Sustainable development of water resources systems with regard to long-term changes of design variables

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Abstract Conventional planning of water projects usually implies a decision for optimum use of available resources for both present and forecast water demands. Sustainable development, however, requires consideration of the interaction of a planned system with nature and society under present and long-term future conditions. Therefore, possible future changes in all design-relevant variables have to be forecast and considered. Examples are presented. Forecast scenarios of many potential development paths of design-relevant parameters are used in order to specify a "possibility function" for each parameter forming the basis of a decision support system. The combined multi-dimensional possibility functions are transformed into hydrological or socio-economical design variables with the aid of models. This way the design variables are presented in the form of a multi-dimensional possibility function showing potential future conditions having low, medium or high possibility of occurrence. With the aid of this decision support system it will be possible to design a water project which will be flexible in order to meet future conditions. In the future, the principle of flexibility should replace that of optimality in sustainable development of water resources.

INTRODUCTION

The public and scientific discussion about sustainable development during the last five to ten years focuses mainly on the question of what is meant by sustainable development, i.e. the question of definition, and on statements on the requirements to be met in order to make a development sustainable. Most of this discussion, also in the scientific world, is verbal and qualitative (e.g. Plate, 1994). Some ecologists claim that sustainable development which meets all these requirements is, perhaps not impossible, but certainly unfeasible.

The objective of this paper is to overcome this purely qualitative discussion and try to develop a quantitative approach for planning sustainable water resources systems. The difficulty here is the fact that such systems must be planned such that they will function also in the long-term future, under conditions which are not known at present. The conventional procedure to forecast, e.g. water demand, and to design the project for this future water demand, is certainly not adequate any more. Sustainable development requires consideration of the interaction of a planned system with nature and society under present and long-term future conditions. This "anticipatory approach", therefore,
requires prediction of possible future changes, not only in parameters directly concerned with water, but in all variables relevant to the project design, e.g. hydrological and ecological conditions, as well as socio-economic conditions, including a potential change in society’s value system. The strong interdependency between the environment, socio-economic conditions and project requirements are recognized. In this paper some of these changes, and their impact on the design of water resources systems, will be discussed.

The general idea of the approach consists in the consideration of many potential changes for all relevant parameters, forecasting those developments, transforming these forecast developments into hydrological design variables, and finally in the proposal of suitable, i.e. sustainable, project alternatives. In order to do this, forecast scenarios are developed, the result of which allows the formulation of a possibility function (simplified analogy to probability functions) which allows the specification of future values, e.g. for the planning horizon, with higher and lower possibilities of occurrence. A project meeting all requirements at the level "high possibility" comes close to conventional solutions using just one single forecast alternative. In the sense of sustainable development, project alternatives which can function also under conditions of medium or low possibility are much more valuable. Those solutions will be much more flexible in the sense of adaptability to future conditions.

Although this procedure sounds rather complicated, the approach is certainly feasible, as will be shown in the following sections.

CHANGES IN THE ENVIRONMENT

It is beyond the scope of this paper to discuss potential changes of all parameters and variables relevant to hydrology and water resources management. Therefore it is the intention of the following chapter to give examples of potential changes, illustrate the principle of generating potential development paths for these parameters, and combine the results to form possibility functions.

In many river basins we observe rapidly growing metropolitan areas having a significant impact on hydrological processes. Figure 1(a) shows the Alzette River catchment in the state of Luxembourg in August 1989. In order to know the future situation, scenarios were developed for the state of urbanization in the future, e.g. the year 2040 (Fig. 1(b)). Such scenarios are developed under the assumption that the rate of growth of the urban areas in future will be the same as it was during the past 15 years. Thus Fig. 1(b) represents only one scenario of potential future development. For sustainable development it is, however, necessary to know many different potential future changes, i.e. a large number of such scenarios has to be developed. Figure 2(a) shows the development paths for various scenarios of urbanization, some of which have low, some medium and some high possibilities of occurrence. It would be more desirable to specify quantitatively mathematical probability distribution functions. Since, however, the knowledge for this task is not available, it is still possible to specify development paths with higher and lower possibilities of occurrence. On the basis of such a large number of possible different future development paths, one can quantify a "possibility function" for urban developments instead of the otherwise preferred pdf. Figure 2(b) which is comparable to the membership functions in fuzzy set theory, represents, however, a
possibility function following the mathematical possibility theory (Zimmermann, 1992). As can be seen from Fig. 2(b) the present conditions will be at the border between low and medium possibility if a time horizon of the year 2040 is considered. Also the scenario represented in Fig. 1(b) is estimated to have a medium possibility for the year 2040.

An issue of major concern is presently the question of a potential climate change in the future. It can be expected that such a climate change may have an impact on hydrology and thus on water resources management. Therefore for sustainable development such changes have to be taken into consideration. On the basis of the climate model of the Max Planck-Institute for Meteorology in Hamburg a scenario has been computed for the situation of $3 \times \text{CO}_2$. The question that such scenarios resulting from climate models are still highly unrealistic on a regional scale shall not be discussed here. In the context of sustainable development it is only important that such a change may occur. Figure 3 shows a comparison of two runs of the climate models, i.e. the control scenario (present conditions) and a scenario of tripling CO$_2$ concentration in the atmosphere. As can be seen from Fig. 3 major changes in monthly precipitation can be expected. Besides the development paths of tripling CO$_2$ (Fig. 3) many other potential development paths for climate change can be assumed yielding again results of low, medium and high possibility, equivalent to the diagram shown in Fig. 2(a). Analogous to the previous examples the corresponding possibility function has been constructed having a similar structure as that of Fig. 2(b).
Urbanization (% of area) vs Possibility

(a) Future development paths for urbanization with associated qualitative evaluation of possibilities

(b) Possibility distribution function of potential future developments of urbanization

Fig. 2 Potential future developments of urbanization.

Mean monthly precipitation [mm]

Fig. 3 Scenario of climate change impact (3 × CO₂) on precipitation in the Mosel River catchment (based on the ECHAM climate model).
GENERALIZATION OF APPROACH FOR PLANNING DECISIONS ON SUSTAINABLE WATER PROJECTS

The previous examples all follow the same principle:
(a) define a scenario of potential future development;
(b) define many alternative potential future development paths; and
(c) define the possibility function for the changing parameter.

This consideration was made for each parameter separately. Under real-world conditions, however, we observe simultaneous changes or consider potential future simultaneous changes of several parameters relevant to hydrology. Figure 4 shows this situation for two parameters, parameter A (e.g. urbanization development) and parameter B (e.g. precipitation changes due to climate change). This way we get estimates of potential future states of the system for two parameters. In order to specify possibilities of occurrence within this two-dimensional state of future (at state i) environmental conditions of the system given in Fig. 4, the two one-dimensional possibility functions are transformed into a two-dimensional possibility function as presented in Fig. 5(a).

Usually changes of more than two parameters have to be considered, thus generating an n-dimensional state of future environmental conditions. In this case we have parameters $X_i$ ($i = 1, 2, ..., n$), the product space $X_1 \times X_2 \times \ldots \times X_n$ and the possibility function $\mu(X_1, X_2, \ldots, X_n) = \min \{\mu(X_i, i = 1, 2, \ldots, n)\}$.

Such a joint possibility function, as given in Fig. 5(a), or for the n-dimensional space as described above, contains the information of potential changes of various parameters relevant to hydrology and the possibility values associated with these changes. This information is, however, not suitable yet for decision making in water management. Therefore it is necessary to transform this n-dimensional possibility function into a possibility function which can be used in water management decision making. Figure 5 shows this transformation procedure. The pyramid of Fig. 5(a) may be represented by a two-dimensional rectangular graph as given in Fig. 5(b). This information serves as input to hydrological models, water balance models or water quality models, in order to be transformed into the possibility function of a parameter relevant in water project design. This transition is shown in Figs. 5(b) and (c). If only one hydrological parameter is relevant for the design, it is possible to transform the n-dimensional possibility
function (in Fig. 5(a) shown as a two-parameter case) into a one-dimensional possibility function given in Fig. 5(c).

TRANSFORMATION OF ENVIRONMENTAL CHANGES INTO HYDROLOGICAL VARIABLES

Following the principle discussed in the previous section, examples for the transformation of the possibility function of various environmental variables into a possibility function for a hydrological design parameter, e.g. mean monthly runoff, will be demonstrated. The examples represent the transformation of only one development path for only one parameter.

In Fig. 1(b) a scenario of the development of the urban areas in the Alzette catchment was presented. Under the assumption of continuation of the previous growth rate until the year 2040, the hydrological impact of this development on the mean monthly runoff values of the Alzette River was computed with the aid of a complete

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![Diagram](image_url)  

**Fig. 5** Transformation of a possibility function of two environmental parameters into a one-dimensional possibility function of a hydrological design parameter.
hydrological water balance model. Figure 6(a) shows the result, where higher summer runoff values and lower winter discharges can be observed. It could also be shown that flood peaks become higher and low-flows lower. These expected negative effects are certainly relevant for the design of water projects.

In Fig. 3 changes in mean monthly precipitation values were presented due to a climate change scenario ($3 \times CO_2$). If this change is also transformed into changed runoff conditions following the principle presented in Fig. 5, the result is computed with the aid of a water balance model (Fig. 6(b)). It can be shown that at least for some months a change in runoff can be expected.

**CHANGES IN SOCIO-ECONOMIC CONDITIONS**

Planning and design of water projects in the framework of sustainable development require thorough consideration of potential changes in two fields, i.e. (a) environmental conditions and (b) socio-economic conditions.

While the changes in environmental conditions and their impact on hydrological design variables have been discussed in the previous sections, here just a brief example of changes which may occur in future in society are presented. Figure 7(a) shows potential development paths for the total water demand in a certain area (in this case supply region of the Jubach and Glôr Dam in Germany). In an analogy to the previous sections of the paper, a possibility function can be developed for this parameter also, as shown in Fig. 7(b).

In recent times, an increasing demand of society for better river water quality can be observed. This requires changes and improvements in the performance of sewage treatment plants, reduction in the use of fertilizers, etc. Scenarios of potential future developments in water quality can be generated. Figure 8 shows present conditions and a scenario for a potential future development (after the introduction of new water quality standards in Germany) for the Ruhr River. Here again many possible scenarios can be developed and on the basis of the results of these many potential development paths, a possibility function can again be constructed.

There are many other parameters influenced by society’s behaviour and value systems which may change in the future and influence the design of water projects. Such
(a) Possible development paths for total water demand

(b) Possibility function for water demand based on Fig. 7 (a)

Fig. 7 Water demand development paths (over 80 years) for the water supply region of the Jubach and Glôr Dams in Germany and resulting possibility function.

Fig. 8 Longitudinal section of water quality conditions (COD), present conditions and future scenario, Ruhr River in Germany (computed for mean annual runoff and mean annual pollution loads by water quality model REWARD).

parameters may be the discount rate, development of technology, development of financial capacity and change in society's value system, e.g. requirements of increased safety against floods or reliability of water supply.

For all these parameters the same procedure can be used as for the above mentioned parameters, all resulting in possibility functions which have to be combined again in a multi-dimensional possibility function of socio-economic changes. These again have to be transformed into design relevant variables, e.g. water demand in a procedure as presented in Fig. 5.

DECISION SUPPORT SYSTEM ON THE BASIS OF FORECAST ENVIRONMENTAL AND SOCIO-ECONOMIC CHANGES

Since, in both cases discussed above (environmental changes as well as socio-economic changes), it was possible to transform the multi-dimensional possibility function of the
changes into a one-dimensional possibility function (Fig. 9(a) and (b)) of the design parameters (e.g. water availability and water demand), it becomes possible now to support the decision to be made by a two-dimensional possibility function. This means, we assumed the simplest possible case, which can usually not be achieved in practice. Combination of these two one-dimensional possibility functions of Fig. 9(a) and 9(b) would result in a three-dimensional graph as shown in Fig. 5(a) which can be reduced to a two-dimensional graph as shown in Fig. 9(c). Here we recognize the areas of low, medium and high water demand as well as water availability. If the water project for this purpose consists of the design of a water supply dam, in the sense of sustainable development, the optimum solution out of many possible project alternatives would be one which covers all potential future developments of low, medium and high possibility. This is the outward edge of the rectangle specified as low possibility in Fig. 9(c). The curve identified by the project alternative of type B does not cover the whole area, but would be close to the optimum solution since it meets the principle of flexibility to a high degree. The present condition is shown by a point and a curve in the graph which

(a) Hydrologic conditions:

(b) Socio-economic conditions:

(c) Project alternatives:

Type B: possible performance (more flexible !)
Type A: possible performance (less flexible !)
Performance of the present supply system
(e.g. different operation rules)

Fig. 9 Assessment of alternative strategies for possible future conditions based on possibility functions for changing hydrological and socio-economic conditions.
covers only a small area of low and medium possibility. The point in the centre of the rectangles and the curve next to this point would specify a project alternative (type A) which meets at least the conditions of high possibility. A decision based on Fig. 9 would favour a project alternative of type B as optimum in the sense of sustainable development.

An item of high relevance has not been discussed yet, i.e. project costs. If project alternative B (Fig. 9(c)) would cost not much more than alternative A, then alternative B should be chosen, since it shows a higher flexibility. If, however, such a flexible design becomes much more expensive than one meeting only the high possibility area, a trade-off evaluation between flexibility and costs has to be made.

While the development of various scenarios for various environmental parameters has been carried out in the research work presented here, the application of the decision support system based on the two transformed possibility functions is still in the research phase. At present necessary computations for the analysis of this principle are under way for a selected economic region in a German river basin.

The authors are aware of the fact that besides environmental and socio-economic changes discussed in this paper, many other parameters influence the decision about water projects. These other parameters are, however, purposely neglected in this discussion in order to make the general approach presented in this paper clear.

REFERENCES