Sustainable water infrastructure planning for an uncertain future

Water supply and wastewater disposal networks have a long service life and thus require long planning horizons. How can the services they provide be assured for future generations? How are we to deal with the associated uncertainties? How can sustainability be included in our planning procedures using quantitative methods? These questions were addressed by Eawag as part of National Research Programme 61.

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Fig. 1: Are the sewers under Zurich's glittering Bahnhofstrasse in good repair or in need of renovation?

Water infrastructure – water supply networks, sewers and wastewater treatment plants – is indispensable for our society, providing not only public health benefits but also protection against flooding and environmental pollution. With a service life of 30–100 years, assets of this kind are extremely long-lived, which tends to offset the high capital investment costs.

Much of Switzerland's water infrastructure is ageing. About a quarter of the sewers built in the 1960s and 1970s now show clear signs of damage and will require renovation in the coming years. We estimate that, over the next 40 years, depreciation of public water infrastructure will amount to some CHF 81 billion. This means that society will have to make major investments in system maintenance, which in turn highlights the importance of sound investment decisions and good planning procedures. However, infrastructure planning is a complex process – all the more so given the need to predict future requirements and demand.

Development of planning instruments

The main aim of the NRP 61 project "Sustainable Water Infrastructure Planning" (SWIP) was to develop a scientific basis for instruments to optimize planning for the renewal of Switzerland's water supply and drainage systems. At the same time, a balance was to be sought between economic (predicted costs), environmental (ecosystem effects) and social aspects (stakeholders' values). Particular attention was paid to the fact that precise data on local infrastructure is often lacking, and that future developments cannot be predicted with certainty.

SWIP focused on questions in four areas: (1) What are the requirements of the various stakeholders concerned? How can their objectives be determined in the decision-making process, and which of the available options will best meet these objectives? (2) How will the condition of water supply and sewer networks change over time? How should we deal with inadequate data? Can experts' experience be incorporated in a quantitative manner? (3) How will climate change affect infrastructure, and how is this to be taken into account in planning? (4) How can socio-economic factors such as demographic changes, development of settlements and economic growth be taken into consideration?

Transparent decision-making

The method known as Multi-Criteria Decision Analysis (MCDA) makes it easier to handle complex decisions thanks to a structuring process which increases the transparency of decision-making. With this method, consideration is given to stakeholders' subjective preferences and objectives as well as to quantitative data, such as the costs or benefits of a given option (decision alternative). Using MCDA, robust alternatives can be determined which perform well for most stakeholders and for different scenarios, and can thus be recommended.

In a case study, we carried out an MCDA for the Mönchaltorfer Aa region (Canton Zurich). We collaborated closely with a wide variety of stakeholders at the communal level – policymakers, building authorities, planning engineers and water supply officers. Also involved in the process were representatives of cantonal and national agencies and associations. Particularly important from our perspective was the generalizability of the analysis, so that individual elements can now be taken over and adapted to other cases.

The six main objectives of the stakeholders involved comprise not only a good water supply, safe wastewater disposal, protection of resources (e.g. ground and surface waters) and low costs, but also goals that have previously tended to be neglected, such as intergenerational equity (not shifting the burden of rehabilitation onto future generations, ensuring the greatest possible flexibility of systems) and high social acceptance [1]. The stakeholders were asked to rate the importance of the various objectives. For most of the respondents, ensuring a good water supply and wastewater disposal, protection of water and other resources, and intergenerational equity was more important than minimizing costs [2, 3].

Together with the stakeholders, we defined options for attaining the objectives. As well as existing approaches, these included decentralized systems where, for example, drinking water is bought in supermarkets, rainwater is recycled and wastewater is treated on site. Also considered were management aspects and different forms of collaboration – e.g. between communes and between service sectors.

Emphasis on collaboration

Using mathematical models, we were able to determine for each option how effectively various objectives could be achieved. We were thus able to assess, for example, how different options would affect the condition of sewers. We could then determine the levels of surface and groundwater pollution arising in each case, or disturbances due to defective pipes. For other predictions – regarding microbiological water quality or the flexibility of engineering measures (dismantling/expansion) for each infrastructure option – we consulted experts.

The various decision alternatives were then ranked, so as to determine which options performed particularly well or poorly, and for what reasons. No approach was found to be clearly the best under all conditions. However, a number of options and elements were found to per-

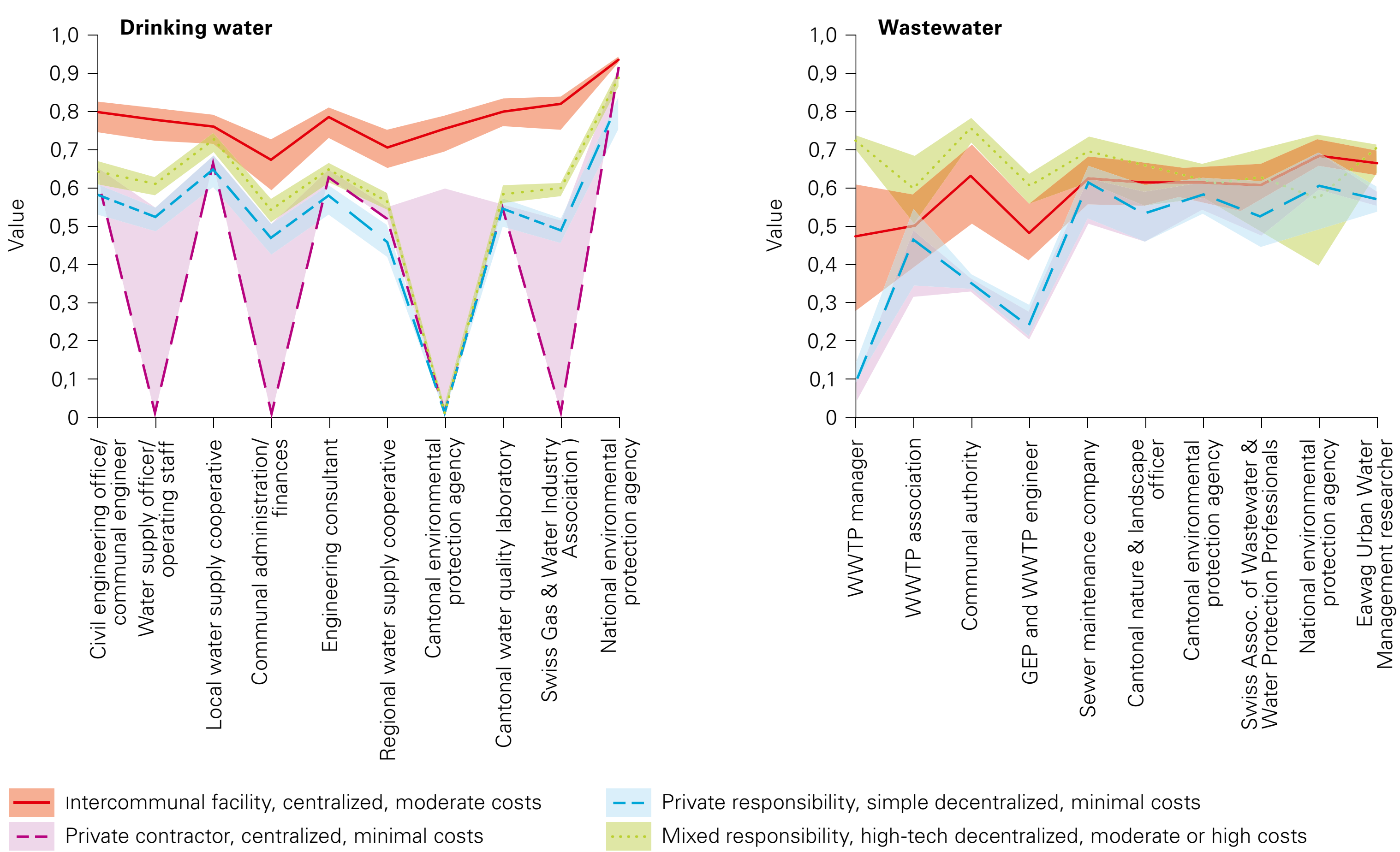

Fig. 2: Ranking of various alternatives under the "Status quo" scenario (see text) for ten stakeholders in the drinking water and wastewater sectors. The lines connect the median values, the shaded areas indicate the range of uncertainty. 0 = worst value, objectives not met; 1 = best value, all objectives fully met [6].

form well, on average, for all stakeholders and under all scenarios (see below) (Fig. 2). The results were strongly influenced by rehabilitation efforts (associated with higher costs), as these relate to several objectives that are important to numerous stakeholders – e.g. intergenerational equity, good water quality and water supply reliability. Accordingly, decision alternatives involving a proactive approach to rehabilitation management – such as replacement of at least one per cent of the oldest pipes in worst condition annually – performed better than the lower-cost strategy of only replacing pipes when failures occur [4].

Options involving intercommunal and intersectoral collaboration generally obtained a good ranking. However, as shown by a social network analysis, Switzerland's water sector is highly fragmented: There is little collaboration between the wastewater and the water supply sector, or between local, cantonal and national actors [5]. But from the stakeholders' perspective such collaboration would be necessary in order to increase planning efficiency, achieve longer-term objectives and improve catchment management.

In contrast, the technical design of systems does not appear to be decisive, as long as the key objectives are attained. In the wastewater sector, for example, the "decentralized high-tech system" option also achieved an excellent ranking for stakeholders who attached particular weight to a low rehabilitation burden and a high degree of flexibility [3]. Lastly, decision-makers' attitude to risk also proved to be extremely important. Decision alternatives involving low levels of uncertainty are to be recommended for risk-averse stakeholders [2].

Long-term data often unavailable

For long-term planning, it is vital to be able to make reliable forecasts of the future condition of infrastructure. This is especially true of pipe systems, which account for around 90 per cent of all investments. Assessment of future rehabilitation requirements for water supply and sewer networks calls for models capable of predicting pipe deterioration and lifespan.

In practice, records of damage and pipe replacement are frequently incomplete or only cover a short historical period. In addition, available data on small or relatively new networks is not sufficient to permit robust calibration of prediction models. Incomplete replacement records mean, for example, that pipes in the poorest condition are not represented in the data set, which distorts the overall picture. For this reason, conventional models significantly underestimate the pipe failure rate (Fig. 3a).

This is the situation for most networks in Switzerland. In the SWIP project, this challenge was tackled in two ways: Firstly, we developed new models which take account of missing data in an explicit and mathematically correct manner. The price to be paid are greater uncertainties, which are strongly dependent on the available data (Fig. 3b). Secondly, using Bayesian inference, we combined prior knowledge with local data. Expert knowledge and experience from other water supply networks can thus be used to compensate for missing data. As part of SWIP, we developed an approach for obtaining expert data on pipe service life and used this to calibrate prediction models [7, 8]. These models were successfully employed to characterize various networks. As a next step, the results can be combined with a rehabilitation strategy so as to estimate future rehabilitation requirements [9].

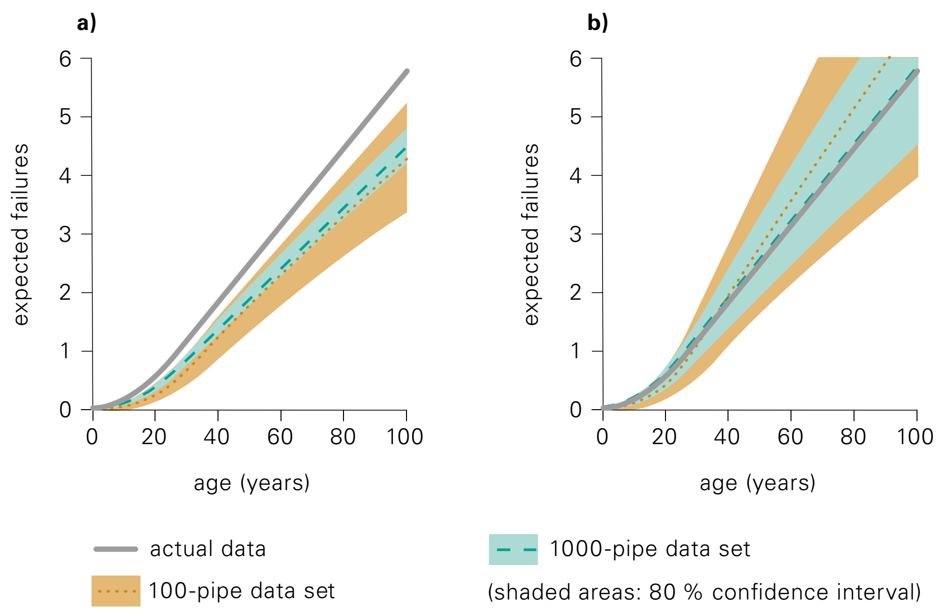

Fig. 3: Influence of missing pipe replacement records on predicted failure rates: The first simulation (a) shows that deterioration is typically underestimated if the replacement of damaged pipes in the past is not taken into account. Also clearly apparent is the influence of the size of the data set on the uncertainty of estimates. The models developed in the SWIP project (b) can compensate for the problem of missing historical records, although uncertainty is increased with this approach [7].

Limited influence of climate change in the medium term

In investigating the implications of climate change for future water infrastructure, we focused on how extreme rainfall events would affect the performance of urban drainage. Using a stochastic approach, we modelled rainfall characteristics for the Mönchaltorfer Aa region over the period 2036–2065 according to the best knowledge currently available. The model used is capable of simulating rainfall events which are statistically indistinguishable from actual measurements [10].

Figure 4 shows the influence of the modelled rainfall series on the frequency of flooding from sewer networks. No significant differences between current and future network performance can be detected for either of the two catchments studied. These results suggest that, over the medium term (up to 2050), there are no grounds for adapting the dimensioning of sewer networks to climate change. However, this conclusion only applies to the case study region, and its validity is also limited by the deficiencies of global and regional climate prediction models.

Future scenarios from doom to boom

How can we carry out long-term infrastructure planning if we do not know what the future holds? Some uncertainties – such as those associated with predictions and with stakeholders' preferences – can be directly incorporated into the models and the MCDA. But to address the uncertainty of socio-economic development, we adopted a scenario approach. For various future scenarios, we developed coherent descriptions, irrespective of their desirability or likelihood of occurrence.
In collaboration with stakeholders in the project region, we produced four future scenarios for 2050 [1]. In the "Status quo" scenario, the situation is essentially unchanged from today. The "Qualitative growth" scenario involves economic prosperity combined with sustainable development. In the

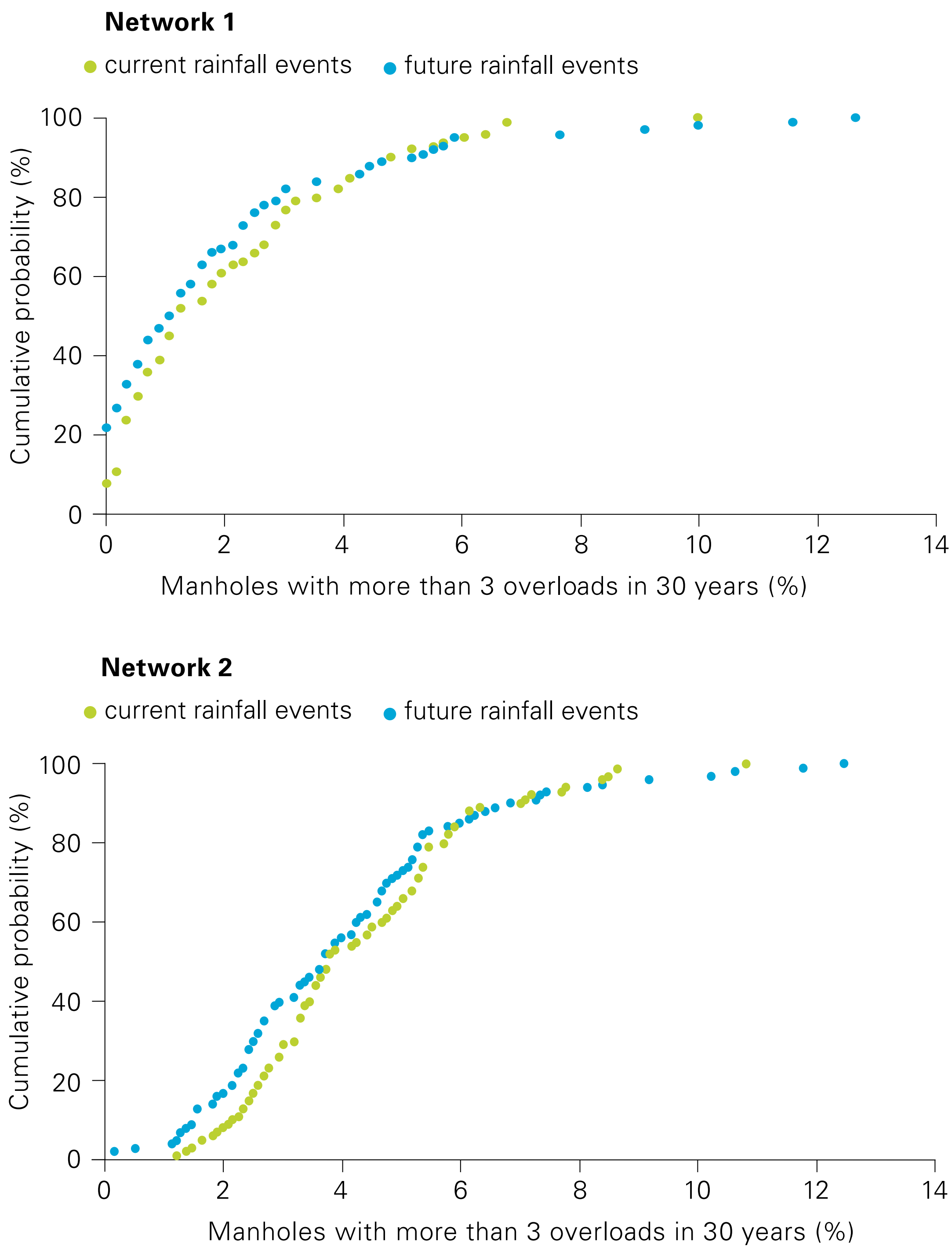

Fig. 4: Predicted frequency of flooding from sewer networks in two catchments of the Mönchaltorfer Aa region, with current and future rainfall events. No significant influence of climate change on sewer network performance is evident from the two curves. The charts indicate the probability that the percentage of manholes with more than 3 flooding events over a 30-year period will be less than or equal to a given value. In Network 1, for example, there is an 80 % probability that ≤3.5 % of manholes will experience such flooding [10].

"Doom" scenario, a slight population decline is accompanied by a severe lack of economic resources. The "Boom" scenario, in contrast, envisages massive economic and population growth and technological innovations.

We developed detailed predictions as to how the various scenarios would influence water infrastructure. The greatest effects were seen with the "Boom" scenario. Here, options which, in the MCDA, performed well under the other scenarios for most stakeholders achieved a much poorer ranking – and vice versa. This was partly due to the fact that massive urbanization would lead to overexploitation of local groundwater resources, thus adversely affecting an important objective for certain stakeholders. With this knowledge, a new decision alternative could now be created – e.g. providing for imports of water from Lake Zurich. Given that, for many stakeholders in this case study, the objective of "resource autonomy" was not especially important, greater interconnection of water supplies would presumably be an acceptable compromise. The combination of MCDA and scenario analysis is thus useful in assessing the robustness of decision alternatives under a wide variety of (uncertain) future developments.

Practical applicability of methods and results

In view of the major challenges which Switzerland faces in managing its water infrastructure, careful development of methodological foundations is crucial. We are convinced that, here, the SWIP project has made important contributions. The instruments developed should facilitate a shift from problem-based repairs towards proactive, long-term planning of maintenance and renovation. Although the orientation of the project was scientific rather than practical, we see substantial potential for making the methods developed and the results obtained applicable in practice.

In a follow-up project, we are currently seeking to generalize the results concerning climate effects for the whole of Switzerland. The prediction models for pipe failure rates can be readily applied by engineering consultants with the relevant expertise. The main challenges here – apart from the non-user-friendly interface – lie in the preparation of data, which is often laborious, given the heterogeneity of communal data storage practices. Greater efforts would be required, however, to adapt and simplify the MCDA and to translate this highly specific knowledge into engineering practice.

Incorporating stakeholders' knowledge and preferences

Eawag's Sustainable Water Infrastructure Planning (SWIP) project is among the first worldwide to involve stakeholders in quantifying the sustainability of long-term planning for small-scale water infrastructure networks. SWIP links into Switzerland's existing planning instruments, such as the General Wastewater Management Plan (GEP) and the General Water Supply Plan (GWP), and additionally introduces forward-looking, participatory elements. The project focused in particular on dealing with limited data and the uncertainty of future developments, as well as ensuring high acceptance of the decision-making process among stakeholders. A consistently transdisciplinary approach was adopted, with stakeholders' experience, expertise and preferences being taken into account in the various phases of the research. SWIP was supported by the Swiss National Science Foundation under the National Research Programme "Sustainable Water Management" (NRP 61).

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