Design and Sustainability Assessment of Scenarios of Urban Water Infrastructure Systems

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Abstract

The basic concept of today's infrastructure systems for water supply and wastewater treatment dates back more than 100 years. In the paper it is questioned whether the traditional concept, which is characterized by centralized structures, mixing of wastewater streams of various qualities, and open loop design is suitable to fulfill the new requirements in terms of sustainability. The results of an interdisciplinary analysis and assessment performed within the ongoing project AKWA-2100 for two German municipalities as case studies is presented. Using the scenario approach three scenarios are developed with a long-term perspective of 2050 plus to integrate technological, organizational, and institutional innovations into coherent alternative urban water systems with improved eco-efficiency. Since water infrastructure systems strongly affect the sustainability of water resources management the scenarios are evaluated with respect to their sustainability using a total of 44 criteria. In an iterative procedure supported by the Analytic Hierarchy Process the criteria were structured and the individual assessments of the AKWA-2100 research team members were integrate into a joint assessment. Preliminary results indicate that infrastructure scenarios with decentralized components, closed loops of water and other materials and specific treatment for different qualities of wastewater prevail with regard to most of the criteria.

Keywords: urban water infrastructure, sustainability, scenario analysis

1. Introduction

The basic concept of today's centralized water infrastructure systems for water supply and wastewater for urban areas in Germany as in other industrialized countries dates back more than 100 years. Since then the systems have been continuously extended to spreading urban areas, adapted to changing needs of the population served, and to changing requirements with respect to public health and environmental concerns. In addition, these infrastructure systems are characterized by both very long useful life-spans and sunk costs. Thus, the water infrastructure can be characterized as a system with a very high technological path dependency.

More recently, however, a debate on new technological trajectories for the urban water infrastructure is emerging. First, there are technical reasons which push such a debate: There seem to be limits for the old paradigm which is characterized by centralized structures and open loop design with respect to water and nutrients on the one hand. It is questioned whether or not this paradigm is suitable to fulfill the new requirements in terms of sustainability. On the other hand, there are several technological breakthroughs which promise to reach the ecological aspects of sustainability. However, they cannot be integrated easily into the existing system and rather constitute a separate technological trajectory. Second, the debate on deregulation of the water industry might lead to institutional changes which could perhaps foster alternative technological paradigms. Third, major parts of the existing system are reaching the end of their life-time. Thus, the high reinvestment requirements will make a future change in trajectories more likely than in the past.

To illustrate the pressure, under which the governing paradigm in urban water infrastructure has come under consider the following examples:

- Substantial financial efforts are needed to repair, rebuild, and adapt the existing urban wastewater systems to new requirements. In Germany, for example, estimates are, that over the next 15 years a 12 Bill. Euro/a are required (6,5 Bill. Euro/a for investments and 5,5 Bill. Euro/a for operation and maintenance) to keep the urban wastewater systems operational.
- Of the overall expenditure for urban wastewater systems in Germany on average 80 % are brought up for the collection and only 20 % for the treatment of municipal wastewater. This high proportion of fixed cost associated with the sewer system is typical for other industrialized countries, too.
- Increasing emission and immission standards, as they result from the new European Water Framework Directive will require substantial additional investments of largely unknown height in wastewater treatment.
- Finally, more and more substances like pharmaceuticals and their metabolites, antibiotic and endocrine substances are finding their way into the wastewater. Since the present treatment technology can not handle these pollutants, new treatment technology are required to protect our waters, the aquatic habitats and ourselves from chronic damages. There are no estimates about the financial needs, but they probably will be considerable.
- Due to the prevailing concepts of using water as transport medium for wastes and collecting residential and industrial wastewater in the same system the sludge from public owned wastewater treatment plants is contaminated and no longer suitable for agricultural use as fertilizer. Instead, the sludge has to be either deposited on waste disposals or incinerated, both causing substantial costs.
- On the water supply side costs to provide high quality drinking water to urban areas are increasing, too. For example, substantial part of groundwater resources including those used for water supply are contaminated by nutrients (nitrogen) and pesticides from agriculture and therefore, require treatment. Another example are hygienic problems in public water supply systems, which are caused through the reduction of the water consumption of private households and industry leading to a reduced throughput and thus to an increased residence time of water in the distribution systems.

Before spending lots of money into the traditional centralized concepts it is necessary to assess the options available with regard to their sustainability. This requires first the design and analysis of alternative technological trajectories, and second their assessment with regard to sustainability.

The goal of the on-going AKWA-2100 project is to identify long-term strategic options and concepts for urban water infrastructure systems in Germany which contribute to a sustainable development. The primary interest is to conceptualize options especially for re-developing sanitation systems in already existing urban areas and not so much for systems to be build on green fields during the development of new areas. Since the local characteristics and circumstances are the most important determinants for urban sanitation systems AKWA-2100 is build around two case studies. These are the water infrastructure systems of Asseln, a suburb of Dortmund, and of Bork, a suburb of Selm two municipalities in the state of North-Rhine Westfalia, Germany. Members of AKWA-2100's interdisciplinary project team are the two municipalities, four scientific institutes (civil engineering, sanitary and waste engineering, economics, systems and innovation research), an engineering consulting firm and three industrial partners.

2. Methodology

In AKWA-2100 the scenario approach as it was advanced by Schwartz (1991) is used to develop long term alternatives because scenarios are especially suited to deal with complex planning situations and high degree of uncertainties as it is the case for urban water infrastructure systems. Such situations can be characterized as follows:

- A large number of actors / stakeholders is involved.
- There are various pervasive uncertainties involved: For example the uncertainty with respect to future goals and objectives of the various actors or the uncertainty with respect to future technological, social, economical etc. developments.
- The future consequences of today's decisions are hard to diagnose.
- Decision makers are often restricted in their scope although .
- There are complex interactions of a multitude of spheres of life to be considered.
- For various reasons they also show a tendency to be „short sighted" with respect to time.

The scenario approach helps to deal with these difficulties constructively. It stimulates the imagination of those involved, provides a common language for multidisciplinary teams, supports a shared understanding of the problem under research by structuring the group thinking processes in interdisciplinary project teams, and finally, enables the appropriation of the results by the decision makers.

3. AKWA-2100 scenarios

Using the scenario approach the different technological options of urban water infrastructure systems are bundled into trajectories with a long-term perspective of 2050 plus. Three scenarios were developed called "Continuation", "Municipal Water Reuse", and "Local Recycling". In these scenarios technological, organizational, and institutional innovations are integrated into coherent alternative urban water systems with improved eco-efficiency with respect to water, nutrients, and water polluting materials.

In the following a brief outline of just the major technical aspects of the 3 generic scenarios is given. The institutional, organizational, and the other non-technical aspects associated with the scenarios not explicated due to space limitations.

The first scenario is called **"Continuation".** It is a direct descendant of today's system (Figure 1). It preserves the two basic characteristics of today's system, the combined sewer concept and central treatment plant. In this scenario the water consumption of the private households - which is completely supplied with drinking water quality - is reduced to 100 Liter per person and day (l/p/d) through standard application of water efficient fixtures and appliances. Potable water, in this scenario, is still supplied through by a central water supply utility.

Further, in industry freshwater consumption and wastewater discharge to the public sewer systems have been strongly reduced. This was possible through adoption of the eco-efficiency paradigm by the industry which led to a systematic substitution of water and the application of highly water efficient process technology and a high degree of water reuse in water using processes. This was made possible through membrane technology, which has gained substantial application in all fields of water and wastewater treatment. Especially in industry this technology allowed a high degree of reclamation and reuse of process water as well as the recycling of valuable resources in the wastewater. In public sanitation membrane technology became an important treatment technology, too. Co-fermentation of sewage sludge and organic wastes became a standard.

About 30 % of the rainfall runoff are now uncoupled from the combined sewer system either by direct on-site infiltration or by collection in a storm sewer system with appropriate treatment and direct discharge to receiving waters.

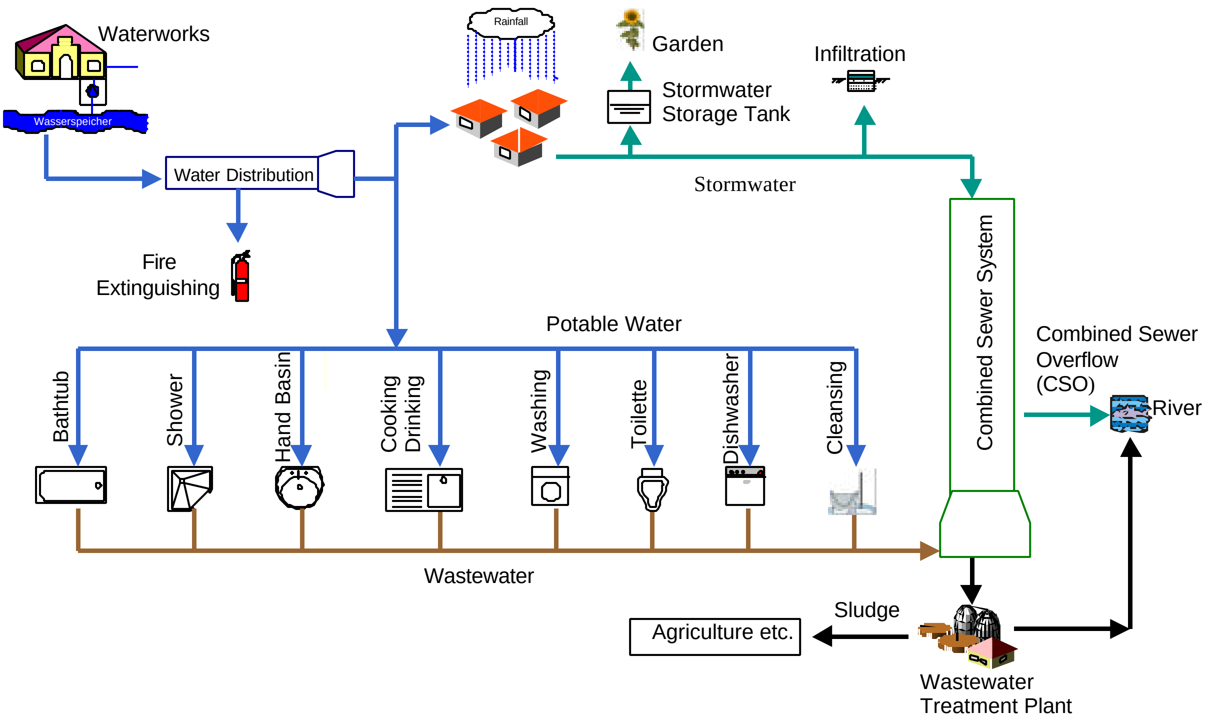

Figure 1: AKWA-2100 scenario "Continuation".

The second scenario is called „**Municipal Water Reuse“** (Figure 2). It represents a fundamental extension of today's sanitation system. In this scenario the various urban water streams are managed much more separately than in the "Continuation"-scenario. Storm water is collected and managed separately from sanitary wastewater. Further the sanitary wastewater is deprived from its nitrogen load and from pharmaceuticals and their metabolites through separation of the "yellow" fraction (i.e. urine) .

The sanitary water is treated and disinfected to very high standards in the central wastewater treatment plant using membrane and anaerobic processes. But instead of discharging the treated wastewater to receiving water bodies, the water is primarily reclaimed for non-potable uses. It is distributed through a dual distribution system. The most important non-potable uses are requirements to provide continuous flushing of the sanitary sewer system, fire requirements, and non-potable uses in industry. Continuous flushing of the sanitary sewers made it possible that solid bio-wastes from households can be discharged through sink garbage disposal systems together with the sewage (brown and gray water) into the sewer system without the risk of sedimentation and clogging. This not only made the bio-garbage bin superfluous and improved the handling of bio-wastes in private households but the high-in-carbon wastewater is ideally suited for anaerobic treatment in the central treatment plant. The biogas is used for energy generation (and in an increasing amount it is converted to methanol by the use of special catalysts). Since – as in the "Continuation"-scenario - the sewer systems only receives minor amounts of industrial wastewater, the sludge is ready for agricultural reuse (and thus for recycling of C, P, and N).

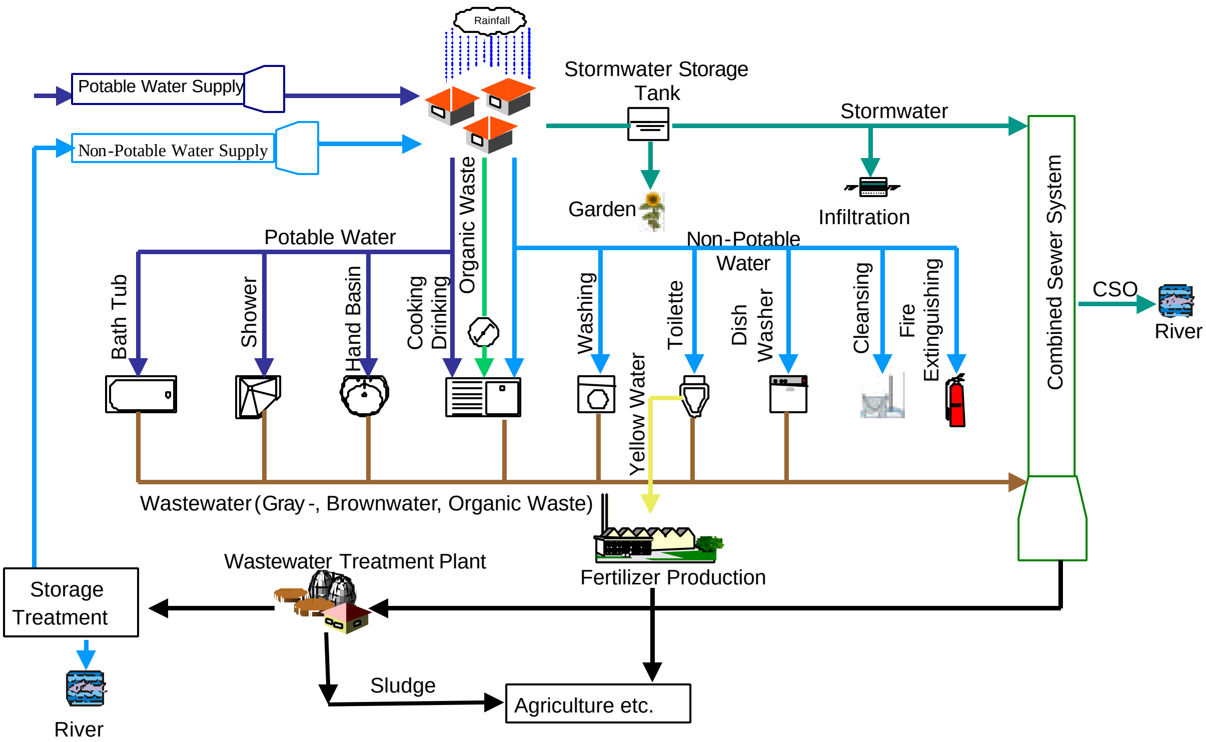

Figure 2: AKWA-2100 scenario "Municipal Water Reuse"

The “yellow water” (i.e. urine) fraction from private households is separately accumulated on-site and periodically collected by a truck-based system. The yellow water is used as raw material for industrial fertilizer nitrogen production.

Where possible, the storm water is used on-site for non-potable purposes or is directly infiltrated into the ground water. If this is not possible due to unfavorable hydro-geologic conditions the storm water is collected in storm sewers and, if necessary, treated in special semi-decentralized treatment systems. The storm runoff is reclaimed as complementary supply source for the non-potable water system. The excess is discharged into receiving waters or infiltrated into groundwater in semi-decentralized infiltration systems.

The use of water efficient fixtures and appliances has reduced the water consumption to 90 l/p/d with 60 l/p/d of potable and 30 l/p/d of non-potable water. Due to the continuous flushing of the sewer system the water consumption of the household appliances and fixtures is no longer key to the functioning of the gravity sewer systems. This spurs innovations in improving the water efficiencies of these appliances and fixtures. Potable water is still centrally supplied.

The third scenario is called **“Local Recycling”** (Figure 3). It differs most radically from today’s systems. There is neither a central water supply nor a central wastewater infrastructure system. Individual houses or groups of houses provide their own water supply and wastewater systems based on on-site treatment technology which heavily relies on membrane technology.

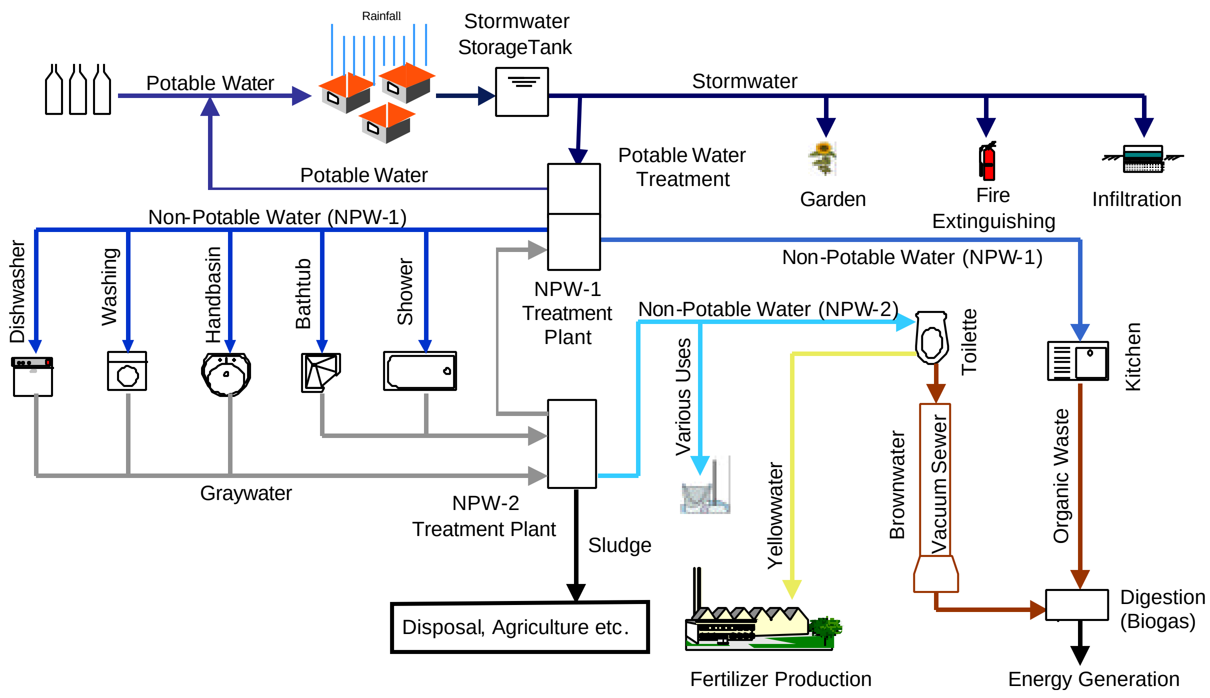

Figure 3: AKWA-2100 scenario "Local Recycling".

Rainfall provides the source for potable water supply. The systematic separation of the various water and wastewater streams enables highly efficient treatment processes and opens the way for reclamation and multiple cascading reuse of water of various qualities. Using water efficient fixtures and appliances the fresh-water input is reduced to 40 l/p/d and the total water consumption of the all the various qualities is 70 l/p/d.

As in the “Municipal Water Reuse”-scenario yellow water is collected as raw material collected by vacuum technology and treated in bio-digesters available for groups of houses.

4. Sustainability Assessment

There are many definitions of sustainable development. Since each of these definitions was given to provide guidance to the analysis of different aspect and sectors of society. For a compilation of a great variety of definitions please refer to Murcott (1997) or MacLeod (1992). Common to all of these is, that sustainable development is a process for incorporating social, economic, and environmental issues into decision making to promote the health an vigor of all three sectors.

The International Council for Local Environmental Initiatives (1994) gave the following practical and local interpretation of the concept of sustainability as it applies to urban areas: "Sustainable development is development that delivers basic environmental, social and economic services to all residents of a community without threatening the viability of the natural, built and social systems upon which the delivery of these services depends." With respect to the sustainability of metropolitan and urban areas but also to the sustainability of water resources management the urban water infrastructures play a central role. Water infrastructure not only provides essential services to enable economic and social development in densely populated areas but also strongly affects the way society handles water as one of the most precious and limited resources. This is covered by ASCE's (1998) and UNESCO's (1999) definition of "sustainable water resource systems" being those water resource systems "designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity." Almost immediately water and wastewater engineers raise the question whether sustainable development is different from what has been practiced to date. Obviously, water and sanitary engineering has provided substantial social benefits and helped to protect the environment from impacts. Sustainable development is not about looking back at our accomplishments to defend or criticize but about using this platform of existing infrastructure as a springboard for the future. The task is to look ahead and ask ourselves how we can make it even better, taking into account that the world transforms with increasing population, changing values and technological progress.

Following the argument of W. James (1999) who states that true sustainability of the water systems of large cities is implausible, the goal of the AKWA-2100 project is to identify urban water infrastructure concepts which reduce the un-sustainability of future infrastructure.

The scenarios presented in the previous section are meant to be visions of different ways to reduce the un-sustainability of today's urban water infrastructure in general and to provide long-term orientation to the pilot-communities on the options available to them to improve their existing water infrastructure towards sustainability. To assess the relative advantages sustainability of each of the scenarios a hierarchical criteria system was developed. In each of the three main dimensions of sustainability, representing social, economic and ecological aspects, criteria and sub-criteria were developed.

A total of 44 criteria (Figure 4) was developed by AKWA-2100's interdisciplinary project team to provide a first rough assessment the sustainability of the scenarios. The criteria represent the economic, social, and ecological dimensions of sustainability. Each criterion has to be adapted to address the specific requirements associated with the evaluation of sustainability of water infrastructure systems. Table 1 illustrates the kind of criteria defined to compare the scenarios in terms of "Cost/Return"-related aspects in the "Economic"-dimension of sustainability.

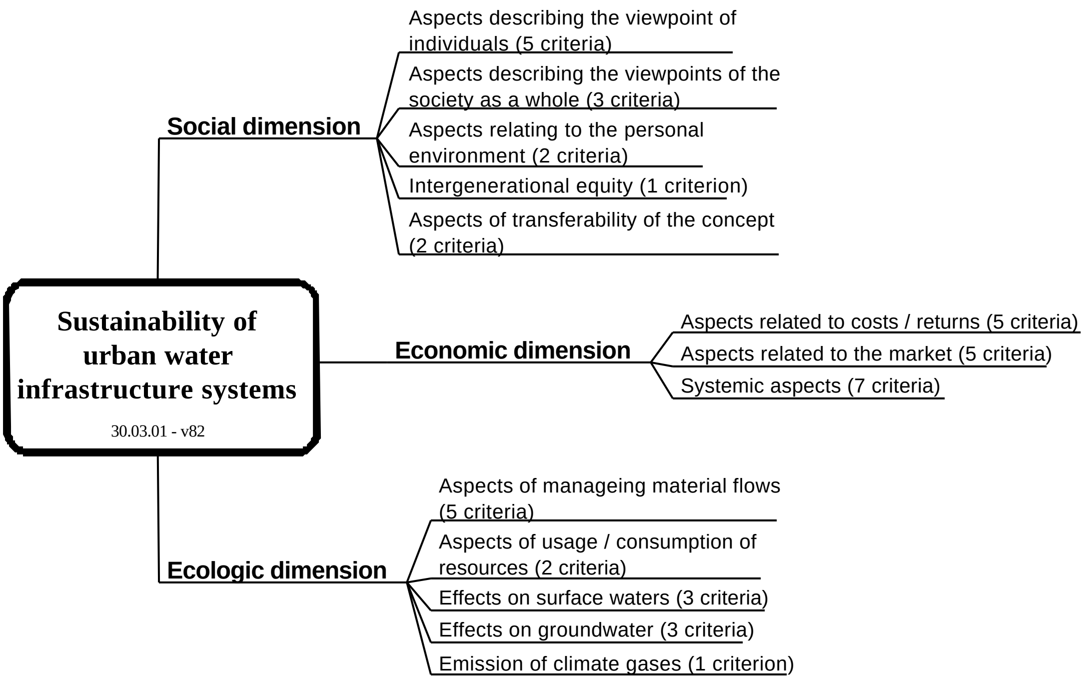

Figure 4: Basic structure of criteria system used to compare the sustainability of urban water infrastructure systems

To structure the evaluation model and to define the criteria system the Analytic Hierarchy Process (AHP) (Saaty, 1990) was used. Throughout the processes of defining the criteria system and of the assessment a discussion process was applied to reach results supported by all members of the project team. Once the hierarchical criteria system was defined, the members of the project team individually assessed the three scenarios with respect of to each of the criteria in a pair-wise procedure and derived his/her personal preference structure for the set of criteria according to AHP. This resulted in 14 complete weighting sets for the criteria and corresponding rankings for the scenarios. From the individual data an average weighting set was calculated and resulted in a ranking of the three scenarios which represents the preference of the overall project team. The result of this preliminary assessment is shown in Table 2.

Table 1: Criteria used to assess the "Cost-Return"- sub-goal within the economic dimension of sustainability.

Sub-Goal	**Criteria**
Aspects related to costs / return	Which scenario requires (1) smaller investment costs (from private and from public investors)? (2) smaller operation and maintenance costs over the whole life-cycle (for private and for public investors)? (3) smaller external costs during construction? (4) smaller external costs during operation? (5) smaller costs for the change from the existing water infrastructure system?

Table 2: Preliminary results of the project teams sustainability assessment of the scenarios: The weighting set for each of the three dimensions of sustainability, the ranking of the scenarios under each dimension and the overall ranking (1 = most preferred, 3 = least preferred.)

Dimension of Sustainability	**Overall Ranking**	**Economic Dimension**	**Social Dimension**	**Ecologic Dimension**
Weights ® **Scenario ¯**		0.48	0.21	0.31
Continuation	(3)	(2)	(3)	(3)
Municipal Water Reuse	(2)	(3)	(2)	(2)
Local Recycling	(1)	(1)	(1)	(1)

As Table 2 shows, the **"Local Recycling"**-scenario is the top ranking , **"Municipal Water Reuse"** on rank 2 and **"Continuation"** on rank 3. The "Local Recycling" scenario also consistently ranks top in each of the dimensions of sustainability . "Municipal Water Reuse" ranks second and "Continuation" ranks third for the social and economic dimension. Only with respect to the economic dimension the scenarios "Municipal Water Reuse" and "Continuation" swap ranks. A sensitivity analysis was carried out indicating a robust result of the ranking.

The three generic scenarios were developed further for each of the pilot communities Asseln and Selm to specifically address the local conditions. During this process detailed lists were developed for each scenario describing all the technical components as well as the respective quantities of technical equipment required to implement the scenario under the local condition of each of the pilot communities. These lists provide the basis for the economic assessment of the scenarios which is performed at the time of writing and which is part of the second iteration of the sustainability assessment.

In the next step, the site-specific scenarios together with their sustainability assessment will then be presented to representatives of the two cities' decision making bodies who will select one scenario for further elaboration in the second phase of the project. The elaboration will not only cover a more detailed technical specification of the scenario for the specific conditions in the pilot communities but also cover the development of a transition strategy from today's sanitation system to the one described in the elaborated scenario. The elaborated scenarios will then be re-assessed with respect to their sustainability. They will provide a long-term vision of the urban water infrastructure system for the municipality and support the long-term planning in the cities.

The project will be finished by the end of 2001. Further information can be found on the project's web-site at http://www.akwa-2100.fhg.de .

5. Conclusions

Since AKWA-2100 is on-going final conclusions about the sustainability of various options of urban water infrastructure can not yet be provided. However, some preliminary conclusions regarding usefulness of the scenario-approach can be given here.

In AKWA-2100, the scenario approach was very useful to structure the group thinking processes within the project team. Since it stimulated the imagination and provided a common language the approach contributed much to a shared understanding of the members of the project team, who are very diverse in terms of background and experiences. The scenario approach was instrumental in identifying the large number of technical as well as non-technical elements and driving forces shaping our future and the future of sanitation. The scenarios helped to integrate these into coherent alternative visions and to illustrate the vast spectrum of options available to fundamentally innovate our urban water systems facing the imperative of sustainable development.

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