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A framework for systems analysis of sustainable urban water management

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Abstract

The increasing demand for sustainable development will have a profound impact on all types of urban infrastructures. However, there is a lack of knowledge of how sustainable development should be attained and how sustainability of various technical systems should be assessed. This paper describes the framework of a systems analysis project dealing with the above issues, which focuses on urban water and wastewater systems. The project is part of large national research program in Sweden entitled "Sustainable Urban Water Management." A set of sustainability criteria—covering health and hygiene, social and cultural aspects, environmental aspects, economy and technical considerations—are defined. To promote the practical use of a set of sustainability criteria it must be concise and related to quantifiable indicators that are easily measured. This paper suggests suitable indicators for the proposed criteria. It also contains a brief analysis of the contribution to various environmental effects and resource utilization of the Swedish urban water system in relation to the impact of Swedish society in total, to allow for a correct prioritization of the criteria. © 2000 Elsevier Science Inc. All rights reserved.

Keywords: Systems analysis; Sustainable urban water management; Sustainability criteria; Criteria prioritization

1. Introduction

Urban water and wastewater systems should—without harming the environment—provide clean water for a variety of uses, remove wastewater from users to prevent unhygienic conditions, and remove storm water to

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avoid damage from flooding. Existing urban water systems in Sweden fulfil these fundamental requirements to a high degree. Over the last 10 years, however, the existing systems have been increasingly criticized from the viewpoint of sustainability. Similar discussions have also arisen within other sectors of the urban infrastructure, for example, power and transportation.

To improve and raise the knowledge with regard to sustainable water and wastewater management, the Swedish Foundation for Strategic Environmental Research (MISTRA) in 1999 initiated a 6-year Swedish research program entitled "Sustainable Urban Water Management" [14]. The vision of the program is defined as: "Every human being has a right to clean water. For urban areas, our vision is water management where water and its constituents can be safely used, reused and returned to nature." The main objectives for a sustainable urban water and wastewater system as well as for the majority of any urban infrastructure and, consequently, for the initiated research program can be summarized as: (a) moving towards a nontoxic environment; (b) improving health and hygiene; (c) saving human resources; (d) conserving natural resources; (e) saving financial resources.

A number of supplementary requirements for a sustainable urban water system have also been defined for the program. They state that the system should (a) have a high degree of functional robustness and flexibility, (b) be adapted to local conditions, and (c) be easy to understand and thus encourage responsible behavior by the users.

The systems analysis project within the program is carried out by a group of senior researchers. However, the complete research program covers both technical and integrated projects, which have been set up for PhD students (14 projects altogether). The technical projects deal primarily with: (1) drinking water—treatment and distribution; (2) storm water management; and (3) wastewater and sludge—recovery of products. The integrated projects focus on: (1) social-economical aspects, (2) hygienic aspects, (3) risk assessment and communication technologies, and (4) use of products from the urban water system.

The systems analysis is the core of the program, aiming at synthesizing results from the other research projects and analyzing results with respect to the overall visions and the goals of the program. The work procedure of the systems analysis involves studies of different combinations of model cities, system structures (technical systems) and scenarios (future events in society directly or indirectly affecting the water and wastewater systems). A more complete description of the systems analysis project is given in Jeppsson et al. [9].

The intention of this paper is to present the framework for a systems analysis of urban water management. The paper starts with a general description of the proposed work procedure of the systems analysis project. Furthermore, a set of operational sustainability criteria and their related indicators are suggested. The contribution to various environmental effects and resource utilization of the Swedish urban water system in relation to the impact of Swedish society in total is analyzed. The reason for this is to correctly prioritize which are the most important criteria for a sustainable development with regard to urban water management. Finally, a priority list of eight practical sustainability criteria/indicators is proposed.

2. Work procedure

A model city, together with a system structure, scenario, and system boundaries, are the components that define the total system to be analyzed and evaluated. A model city represents all aspects of a city that have an influence on the urban water system without actually defining the urban water system structure itself. Initially, five conceptual priority model city types, which cover the majority of the Swedish urban environment, have been selected: (1) a newly built urban area; (2) an old urban area in or near the city center; (3) a small town (<2000 inhabitants) surrounded by agricultural areas; (4) a densely populated urban area built during "the Million Program" (around 1970); and (5) a "pipeless" city (a possible vision for a future sustainable urban structure).

The conceptual model cities are then used in combination with physical cities, which have been selected to be as true representatives of the priority city types as possible.

A system structure represents the available systems for drinking water, storm water, and wastewater production/transportation/treatment, resources required and products produced in these processes. It may be either an existing type of system or a hypothetical new system. The principal system structures that are to be studied within this research program can be separated along three axes (applicable to drinking water, storm water, and sanitary wastewater): degree of centralization, degree of source separation, and system scale. It should be noted that the model cities and the system structures are modular building blocks defined so that they may be exchanged and recombined in any order. This approach will allow a wide range of different total system descriptions to be analyzed, i.e., several types of model cities may be combined to form one heterogeneous city with several different system structures for its water and wastewater management.

Scenarios—or surrounding factors—represent a framework of factors influencing a model city and a system structure over time, for example, water shortage, energy shortage, behavioral changes, and availability of economic resources. The definition of system boundaries includes the spatial dimension as well as the time scale of the evaluation. It is essential that the system boundaries are wide enough to avoid harmful suboptimization and prevent problems to be "exported" in time and space [12]. Hence, the analysis will take into account not only the traditional systems for water

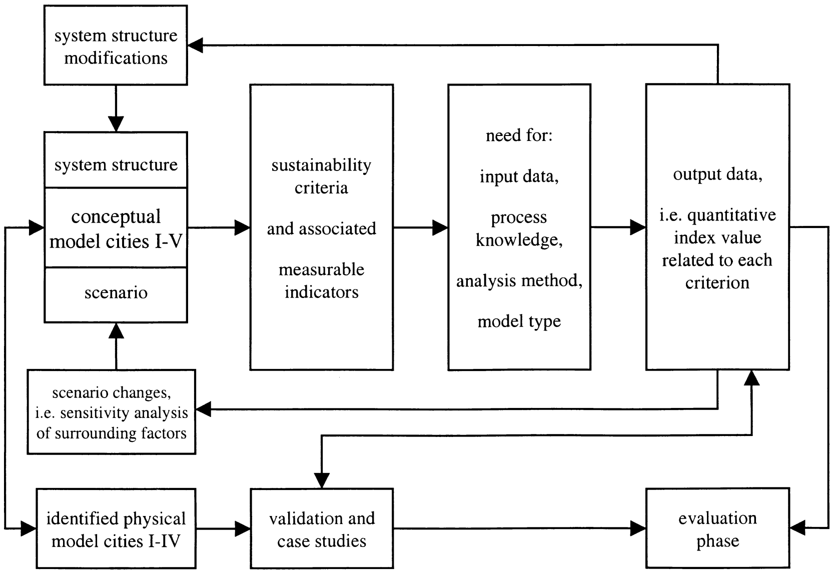

Fig. 1. Schematic description of the systems analysis work procedure within the Swedish research program "Sustainable Urban Water Management."

and wastewater, but also the surrounding environment, including for example the use of products from wastewater treatment in agriculture.

The analysis work will be carried out in parallel using both the conceptual and physical model cities (see Fig. 1). Experiences gained from one approach will be incorporated into the other. The work based on the conceptual model cities is primarily model based (mathematical and/or mental models) using computer simulations and other computer-based analysis methods. At this stage the most promising tools are: cost-benefit analysis, functional risk analysis, microbial risk analysis, life-cycle assessment, sensitivity analysis, material-flow analysis, and behavior/attitude investigations based on interviews and action research [6]. The work based on the physical model cities is a combination of the systems analysis project and of the different PhD projects within the research program. Here, the collection of new data is one important aspect, and also the physical model cities provide the possibility to validate results achieved from the model-based evaluations of the conceptual model cities. As the work proceeds, new system structures will be incorporated and investigated within the conceptual model cities. Finally, the various systems will be influenced by alternative scenarios and evaluated. The evaluation phase of the results will be based on the work performed on both the conceptual and the physical model cities using various methods of multicriteria decision analysis.

3. Sustainability criteria and associated indicators

Sustainability provides a useful concept, forcing people to think about where development is leading us. The multidimensionality expressed by the definitions of sustainable development emphasizes that thinking in terms of economic costs and benefits is no longer sufficient; social, cultural, and environmental aspects have to be incorporated into the decision-making process, especially with regard to long-term effects. The most common definitions of sustainability are rather vague and imprecise (e.g., [20]). Therefore, it is beneficial to use sets of criteria to make the concept of sustainability more operational and practically useful [2–5,13].

The proposed set of sustainability criteria have been divided into five main categories: (1) health and hygiene criteria, (2) social-cultural criteria, (3) environmental criteria, (4) economic criteria, and (5) functional and technical criteria.

Within each main category a number of subcriteria are defined. For every subcriterion one or more quantifiable indicators are suggested (when applicable). For most of the indicators the contribution to various environmental effects and resource utilization by the urban water and wastewater system used in Sweden today is presented. These values are compared to the impact of Swedish society in total (normalization) to demonstrate which criteria are the most critical ones with regard to the water and wastewater system. Normalization is a procedure proposed to be used in for example life-cycle assessment [8]. The proposed set of criteria and indicators are presented in Table 1.

It should be emphasized that the proposed set of criteria and indicators do not include all possible aspects of sustainability. Moreover, many of the criteria are more suited for relative comparisons of different water and wastewater systems rather than to the total anthropogenic impact. However, the sheer number of criteria and indicators in Table 1 create a multidimensional problem of high complexity. Moreover, to determine values for all the indicators (from databases and actual measuring campaigns) would be both time consuming and expensive. Consequently, to promote the practical and operational use of the sustainability concept and its associated criteria, the number of criteria/indicators must be reduced. A selection of priority criteria has been made by the researchers of the systems analysis group. The criteria have been chosen argumentatively with the intended purpose of defining at least one criterion to be associated with each of the five main criteria categories. An exception has been made for the environmental criteria, where impacts exceeding 10% of the total anthropogenic impacts have been selected. These criteria indicate where there appears to exist a significant potential for further improvements. In Table 2, the selected priority criteria, as well as the associated planned methods for analysis are presented.

Table 1
Sustainability criteria and associated indicators

Criterion	Indicator	Impact from water supply and sanitation	Total anthropogenic impact (in Sweden)	Rel. impact from water supply and sanitation, %
Health and hygiene criteria				
Availability to clean water	Acceptable drinking water quality[a] (% of samples)	>99.5	—	—
	Nonaccess to drinking water (h/p, year)	3.5	—	—
Risk of infection	Number of waterborne outbreaks[b] (no/100,000 p, year)	0.05–0.1	—	—
	Number of affected persons[c] (no/100,000 p, year)	5–10	—	—
Exposure to toxic compounds	Drinking water quality		—	—
Working environment	Number of accidents		—	—
Social and cultural criteria				
Easy to understand				
Work demand				
Acceptance	Violation		—	—
	Omission		—	—
	Ignorance		—	—
Availability				
Environmental criteria			—	—
Groundwater preservation	Groundwater level			
Eutrophication	N to water (kg/p, year)	1.3	9.8	14
	P to water (g/p, year)	23	280	8.2
	OCP* (kg O_2/p, year)[d]	21 (sea)	150 (sea)	14
		7.9 (lake)	62 (lake)	13
Contribution to acidification[c]	H^+-eqv. (mol/p, year)	15	1600	0.9
Contribution to global warming[c]	CO_2-eqv. (kg/p, year)	12	8300	0.1

(*continued on next page*)

Table 1
(*continued*)

Criterion	Indicator	Impact from water supply and sanitation	Total anthropogenic impact (in Sweden)	Rel. impact from water supply and sanitation, %
Spreading of toxic compounds to water	Cd, Hg, Cu, Pb (g/p, year)	Cd: < 0.008 Hg: < 0.02 Cu: 0.8 Pb: < 0.08	Cd: 0.2 Hg: 0.1 Cu: 60 Pb: 1.5	Cd: < 4 Hg: < 16 Cu: 1.4 Pb: < 5
Spreading of toxic compounds to arable soil[e]	Cd, Hg, Cu, Pb (g/p, year)	Cd: 0.041 Hg: 0.061 Cu: 9.0 Pb: 1.2	Cd: 0.43 Hg: 0.11 Cu: 13 Pb: 8.2	Cd: 10 Hg: 54 Cu: 70 Pb: 15
Use of natural resources	Utilization of available land[f] (m^2/p)	<0.1	500–700	<0.02
	Use of electricity and fossil fuels (MJ/p, year)	400	160,000	0.2–0.3
	Total energy consumption[g] (MJ/p, year)	3,000–4,000	—	—
	Use of fresh water (m^3/p, year)	120	—	—
	Use of chemicals: Fe, Al (kg/p, year)	Fe: 2.0 Al: 0.3	— —	— —
	Use of materials for construction of infrastructure (m pipe/p)	2.0 (water pipe) 3.5 (sewer)	— —	— —
	Potential recycling of phosphorus[h] (g/p, year)	720	2300	31
Economical criteria				
Total cost	Capital cost (Euro/p, year)	34	22900 (GDP/p)	0.15
	Operation and maintenance (Euro/p, year)	63	22900 (GDP/p)	0.28

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Table 1
(*continued*)

Criterion	Indicator	Impact from water supply and sanitation	Total anthropogenic impact (in Sweden)	Rel. impact from water supply and sanitation, %
Functional and technical criteria				
Robustness	Overflow (m^3/p, year)	0.4 (0.3% of flow)	—	—
	Nonaccess to clean water (h/p, year)	3.5	—	—
	Sewer stoppage (no/100,000 p, year)	70	—	—
	Flooding of basements (no/100,000 p, year)	5	—	—
Performance	Out-leakage (m^3/p, year)	20 (16% of flow)	—	—
	In-leakage (m^3/p, year)	13 (10% of flow)	—	—
Flexibility			—	—

If not specified, data in column 3 by courtesy of Stockholm Water Co., and data in column 4 (Swedish national values) from SCB [18]. Blank entries in column 2: indicators not formulated; blank entries in columns 3 and 4: data not available or indicator cannot easily be related to a total anthropogenic impact.

* OCP—oxygen consumption potential, based on amount of organic material, nitrogen, and phosphorus.

[a] Restrictions of drinking water quality from SLV [19].

[b] Data on the risk of infection from Jong and Andersson [10].

[c] Data on the impact from water and sanitation of a conventional system from Kärrman and Jönsson [11].

[d] Fresh water situation and marine water situation respectively according to Ødegaard [15].

[e] Impact from water based on 100% recycling of excess sludge. Data on the total anthropogenic impacts calculated from average concentrations in mineral fertilizers [1], usage of mineral P-fertilizer in 1995 [17] and the usage and concentrations in lime [1].

[f] Data of land use in Sweden from SCB [16].

[g] Estimations of exergy consumption based on data from Hellström and Kärrman [7].

[h] Impact from water based on 100% recycling of excess sludge. Data on the total anthropogenic impacts based on the purchase of mineral fertilizers from SCB [18].

Table 2
The priority set of criteria and the associated methods for evaluation for the systems analysis project of the research programme "Sustainable Urban Water Management"

Criterion	Method for evaluation
Health and hygiene criterion	
Risk for infection	Microbial risk assessment
Social and cultural criterion	
Acceptance	Action research and assessment scales
Environmental criteria	
Eutrophication	Life-cycle assessment, computer-based
Spreading of toxic compounds to water	modeling, material-flow analysis, and
Spreading of toxic compounds to arable soil	exergy analysis
Use of natural resources	
Economical criterion	
Total cost	Cost-benefit analysis
Functional and technical criterion	
Robustness	Functional risk analysis

4. Conclusions

In this paper, a framework has been proposed for analysis and comparison of urban water systems with respect to sustainability. This type of assessment involves multidimensional criteria, including economic, environmental, social, cultural, technical, and health-related aspects. The concept of separating the entire system to be analyzed into modular blocks made up of model cities, system structures, and scenarios (surrounding factors) that can be combined in any fashion, will allow for a wide range of different water management systems to be analyzed and compared while exposed to different situations. However, the available methods for evaluation are not satisfactory in all areas. Several tools are available for analysis of environmental impact and resource utilization, risk assessment, and economic evaluation, whereas methods for evaluating social-cultural and functional criteria must be further developed.

The concept of sustainability must be clearly defined. In this paper, sustainability of the urban water and wastewater system has been defined by a set of criteria. For every criterion one or more indicators (for "measuring" the criterion) are suggested. These indicators must, to a large extent, be quantifiable and easy to measure to promote the practical and operational use of the sustainability concept. By comparing the contribution to various environmental effects and resource utilization by the Swedish urban water system with the contribution from Swedish society in total, the criteria set is further reduced. The priority set of sustainability criteria/indicators represents what is to be investigated initially when an analysis of an urban water system is carried out. If the analyses show poor results with regard to the priority criteria set, then there is no need to continue the evaluation; otherwise, the evaluation could continue using the complete set of sustainability criteria.

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References

[1] Andersson A. Trace Elements in Agricultural Soils—Fluxes, Balances and Background Values. Stockholm, Sweden: Swedish Environmental Protection Agency, Report 4077, 1992.

[2] ASCE and UNESCO. Sustainability Criteria for Water Resource Systems—Prepared by the Task Committee on Sustainability Criteria, Water Resource Planning and Management Division. Virginia, USA: ASCE, ASCE, and working group UNESCO/IHP IV project M-4.3, 1998.

[3] Ayres RU. Statistical measures of unsustainability. Ecol Econom 1996;16:239–55.

[4] Balkema A, Weijers SR, Lambert FJD. On Methodologies for Comparison of Wastewater Treatment Systems with Respect to Sustainability. Wageningen, The Netherlands: Proc. WIMEK Congress on Options for Closed Water Systems, March 11–13, 1998.

[5] Graaf JHJM van der, Meester-Broertjes HA, Bruggeman WA, Vles EJ. Sustainable technological development for urban-water cycles. Water Sci Technol 1997;35:213–20.

[6] Hellström D, Jeppsson U, Kärrman E. Systems analysis of sustainable urban water management—A first approach. Ås, Norway: Proc. 4th International Conference on Ecological Engineering for Wastewater Treatment—Managing the wastewater resource, June 7–11, 1999.

[7] Hellström D, Kärrman E. Exergy analysis and nutrient flows of various sewerage systems. Water Sci Technol 1997;35:135–44.

[8] ISO. Environmental Management—Life Cycle Impact Assessment. Draft International Standards, ISO/DIS 14042, 1998.

[9] Jeppsson U, Hellström D, Kärrman E. Systems Analysis of Sustainable Urban Water Management, Lund, Sweden: Dept of Ind. Electr. Eng. & Automation, Lund Institute of Technology, Technical Report TEIE-7135, 1999.

[10] Jong B de, Andersson Y. Waterborne Outbreaks in Sweden 1992–1996. Smittskydd 1997;1997:67–8

[11] Kärrman E, Jönsson H. Normalising impacts in an environmental systems analysis of wastewater systems. Paris, France: Proc. 1st World Congress of the International Water Association, July 3–7, 2000 (in press).

[12] Larsen TA, Gujer W. The concept of sustainable urban water management. Water Sci Technol 1997;35:3–10.

[13] Lundin M, Molander S, Morrison GM. A set of indicators for the assessment of temporal variations in the sustainability of sanitary systems. Water Sci Technol 1999;39:235–42.

[14] Malmqvist P-A. Sustainable urban water management. Vatten 1999;55:7–17.

[15] Ødegaard H. An evaluation of cost efficiency and sustainability of different wastewater treatment processes. Vatten 1995;51:291–9.

[16] SCB. Land Use in Sweden, 2nd ed. Stockholm, Sweden: Statistics Sweden (in Swedish), 1993.

[17] SCB. Agricultural Statistics Yearbook (Jordbruksstatistisk årsbok). Stockholm, Sweden: Statistics Sweden (in Swedish), 1997.
[18] SCB. Sweden Environment (Miljö Sverige), Stockholm, Sweden: Statistics Sweden's homepage, www.scb.se (in Swedish), 1999.
[19] SLV. Livsmedelsverkets kungörelse om dricksvatten. In: Statens Livsmedelsverks författningssamling. Uppsala, Sweden: Statens Livsmedelsverk, SLV FS 1993:35, 1995.
[20] WCED—World Commission on Environment and Development. Our Common Future. Oxford, UK: Oxford University Press, 1987.