternatives were compared to the existing conventional systems; a local treatment in sand filter beds and a urine separation system. Changes in the wastewater system that might affect surrounding technical systems were approached through system expansion. Again, urine separation was assessed as preferable to the existing, conventional option.

One conclusion that was drawn in paper II is that scale should not be mixed up with technology. Separation technologies have many positive features but are often thought of as small-scale inefficient solutions. If scale and type of technology are not kept separate, the discussion will be confused and misleading. The results from the LCA study showed that a urine separation system combined with conventional treatment of faeces and grey water in fact uses less energy than if all wastewater would be treated conventionally, even though the benefits from the nutrient recycling were not taken into account.

3.3 LCA of sludge handling options (paper III)

Recovery of nutrients, especially phosphorus, is attracting an increasing concern, which has led to the development of alternative sludge handling technologies. The handling of sewage sludge is an urgent concern for the municipalities in Sweden since the two most common options (agricultural use and landfill) are becoming less and less feasible. Farmers are reluctant to spread sludge due to reports of sludge containing undesirable substances and recent legislation restricts and will finally ban, the deposition of organic waste to landfill. New approaches to sludge management need to be considered.

In order to provide information for decision-makers the environmental and economic consequences of four recycling and disposal options for municipal sewage sludge were assessed. The four options were: agricultural use, co-incineration with waste, incineration combined with phosphorus recovery (Bio-Con) and fractionation including phosphorus recovery (Cambi-KREPRO). The results are presented in detail in two reports (Pettersson, 2001; Zetterlund, 2001) and the most important findings are presented in paper IV.

Agricultural use implies that phosphorus, nitrogen and other substances of agricultural value contained in sludge are recycled as soil improvers and can thereby replace conventional fertilisers in agricultural production. Nevertheless, agricultural use is increasingly regarded as insecure as sludge also contains heavy metals, pathogens and organic pollutants that can be transmitted to plants, livestock and humans (Spinosa and

Veslind, 2001). A possible future option is incineration of sludge. In the process where sludge is co-incinerated with waste, the energy content in the sludge can be recovered to generate district heating and electricity, but the nutrients in the sludge are lost due to the contamination from the other waste. Bio-Con and Cambi-KREPRO are two recently developed technologies at the stage of being introduced in Sweden, but their function needs to be further evaluated as well as their environmental impacts and costs (Hultman *et al.*, 2001). Both systems use sulphuric acid to dissolve phosphorus that can be recovered and used as fertiliser. They require substantial amounts of chemicals but on the other hand not only phosphorus but also other compounds such as heavy metals can be removed and taken care of separately.

LCA was used to assess the environmental consequences of the four options. Sludge transport, incineration, spreading, phosphorus processing, and production of chemicals and electricity were within the system boundaries of this study (paper IV). In those options where products can be recovered (fertiliser, chemicals, electricity and heat), these were assumed to replace alternative production of these products. Since three of the four options generate relatively large amounts of district heating, the effects in the district heating system of Göteborg were analysed using the energy system model MARTES (Josefsson *et al.*, 1993). Only impacts imposed by the operation of sludge handling were modelled and not the impacts imposed from the construction of the facilities. Organic pollutants and pathogens were not included, nor was leakage of metals and other environmental effects that originate from disposal of ashes on landfills.

LCIA pointed to energy use, phosphorus depletion and emissions of heavy metals as the three most important environmental aspects of sludge handling. Co-incineration had the best energy balance, but no recovery of phosphorus. In the Bio-Con and Cambi-KREPRO processes both phosphorus and energy could be recovered. Compared to Cambi-KREPRO, Bio-Con was more effective in most respects, but suffered from higher emissions to air. Spreading sludge on agricultural land was the least preferable option from an environmental point of view. Energy was required for transportation, spreading and pasteurisation of the sludge, whereas the other three options enabled energy recovery. Spreading also caused emissions of eutrophication and acidifying substances and transferred the content of heavy metals in the sludge to agricultural soil.

The costs were analysed from a municipal perspective, *i.e.* only the financial costs for the municipality were analysed. In general, the system boundaries were the same for the economic assessment as for the LCA but included both capital and operational costs. The economic assessment showed that agricultural application had the lowest cost of the options, whereas co-incineration had the highest cost. The difference in cost between Bio-Con and Cambi-KREPRO was small, but since the technologies are new and untried in a commercial context, these results are uncertain.

No attempt was made to combine environmental effects and costs but in conclusion the study showed that two sludge handling options, incineration and direct application to agricultural soil, have respectively economic and environmental restrictions. The development of relatively low cost phosphorus recovery technologies has the potential to reconcile the environmental and economic aspects of sustainability even though technologies such as Bio-Con and Cambi-KREPRO must be further improved and tested and become more efficient in order to achieve a future sustainable sludge management.

3.4 Methodological issues on LCA and urban water systems

3.4.1 System boundaries

In figure 3.1, a selection of LCA studies within urban water systems is presented. As the figure shows, very different choices can be made for system boundaries.

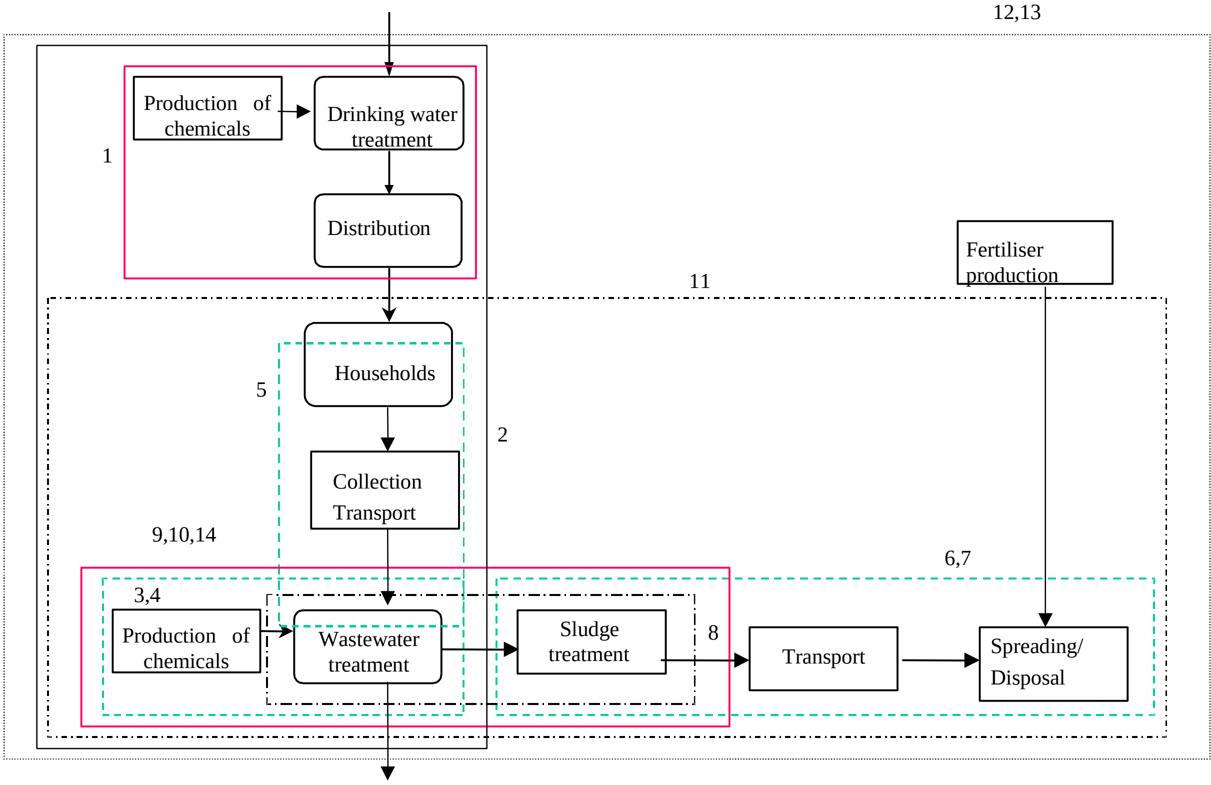

Figure 3-1 System boundaries used in LCA studies of urban systems (paper II).

1 van Tilburg *et al.*, 1997
2 Crettaz *et al.*, 1999
3 Roeleveld *et al.*, 1997
4 Emmerson *et al.*, 1995
5 Ashley *et al.*, 1997
6 Matsuhashi *et al.*, 1997
7 Neumayr *et al.*, 1997
8 Mels *et al.*, 1999
9 Ødegaard, 1995
10 Dennison *et al.*, 1998
11 Dalemo *et al.*, 1997
12 Tillman *et al.*, 1998
13 Bengtsson *et al.*, 1997 and Paper I
14 Grabski *et al.*, 1996

When carrying out an LCA the choice of boundaries for the system under study has been shown to be very important (paper II). Ideally, all the inputs and outputs necessary to the function of the process should be followed upstream and downstream to flows of energy and matter (Tillman, 1994) but this would result in a complicated analysis. Delimitation of the technical system must be decided on. The system boundaries should be chosen according to the purpose of the study (Tillman, 1994; ISO 14041, 1998). If the purpose is to compare a biological and a chemical unit process, the production of chemicals and energy should be included as well as sludge treatment since it is likely that these activities will be affected. However, the collection and transport of wastewater should be the same for the alternatives and could therefore be excluded. On the other hand, if the purpose is to evaluate new, alternative wastewater systems that implies effects on water use, energy use, recovery of nutrients *etc.* system boundaries must include these surrounding systems.

One of the objectives in paper II was to illustrate the effects of extended system boundaries. Since the purpose of the separation system is to keep valuable flows separated, in order to recycle nutrients, the use of mineral fertilisers can be decreased. If system boundaries exclude fertiliser production this would favour existing technologies and systems since the positive features of new solutions is not taken into account and such narrow boundaries will make the introduction of new system solutions difficult. In paper II it was concluded that the advantages with the separation systems appeared when the model of the wastewater system included the production of mineral fertiliser.

The question whether to include capital goods also needs to be addressed. Most LCA studies on urban water systems only include the operation of the technical system studied and exclude the environmental load of the construction phase (Table 3.1). Consequently, questions related to the scale and longevity of the systems are overlooked. Although LCA studies of long-lived technical systems have showed that the environmental impact from the construction phase often is small compared to the operation (Cowell, 1998; Tillman *et al.*, 1998), it was found that the environmental impact of the construction of small-scale systems contribute a great deal to the total load (paper II). Hence, economies of scale can be gained both for the operation and the construction of the wastewater systems.

In paper IV the environmental impact from the construction of the sludge handling options was not included. This delimitation does not favour agricultural spreading since this option requires less changes and investments in existing infrastructure than the other options. An assessment of the construction would give a more complete picture but this was not possible at this stage.

3.4.2 Life cycle impact assessment

A difficulty with LCA is how to analyse and assess the hundreds of substances (emissions and use of natural resources) that are identified in the inventory. The aim of LCIA is to describe the environmental consequences of the inventory results. The LCIA can be divided in four different steps; classification into impact categories, characterisation within these categories, normalisation of the category indicator in relation to the total impact in a given area (*e.g.* a country), and subsequently a weighting of different environmental impacts against each other (ISO 14042, 2000).

In paper IV all four steps within LCIA were taken in order to evaluate the different sludge handling options. Characterisation is well developed for common environmental impact categories such as acidification, eutrophication and global warming potential. However, there is a scientific uncertainty in calculating some impacts *e.g.* human toxicity and ecotoxicity as well as depletion of certain resources such as phosphorus. It was therefore difficult to make a fair comparison of the sludge handling options for certain environmental impacts.

Another finding of paper IV was that if only using characterisation, there is a risk that one technical option's contribution to a certain impact category seems to be very large compared to the other options, but in comparison with the total environmental impact in a region the contribution may be small.

An alternative approach to prioritising different environmental aspects is to use normalisation. In paper IV, the inventory results were normalised by relating specific emissions and resources to the total amount emitted or used in Sweden per person over one year (Kärrman and Jönsson, 2001). In this way the relative magnitude of the impact from a specific sector in an area can be assessed and it was also possible to consider selected heavy metals. In paper IV agricultural application contributed to a higher degree to acidification and eutrophication than the other options, but related to the total impact in Sweden the contribution was less than 0.5%. Instead, the results from the normalisation were that phosphorus recycling to agriculture is an important issue, as well as emissions of certain heavy metals.

The two weighting methods used in paper IV; EPS and ET-long (Baumann and Rydberg, 1994; Steen, 1999) were found to complement each other. EPS weights resource depletion heavier but lacks certain emissions to ground. ET-long weights emissions heavier than resources but excludes the depletion of certain resources such as phosphorus. Since the methods weight the results differently, the options were ranked differently. Using EPS, the Bio-Con system was most preferable, whereas with ET-long, co-incineration ranked highest. Spreading sludge on agricultural land was the least preferable option using both methods. However, in both papers II and IV, the weighting methods were not preliminary used to rank the different options, but as an aid to find the most important impacts and benefits.

LCIA is an area still under development. There are limitations in currently available methodologies for some impact categories and there is no consensus on whether any of the weighting methods are superior. A satisfactory procedure for including aspects of toxicity, water use and phosphorus depletion is missing and these aspects are therefore seldom considered. Even if LCA should, in principal be able to handle toxicity issues, there are several difficulties; available data is limited, knowledge of toxicological effects of substances is limited and often the effects depend on site-specific circumstances. In addition investigations and more sophisticated analytical methods continuously find new substances, generated by chemical use in the society, which may have a negative impact on the environment and human health. Other methods such as risk assessment or substance flow analysis may be more suitable for assessing such impacts.

3.4.3 Energy system modelling

One limitation with most LCA studies on urban water systems is how the interaction with the energy system is modelled. The usual approach is to not include the energy system at all, or to simplify the modelling by using average data on electricity and district heating production. However, using average data often means a large simplification of how the energy system is affected. Since the issue of energy is important it is reasonable to make a more thorough analysis of the consequences using an energy system model. In paper IV, an energy system model, MARTES, was used to model the replacement of alternative energy sources for producing district heating, when the sludge was incinerated. The choice of using the energy system model proved to be important since it had a large impact on what kind of fuels that were replaced. In paper IV, the quality of the results was improved by the use of district heating system model instead of the assumption that average district heating production was replaced.

3.5 Conclusions

Even though LCA has been mostly applied to comparison and development of products, it has now gained wide acceptance for use in the evaluation of processes, such as the provision of water services. Methodological experience has been gained on how to choose system boundaries, what parameters to focus on and how different impact assessment methods can be used to understand and evaluate the magnitude and significance of the potential environmental impacts. The LCA method was found to be applicable for assessing the environmental sustainability of urban water systems, or at least to compare relative sustainability of different solutions. Case studies have provided valuable hands-on experience of the use of LCA in water systems. However, LCA studies need to be complemented with other tools to address important factors such as costs and local circumstances including land use, public acceptance and regulatory constraints. These complementary tools are available and could be applied when constructing SIs for urban water systems taking into consideration the findings from these LCA investigations.

4 CONSTRUCTING SUSTAINABILITY INDICATORS FOR THE WATER SECTOR

In 1996 when this project started, several studies concerning SIs were in progress but few studies had focused on the corporate level or had any connection to the urban water system. In 1997, a first set of environmental sustainable indicators (ESIs) was formulated based on literature studies and discussions with representatives from the water industry (Lundin *et al.*, 1997). The ESIs were hence selected within traditional water resources and process boundaries and without a specific procedure or framework. The set of ESIs was applied in case studies in Göteborg, Sweden and King William's Town, South Africa (Paper I and Zinn, 2000).

One of the findings from the case studies was that a more stringent procedure is required to identify appropriate ESIs. LCA studies on wastewater systems also demonstrated that the choice of system boundaries is crucial to the identification of important aspects for promoting action towards sustainability objectives (paper II). An LCA-based iterative procedure for selecting ESIs was proposed (paper III). A third case study was initiated in co-operation with the Stockholm Water Company, with the aim of applying, evaluating and further developing the proposed procedure (paper V). This study was not limited to environmental sustainability but also covered economic and social aspects. This section describes the iterative procedure and the case studies.

4.1 An iterative procedure for selecting environmental sustainability indicators

4.1.1 Specify overall purpose of indicators use

The iterative procedure is presented in Figure 4.1. The starting point is to specify the purpose of the sustainability assessment and the intended use of the ESIs. The primary aim for most indicator projects in companies is to collect information for internal decision-making. Decisions concerning urban water systems can include the evaluation and comparison of different processes, *e.g.* chemical and biological treatment methods. Another example may be that a water company wants to monitor trends in order to assess how the company can work strategically in their contribution towards sustainability, or to communicate performance to an external audience (communities, consumers and other interest groups). An additional use is for benchmarking purposes. This usually involves a comparison with different companies or organisations providing the same services. Indicators cannot be developed to meet all these objectives and therefore it is important to specify the purpose and the user of the information (Braat, 1991). Tailored sets of indicators can thus be used for different groups with varied information needs. For reporting purposes it is important that the indicators are able to assess conditions and trends, preferably in relation to goals and targets. For benchmarking use, standardised and comparable measures are needed.

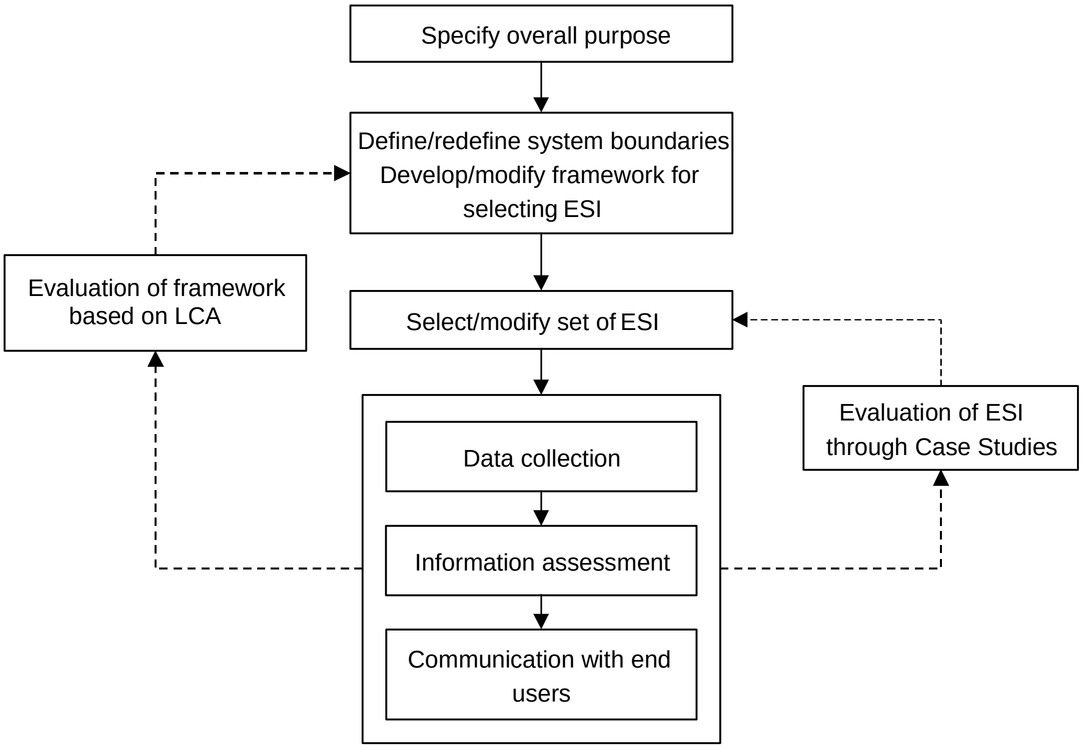

Figure 4-1 Iterative procedure for constructing environmental sustainability indicators (ESIs) to assess the sustainability of urban water systems (paper III).

4.1.2 System boundaries and frameworks

The next step in the iterative procedure is to define system boundaries and develop a framework for ESI selection (Figure 4.1). This step includes choices of which processes and issues to consider, as well as how to handle temporal and geographical dimensions. The choice of system boundaries is essential for sustainability and environmental assessments (paper II; Tillman, 1994; Lundqvist, 2000). Different types of system boundaries have been proposed for SIs, the majority for regional assessments. For a company managing urban water systems, regional boundaries are usually not applicable.

Templates for different SI frameworks have been suggested (see chapter 2). These were found to be less applicable for a company or organisation, where a more practical and systematic approach is needed. Recently a number of approaches for SI selection have been developed for use at a corporate level (Spangenberg and Bonniot, 1998; Bennet and James, 1999; Callens and Tyteca, 1999; GRI, 1999; Tyteca, 1999; GRI, 2000), although few recognise the importance of life cycle considerations (Fiksel *et al.*, 1999; Azapagic and Perdan, 2000).

In paper III, we suggest a framework for ESI selection based on LCA. Since LCA focuses early in the causal chain and can consider all significant impacts (or benefits) that take place throughout the life cycle, such an approach can guide the selection of

ESIs by revealing the most significant environmental loads and identify ‘hot spots’ in the systems where the potential for improvement is high.

The choice of life cycle boundaries has been shown to have important implications on the results (paper II, Tillman, 1994) and needs to be carefully considered. The life cycle (or functional) boundaries define the unit processes to be included in the system *i.e.* where upstream and downstream cut-offs are set. For urban water systems three levels of system boundaries can be identified (Figure 4.2). Process defined boundaries (level 1a and b) are often selected when the aim of the study is to compare different processes. The results are of interest for the process engineer and reveal potential environmental benefits for the specific processes, but it is relatively restricted for assessing the environmental sustainability of an urban water system.

The second level of system boundary is often defined by the management/organisation (level 2). Such a company-oriented analysis can be used to track improvements over time and for benchmarking purposes *e.g.* to compare urban water systems or companies. This provides a more complete view of the system but often separates drinking water from sewage and stormwater. The organisation is usually constrained by legislation rather than proactively seeking options that allow a move towards environmental sustainability. Such a perspective may limit the potential of the company to identify major environmental impacts or improvements through the life cycle.

At a third system boundary level, both urban water systems and surrounding systems interact. Energy supply, fertiliser production and agriculture, are included and upstream and downstream actors such as suppliers, consumers and waste handling companies, are considered.

4.1.3 Selection of environmental sustainability indicators

When the purpose has been defined and a framework agreed on, appropriate ESIs can be selected from case studies, literature reviews and existing indicators already in use within the organisation (Figure 4.1). The use of a functional unit (such as treatment of a certain amount of water) enables comparisons. Several criteria for the selection of environmental indicators and SIs have been presented in previous publications (*e.g.* Liverman *et al.*, 1988; Braat, 1991; Gilbert, 1996; Harger and Meyer, 1996). These include long lists of criteria that the indicators should fulfil; *e.g.* relevance, sensitivity, appropriateness, representativeness, cost-effectiveness, measurability, data availability, understandability and data comparability.

A core set of criteria can be identified and can guide the SI selection. SIs should ideally:

- Be relevant for the indicator users and for Sustainable Development
- Be simple to allow understanding, interpretation and presentation
- Rely on data that is reliable and relatively easy to collect
- Be predictive (do they provide an early warning?)
- Be possible to relate to reference values or targets

The overriding criterion is relevance to Sustainable Development. An acceptable definition or at least a common understanding on what issues should be included is required. Another criterion that is less cited, but may nevertheless be of importance, is whether the SI, or the whole set of SIs, links different aspects of Sustainable Development.

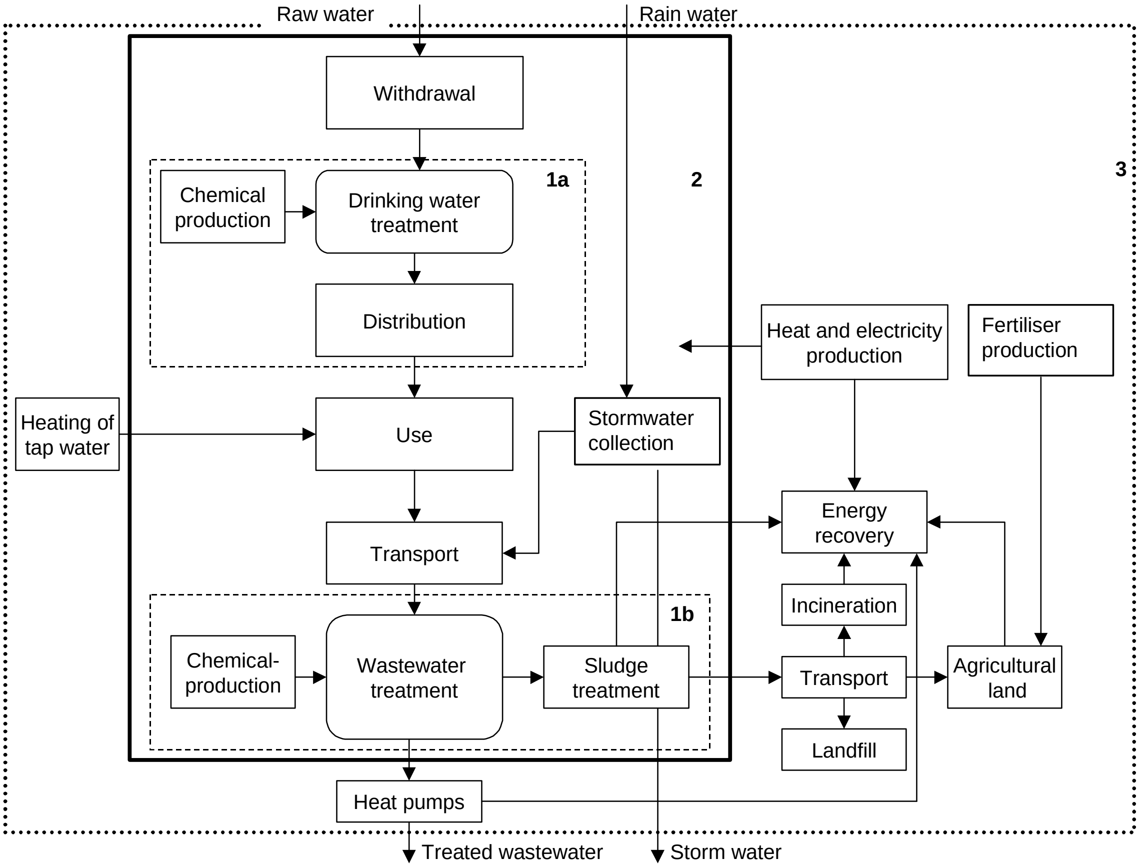

Figure 4-2 Overview of system boundaries for assessing sustainability of urban water systems. Level 1: process-defined, level 2: company-defined, level 3: extended including surrounding systems (paper III).

4.1.4 Information collection and assessment

After selecting ESIs, information can be collected for the assessment (Figure 4.1). If the study is retrospective (*e.g.* monitoring past actions), information collection should extend to several years, or as long as information is available. In this case the variations in the indicators over time can be used to assess progress of systems towards or away from environmental sustainability. If the study is prospective (for making choices with regard to predicted consequences) data must be collected from different suppliers or found elsewhere *e.g.* through LCA modelling.

4.1.5 Evaluation of indicators and framework

After information assessment (Figure 4.1) the ESIs can be evaluated against the desirable characteristics (see 4.1.3). The final step of the iterative procedure is to evaluate the framework in order to improve and modify ESIs after new insight has been gained. In the evaluation it is essential to bring in the ESI users in order to address the most important aspects considered by the intended end users.

4.2 Case studies on evaluating environmental sustainability of urban water systems

Two case studies were performed, (paper I and Zinn, 2000) during this time the iterative procedure was developed. The primary objective was to investigate temporal variations and to assess the current situation, with regard to environmental sustainability. A second objective was to evaluate the ESIs in a developed and a developing region.

The framework initially used was relatively straightforward. The urban water system was divided into four environmental and technical systems following the life cycle of urban water management:

(1) Extraction of freshwater

(2) Production, distribution and use of drinking water

(3) Collection and treatment of wastewater

(4) Handling of by-products such as sludge, biogas and heat

For each system ESIs were formulated for environmental performance and pressure on the environment, such as chemical and energy use, treatment efficiency, discharge to aquatic ecosystems and recycling of nutrients (Lundin, 1997). Table 4.1 lists the ESIs assessed in the case studies.

4.2.1 Case study I: Göteborg, Sweden

In the first case study (paper I), the set of ESIs was applied to the urban water system in Göteborg. Göteborg is situated on the west coast of Sweden and is the second largest municipality in Sweden with a population of approximately 450 000 persons within an area of 450 km². Two municipal companies are responsible for water management. Göteborg Water and Sewage Works operates the water works and the pipe network for both water and wastewater. The Rya WWTP is operated by the Göteborg Regional Sewage Works. The WWTP receives wastewater from 573 000 inhabitants excluding industry. The system boundaries included the technical system for the production and distribution of drinking water, the treatment of wastewater and the handling of sewage sludge, as well as the freshwater resource and the receiving water. The time perspective was 20 to 25 years and information was collected from the early 1970's to the late 1990's.

4.2.2 Case study II: King William's Town, South Africa

The second case study was in the Eastern Cape Province, South Africa (Zinn, 2000). The study included the city of King William's Town and the previously independent municipalities of Breidbach and Ginsberg, with a total population of 35 500. The population has low income and is expected to grow at approximately 3% per year. Two freshwater reservoirs supply the areas with drinking water after treatment at the water purification works. The wastewater is led to one of two treatment plants. The system boundaries for the technical system were the same as for the Göteborg study. However, information was only available for the last three to five years.

Table 4-1 List of environmental sustainability indicators (ESI) assessed in the Göteborg and King William's Town case studies (paper I and III).

Dimension	ESI	Göteborg	King William's Town
Withdrawal	Annual freshwater/annual available volume	•	•
Water consumption	Use per capita and day	•	•
Treatment	Chemical and energy use for water supply	•	•
Distribution	Leakage (unaccounted water/produced water)	•	
Reuse of water	Reused water		•
Production	Wastewater production per day	•	•
Treatment performance	Removal of BOD, P and N	•	•
Loads to receiving water	Loads of BOD; P and N	•	•
Resource use	Chemical and energy use for wastewater treatment	•	•
Recycling of nutrients	Amount of P and N recycled	•	
Quality of sludge	Cadmium content in sludge	•	
Energy recovery	Energy recovered, heat and power	•	

4.2.3 Results from the two case studies

The initial set of ESIs used in the two case studies was within company defined boundaries (Figure 4.2, extension 2) and the indicators relate to the direct impact from the urban water systems. The information collected for the Göteborg study (mainly from environmental and annual reports) showed that extended time series of precise data were available for quantitative ESIs such as water consumption, energy use and discharge loadings. The majority of the ESIs indicate that the urban water system in Göteborg has moved towards a more sustainable status, but that recycling of nutrients to agriculture is limited (Figure 4.3).

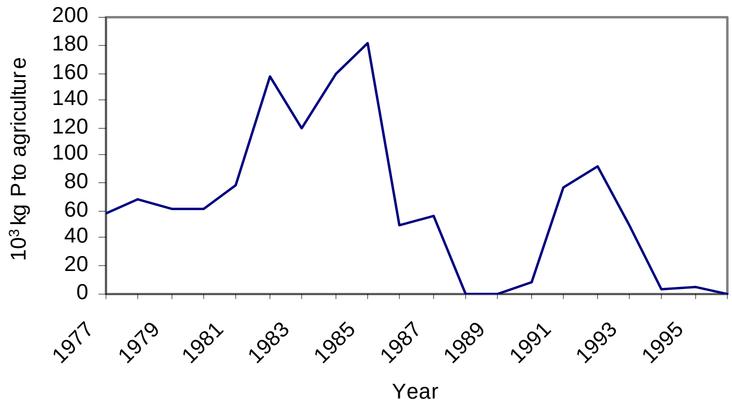

Figure 4-3 Amount of phosphorus from the Göteborg WWTP applied to agricultural land (paper III).

In King William's Town the situation is quite different from Göteborg. Freshwater withdrawal has passed acceptable levels (Figure 4.4), the treatment performance of the wastewater system is poor, and the receiving water, already threatened by eutrophication, is receiving increased nutrient loads. Even though the water use *per capita* has stabilised, the population is growing, increasing the pressure on water resources (Zinn, 2000). The indications are that the urban water system is currently moving from environmental sustainability.

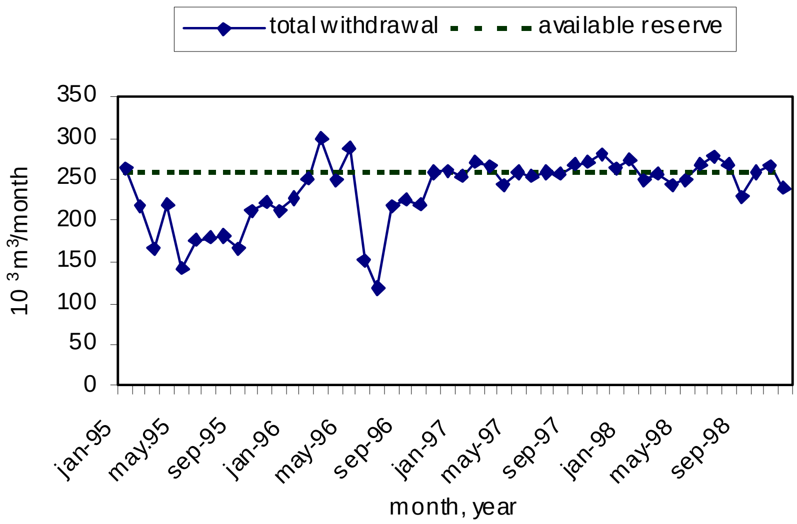

Figure 4-4 Total freshwater withdrawal and estimated monthly available reserve for King William's Town (paper III).

The ESIs were evaluated against characteristics such as their relevance to the environmental sustainability of the specific urban water system, their ability to predict potential problems and the availability and quality of information. As might be anticipated, the relative importance of the ESIs depends on local and regional factors. In the Eastern Cape Province of South Africa, where water is scarce, the specific water use and leakage are highly relevant in order to save water. In south-west Sweden, where water is relatively abundant, other ESIs are considered more important such as the heavy metal content in sewage sludge. The availability of information is superior in the Swedish case, annual environmental reports are compulsory. In the Eastern Cape, information is more difficult to find since several parameters are not measured regularly, which highlights the difficulty of assessment in a developing region. Among the largest difficulties encountered were the access to certain information (*e.g.* drinking water quality), the quality of the acquired information, such as treatment performance, and in some cases apparent lack of information (*e.g.* sewage sludge quality).

4.2.4 Levels of environmental sustainability

The results from the case studies were used to place the urban water systems into one of four levels of environmental sustainability (Paper III). It should be noted that these ideas are conceptual and the placement of urban water systems into levels of environment sustainability does not, as yet, follow a stringent scientific process.

At the lowest level the basic objective of ensuring human and environmental health is not met. Even if sewage systems exist, they are typically under dimensioned, include inadequate end-of-pipe treatment and are in a state of disrepair due to improper management (Varis and Somlyódy, 1997). At the next level, minimum standards for environmental protection and health objectives are met. At a higher level, the organisation meets consumer needs and the water services are often better than standards for environmental protection, but still focus on compliance issues and end-of-pipe solutions. At the highest level, the objectives of environmental and health protection are met, as well as requirements for an efficient use of resources and waste management including recycling of nutrients and water (paper III).

The Göteborg case study is subjectively placed within the second highest level of environmental sustainability, that is a legislated and economic system where the objective is to meet health and environmental goals. As an example nitrogen is removed in the WWTP to protect the coast from eutrophication but the recycling of nitrogen to agricultural land is restricted. The move to the highest level is hindered by existing infrastructure as well as organisational constraints. In King William's Town the organisations dealing with the urban water system are trying to keep up with population growth and are working under crisis conditions. If King William's Town is to leapfrog from the lowest level to the highest, appropriate and affordable alternatives will be required; technologies that save water, increase efficiency and enable the recycling of water, nutrients and organic matter.

4.3 The Stockholm Water case study

A third case study was conducted in co-operation with practitioners at the Stockholm Water Company, with the aim of applying, evaluating and further developing the procedure (paper V). This section describes how the iterative procedure (Figure 4.1) was implemented in this study and how the assessment was performed. The study was not limited to environmental sustainability but the intention was to include economic and social aspects through a participatory approach.

4.3.1 Implementation of the procedure

The Stockholm Water Company is the largest water company in Sweden. Its activities extend to the production and distribution of drinking water for over one million people and the handling and treatment of wastewater for 900 000 people. The company has a long tradition of environmental reporting and an ambition to contribute to the long-term Sustainable Development of society (Stockholm Water, 2002). The case study was initiated by forming a working group including representatives from the company and researchers from Environmental Systems Analysis (including the author of this thesis). In the preliminary meetings, the intended use of the SI project was discussed and led to the case study focusing on identifying SIs with special applicability for the choice of technical option for sludge handling, and also with a general bearing on the development of the entire wastewater system. Thus, the case study had to incorporate two different objectives as well as two different system levels of the SIs (Figure 4.5).

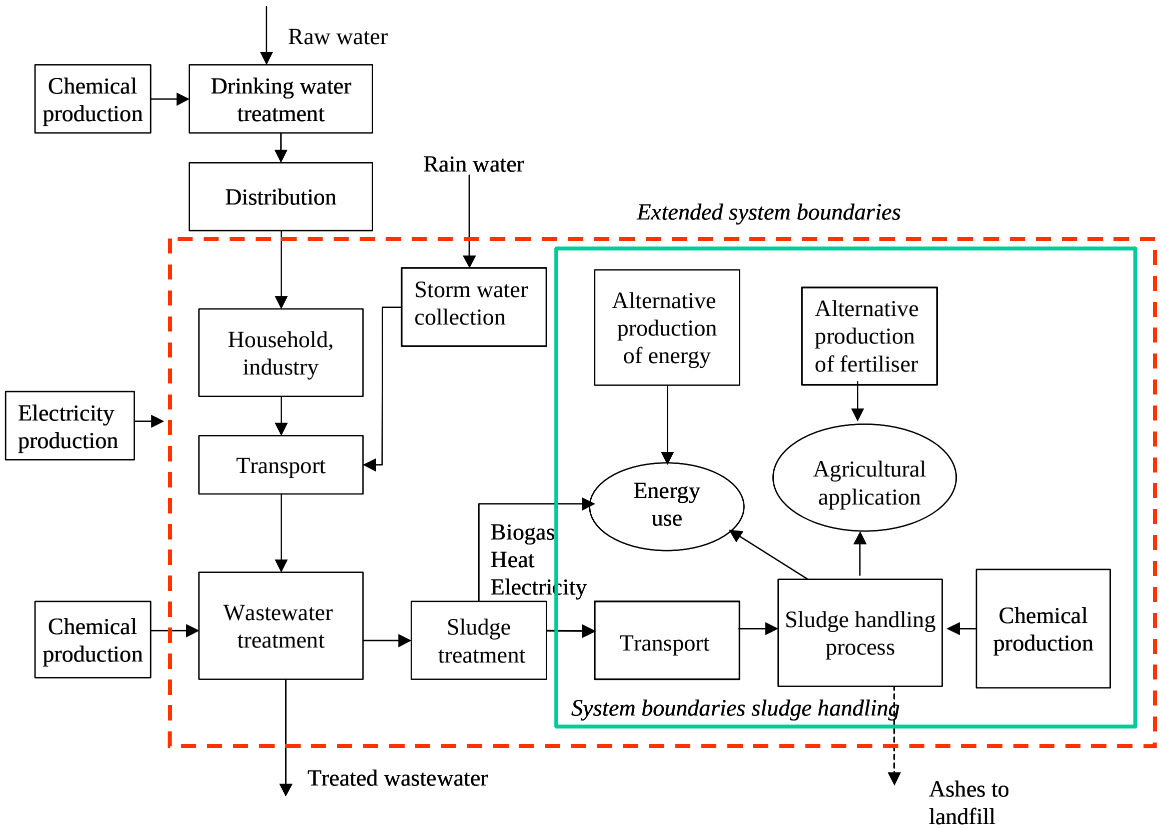

Figure 4-5 System boundaries for SI selection for sludge handling and extended boundaries for SI selection for the wastewater system.

Four sludge handling options were chosen for assessment in the study: spreading of pasteurised sludge on agricultural land, co-incineration with household waste, separate incineration with phosphorus recovery by the Bio-Con process and fractionation by hydrolysis and acidification for recovery of phosphorus with the Cambi-KREPRO process (paper V).

Discussions on the meaning of Sustainable Development were oriented towards the information required in order to assess the different technical options from different aspects. From these prerequisites, a process for the case study was worked out starting from the iterative procedure in Figure 4.1. The process is based on a number of assessment tools including LCA, economic assessment, risk assessment and uncertainty assessment (Figure 4.6).

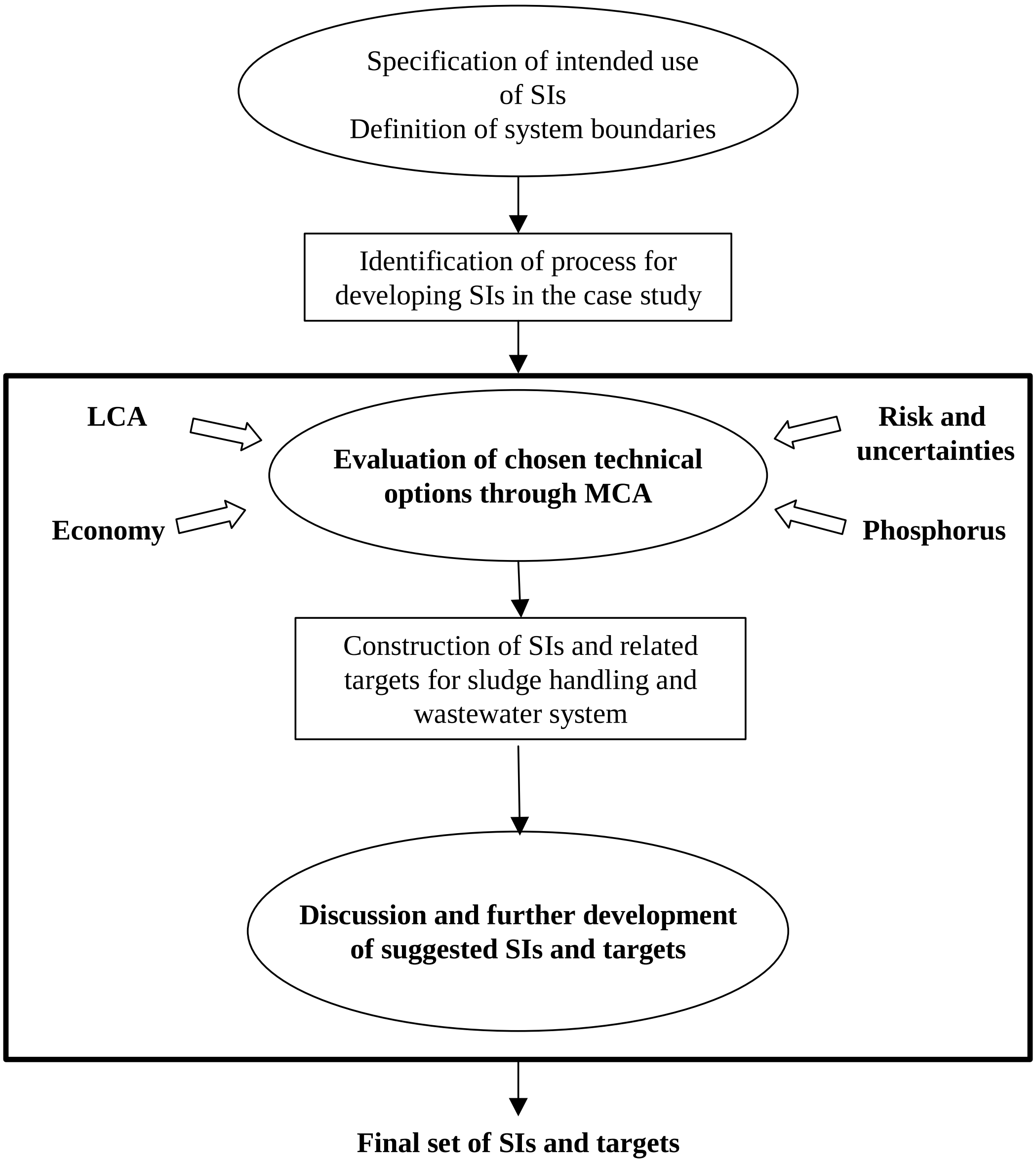

Figure 4-6 Process applied in the Stockholm Water case study (paper V)

4.3.2 Multi criteria analysis

To proceed from the assessment results of the four sludge handling options to a set of SIs, a multi-criteria analysis (MCA) was performed as a means of assessing the results and pinpointing what criteria were considered and why. The chosen process was largely in accordance with Stirling and Mayer (1997). A number of criteria for evaluating the different sludge handling options were selected by guidance of the results from the assessment tools and after discussions with representatives of Stockholm Water. The criteria finally used were economy, resources, energy, emissions to air, emissions to soil, acceptance, reliability of service, working environment and hygiene. After selecting the criteria, the MCA procedure was performed in which the different criteria were weighted related to each other and the four sludge handling options ranked.

The ranking of technical options in the MCA was not considered of prime importance for the selection of SIs, but rather the arguments for making that choice. On this basis two sets of preliminary SIs and sustainability targets were suggested, including one subset applied to sludge handling and one subset, developed theoretically, to apply to the entire wastewater system. These preliminary sets of SIs and targets were evaluated and revised during two subsequent meetings with Stockholm Water before the final SIs were approved (presented in paper V).

4.4 Conclusion on sustainability indicators for the water sector

In this section an LCA based, iterative procedure for selecting ESIs was presented. The methodology was developed in two contrasting case studies of urban water systems in Sweden and South Africa. The results from the case studies demonstrated that the ESIs were useful for assessing environmental sustainability over time. The empirical results helped to reveal information gaps and problems concerning availability and quality of information and emphasised the importance of including site-specific issues.

In these two case studies, involvement of the indicator users was limited and the objective retrospective, *i.e.* to assess sustainability over time. In contrast, the Stockholm Water case study was prospective, focused on technology options. In addition, this study was not limited to environmental sustainability. Another important alteration was the idea of first collecting information, using a life cycle perspective on all aspects of Sustainable Development, and then selecting SIs on the basis of that information. This was to reduce the risk of overlooking important facts. The case study was carried out in continuous dialogue with the SI users, from the problem definition to the final evaluation of the SIs. The participation of Stockholm Water in the entire process ensured that SIs reflecting technical and social criteria of a qualitative nature were considered, whereas the results from the assessment tools provided more quantitative decision support. The process thus combined expert-based and user-based knowledge and enabled a comprehensive set of quantitative and qualitative SIs.

5 CONCLUDING REMARKS

There is an increasing awareness of the need for methods that describe the economic, social and environmental dimensions of Sustainable Development. This thesis provides an overview of selected approaches that support the assessment of sustainability of urban water systems. The emphasis here has been on the environmental dimension and two different tools, LCA and ESIs, although economic and social dimensions were also considered at a later stage.

Decision-makers within and outside an organisation require meaningful information that can help to identify the effects their decisions imply. There are several reasons for using SIs including:

- long term monitoring in order to assess progress over time
- measuring progress towards sustainability objectives
- providing benchmarking information, *e.g.* to allow comparison between different processes, companies or geographical regions

The thesis addresses the need to establish SIs that are carefully chosen and suitable for the purpose that they are intended to measure. If the SIs are poorly chosen and unrepresentative for the system, there is a risk that the sustainability assessment is misleading and even counterproductive (Mitchell, 1996). Therefore a methodology and an analytical framework are required to identify appropriate SIs in a more rational way than earlier attempts. In such a methodology it is important to clearly define the purpose of the assessment and identify the type of information and the level of detail that is needed.

The first approach to develop ESIs for urban water systems were made without any specific procedure with a division of ESIs within traditional water resources and process boundaries. In order to develop a robust framework, an iterative ESI selection procedure based on LCA was proposed. LCA can guide the selection of ESIs by finding the parameters that are most disturbing or typical for the examined sector or product group. LCIA can be helpful in ESI selection. Several groups have applied LCA to assess environment aspects of urban water systems. Each LCA study has a meaning in identifying ESIs for urban water systems but as in all systems analytical methods the choice of system boundaries and inventory parameters will affect the results. Therefore, it is important to know which choices have been made and what has been excluded in different studies. It is also important to understand how the LCIA was done and how the results have been interpreted. The life cycle approach is important at a corporate level since major environmental impacts occur in upstream and downstream processes.

SIs should be selected not only by researchers or experts (top-down) but should rather involve SI users and any audience to whom they are relevant which call for more participatory processes. However, even though such bottom-up approaches are often considered important in the sustainability literature, they can be difficult to apply in practice, since the process is time and resource consuming. Table 5.1 summarises some of the strengths and weaknesses of the different approaches.

Table 5-1 Characteristics of different approaches to SI selection.

Approach	Strengths	Weaknesses
Bottom-up, participatory, involve different stakeholders	Multiple views can provide a comprehensive picture. Common interests or conflicts can be identified and communicated. Involvement = engagement. Local details /specific issues can be captured. In agreement with Agenda 21. Project legitimacy / credibility.	May lack a consistent structure. Time-consuming and costly. Require strong facilitation skills. Less control. Important global issues may be missed.
Top-down, driven by experts and researchers	Provides a more scientifically valid set of SIs. Promotes comparability. More control.	Lacks a sense of local priorities.
Mixed *e.g.* experts develop a framework and stakeholders priorities issues and SIs.	Can combine the strengths of the two approaches. May provide a core set of scientifically valid SIs supplemented by local issues.	Stakeholder involvement may become too strong or weak.

A combination of the two approaches can be the optimal solution, for example experts might suggest a framework to provide a scientifically valid basis for selection, while stakeholders may participate in the selection process. This approach was developed and tested in a case study in paper V. Such an approach is likely to produce SIs that are more comparable and scientifically valid. Hereby, one can agree on a set of SIs that enables meaningful comparisons across products, facilities, companies and countries, without losing specific issues of local interest. The SIs that are selected need to be evaluated and modified to suit new technology and new knowledge. A carefully selected set of SIs, covering different sustainability aspects, can when inspired by the life cycle approach provide the whole system approach necessary to support actions required for sustainability.

5.1 Further research

This research has contributed to the development of methods for assessing the sustainability of urban water systems. The use of LCA in the environmental assessment of wastewater systems have been investigated, as well as an LCA approach for selecting SIs for urban water systems. Some suggestions for further research that might be carried out in the near future are summarised below:

- Compare different strategies for the development of sustainable urban water systems. In this thesis source separation systems such as urine separation and end-of-pipe technologies for sludge handling were investigated. These different strategies would be interesting to compare from an environmental and economic point of view. In order to make a fair comparison, the construction of the different options needs to be considered. Also the possibility to invest in flexible technology for some improvement towards sustainability in the short term, without hindering the introduction of new technology in the long term is of interest to investigate.
- A challenge when constructing SIs for corporate use is to link long-term and global aspects of sustainability to the decision domain of the company. In addition, SIs should be able to integrate or at least consider different dimensions of sustainability. An important question is whether the indicators selected in this research are really indicators of sustainable development or just straightforward indicators of economy and energy use?
- The practical use of SIs within organisations also needs to be further studied. In this research the cooperation with Stockholm Water led to a suggestion of a set of SIs, but the application of these in the assessment of the different technical options were not investigated. In addition the organisation asked for another SI use - management by objectives. This second objective was not thoroughly assessed and should be studied in more detail.
- For further improvement of the SIs, methods such as MCA need to be developed in order to analyse and weight different dimensions of sustainability. In particular, the more qualitative criteria and SIs *e.g.* those relating to acceptability, working conditions and technical aspects need to be more thoroughly investigated.
- The issue of setting sustainability targets is an important but difficult task. In most cases in assessing sustainability no targets can be scientifically set and in several of the current indicator programmes no reference values are reported. Who should decide what targets are appropriate and what short and long term targets are needed in order to move towards sustainable development?

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