AN EPISTEMIC APPROACH APPLIED FOR INTEGRATED WATER QUANTITY AND QUALITY PROBLEMS – CASE STUDY BERLIN

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1. Introduction

Contemporary powerful means, such as systems analysis, mathematical modeling and computer-aided simulation, are inevitable for the investigation of complex systems and systems dynamics. A challenging task of this kind is, for example, the optimization of regional planning processes with the additional objective to preserve sustainable development even under the conditions of Global change. However, the more complex the research object is, the more it becomes unrealistic to expect, that one monolithic model alone could give the potential answer to all questions concerning this object.

Indeed, complexity means not only high numbers of elements, relations and processes. Much more challenging is the combination and difficult interconnection of rather disparate components such as natural and socioeconomic ones, objective scientific disciplines or interdisciplinary approaches and the more subjective participation needs, and, last but not least, small-scale and large-scale phenomena.

Even if we could establish a model comprising all these components and their difficult interconnections, there would be no proper way for its satisfactory validation. Consequently, if applying such a model the uncertainty would often be higher than the significance of possible simulation results.

Instead of this seemingly 'perfective' but rather unrealistic method, we propose an open, i.e. questions-orientated approach. Above that, our toolbox or the intended hierarchically structured methodological framework should be qualitatively and quantitatively open. This means, depending on the current question and situation, it would be always ready to be adapted, extended and improved. And the actual attempt or tool design is strictly focused on the task or problem next to be solved.

In chapter 2, we identify a general epistemic pattern that can often be met in connection with creative processes, and which can be adapted, in order to establish an integrated approach and the mentioned framework. We introduce its basic categories of modeling, which might be considered in principle or must be considered under certain circumstances.

In the main chapter 3, an application of the approach is dedicated to integrated investigations of water quantity and quality problems of an urban agglomeration - the region of Greater Berlin. In addition, this region is affected by problems coming from three other levels to be bridged: the upstream-downstream conflicts of the Spree-region, the structural changes in East-Germany since 1990, and the regional effects of certain components of Global change.

2. An epistemic structure to adapt for integrated approaches

We observed that many of the most creative processes, whether as natural developing ones or as human work, are in a certain way diamond-shaped (Figure 1). This shape is superior by its very clear and one-dimensional starting condition, followed by an extensive multi-dimensional period of growing by selective accumulation until a state of saturation is reached, and finally, by an intensive period of aggregation, structuring and organization of the accumulated material, converging to a result that is again one-dimensional, clear and unambiguous.

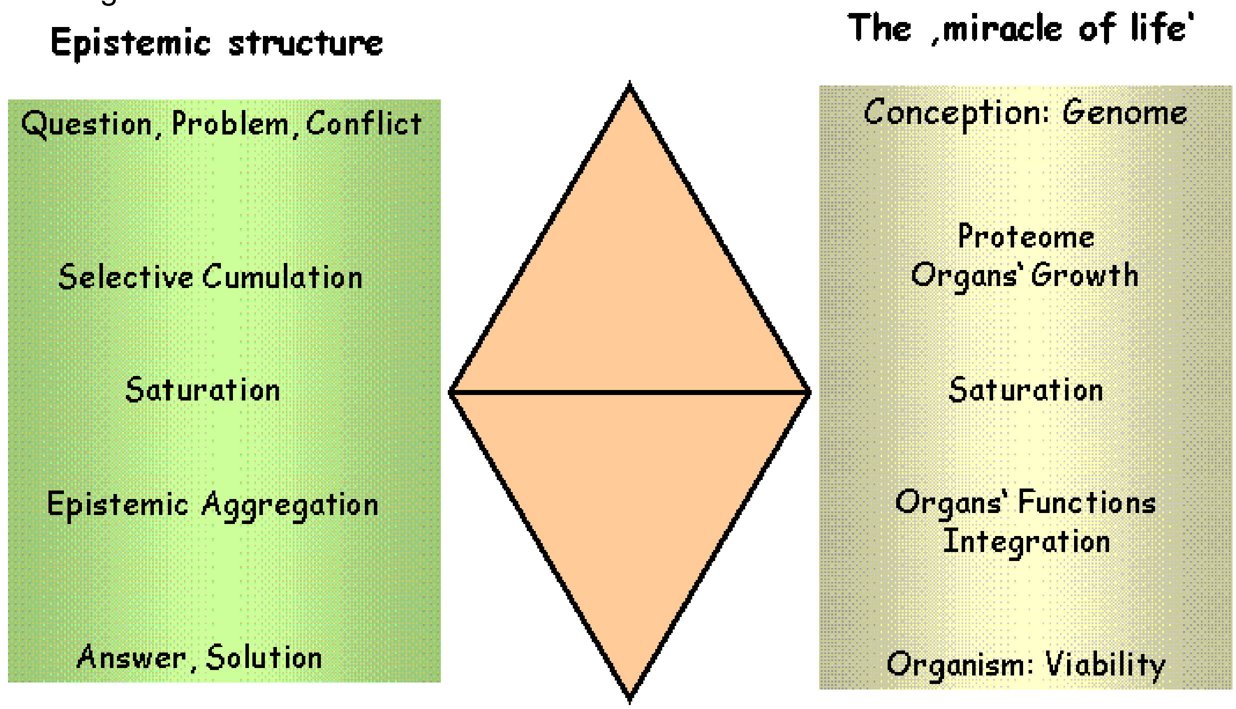

Figure 1: Diamond-shaped epistemic structure

The human prenatal ontogenesis is an impressive example for a natural development shaped in this way, earlier often referred to as the 'miracle of life' (Fig. 1).
We have adapted and translated this pattern to the process of investigating complex systems. The resulting integrated approach supports to investigate the system not once at the whole but rather task after task and problem by problem. Thus, we have to start always with a clear and unambiguous problem definition followed by systems analysis and accumulation of understanding selected according to a specific conceptualization of problem solving.
The complete adaptation of the diamond-structure to a structured epistemic approach for investigations of complex systems needs the translation of its important steps into appropriate categories such as systems analysis, modeling, simulation, participation, control, management, evaluation and decision support.
A complete list of basic categories of a stringent language calculus for a questions-orientated integration approach is given in Table 1. We assigned to them 3-letter-symbols that will be used in the following, in order to identify these categories when they are applied to the case study of Greater Berlin, which will be laid out in chapter

3.

#	Category	Symbol
1	**Regions:** *Geographic objects of investigation*	***REG***
2	**Time Range:** *Simulation interval for scenarios*	***TIR***
3	**Time Units:** *Time steps of models*	***TIU***
4	**Master Scenarios:** *Regional problems, conflicts, tasks*	***MSC***
5	**Stakeholder:** *Interest groups, institutions*	***STA***
6	**Exogenous Drivers:** *Components of Global change, driving forces*	***EXO***
7	**Alternatives:** *Management strategies, Bundles of options*	***ALT***
8	**Management Fields:** Fields for management activities	***MTF***
9	**Management Options:** *Activities quantitative*	***MTO***
10	**Models:** *Methods, facilities*	***MOD***
11	**Single Indicators:** *Variables, states*	***IND***
12	**Index-Variables:** *Aggregated indicators*	***IDX***
13	**Criteria:** *for integrated evaluation*	***CRI***
14	**Alternatives vs. Criteria:** *Impact-matrix for Multi-criteria analyses*	***AvC***
15	**Alternatives vs. Stakeholders:** *Equity-matrix for Conflict analyses*	***AvS***
16	**„Leitbilder“:** *Common, generally excepted Values*	***LBD***
17	**Integrated Impact Analysis**	***IIA***
18	**Multi-criteria Analyses**	***MCA***
19	**Equity Analyses**	***EQA***
20	**Negotiations**	***NEG***

Table 1: Catalogue of Basic Categories

3. Case study Greater Berlin: Integrated water quality and quantity research for an urban agglomeration

3.1 The research object

The region of Greater Berlin is part of the Elbe basin and belongs to the sub-basin of the Spree/Havel-tributary. Except the Spree and Havel rivers the flow network in this area consists of a number of smaller affluxes and of channels. In particular, Teltowkanal and Spree are the most important pathways of discharge down to Havel-river. Fig. 2 gives a spatial definition of the concerned system; the time range is 2000-2050.

Figure 2: River system of Greater Berlin

Greater Berlin is a typical urban agglomeration with most sensible water quality conditions, especially, because of the numerous and widespread dams and locks and the resulting low flow-velocity. In this way, water quality depends strongly of water availability. Consequently, reasonable investigations of the water conditions of Berlin must reflect the interconnection of both components.

Two other sub-regions of the Spree basin in upstream direction have extremely different conditions:

1. Spreewald region with biotope character, tourism and the production of specific agricultural goods
2. Upper Spree region (Lusatia) with extensive opencast lignite mining that has been

considerable reduced in connection with the drastic structural changes since 1990.
The first region needs water for biotope protection and agricultural production, while the second wants better to hold this water upstream for the regulation of groundwater levels and for an immediate restoration of abandoned mining holes. It would deteriorate the water amount and quality conditions in Berlin, if both measures would be applied unscheduled. This conflict situation could be even intensified under the conditions of Global change and should be diminished or solved by applying optimal distribution measures.

3.2 Problem definition and analysis

***MSC*: Master scenario**
The conflict situation laid out in the previous section allows us now to precisely formulate the problem or task, which has in first order to be solved in the Berlin region:

Ensure water supply security and expected waters quality for Greater Berlin under the conditions of Global change.

***STA*: Stakeholder participation**
First stakeholder contacts gave already an orientation for what should be understood under *expected*, namely, water quality class II on a predefined scale (LAWA, 2002) and conditions for water quality at public bathing sites as defined by the European Commission in 1975. An actualisation of these rules is just in progress.
The consultations serve in this initial step to grasp the sector-specific knowledge and to clear up the subjective interests of the stakeholders, the competence of institutions and their scope for activities, in order to judge if potential activities can really be implemented and if their effects would be helpful or not.
The complete list of interest groups and concerned institutions or administrations which has been identified is as follows; some key words about their interests are added:

- Regional development authorities -
  Planning for wastewater treatment and water plant capacity and allocation
- Environmental policy authorities -
  Reduction of P- and N-concentrations, Improved landscape water balances
- Health authorities -
  Quality of drinking and surface water, Eatable fishes
- Water suppliers
  Supply security, Rain water management
- Energy suppliers
  Economic capacity vs. environmental standards
- Navigation agencies
  Dam and locking conditions to enable navigation
- Environmental protectionists -
  Biotope protection, Local Agenda 21
- Public Bathers
  Near, cheap and clean public bathing sites

- Fishermen and angler -
  Protection of fish habitats.

After institutional analyses it follows a legal analysis leading also to identification of the guiding common values, which must not be subject of conflict analyses. We mentioned already the rules for bathing sites. This also concerns, however, given threshold values for the concentrations of certain compounds. Most relevant examples are phosphorus, nitrogen, heavy metals, and oxygen. In addition, all the economic sectors have to consider the given environmental standards.

3.3 Conceptualisation for problem solving

***MFD & MOP*: Identification of potential actions**

An important result after the analyses of stakeholder interests and competences has been the choice of the following 6 sectors or management fields:

- Senate's water policy (WP)
- Purification plant performance (PP)
- Rain water management (RW)
- Energy policy (EP)
- Flow regulation (FR)
- Environment protection (EN)

We define now actions or management options for these sectors on three levels of intensity.

Business as usual (0):

WP0 – Senate's planning variant 2025A
PP0 – Present equipment of purification plants
RW0 – Soil sealing trend grows proportional with urbanization
EP0 – Capacity and allocation of power plants as before
FR0 – Normally used 'adaptive Berlin-control'
EN0 – No additional environmental protection measures

Moderate improvement (1):

WP1 – Senate's planning variant 2025B
PP1 – Additional P-elimination in 3 important purification plants
RW1 – Remove the sealing from 30% of sealed areas
EP1 – Reduction of power plant capacity after energy import
FR1 – Up to 6 m^3/sec water transfer from river Oder
EN1 – Biotope enhancement by purified wastewater

Advanced control (2):

PP2 – Implementation of membrane filtration or UVC-technique for 2 PPs
EN2 – Additional redirection of purified wastewater.

***CRI & IND & IDX*: Identification of criteria and indicators**

Criteria and indicators are needed for the evaluation of impacts and they correspond to different levels in the structural scheme shown in Fig. 3. The approved partial models MOD_i belong to the integrated model in Fig. 4 and, when applied for impact analyses, deliver trajectories for state variables and single indicators. On the other side, the values, which will be used at the end for multi-criteria analyses, measure the impacts with respect to given criteria. In order to calculate these numbers, we introduced another hierarchic level dedicated to aggregated index variables IDX_i. As a rule, the criteria are corresponding to certain threshold values just concerning such index variables. And any value that is then used in multi-criteria analysis is the difference between the threshold value and the actual value for the index with standardization to the interval (0,1). The most interesting but in the same time demanding step in this procedure is the derivation of the index from appropriate single indicators where systems analysis and modelling efforts are needed (see Fig. 3).

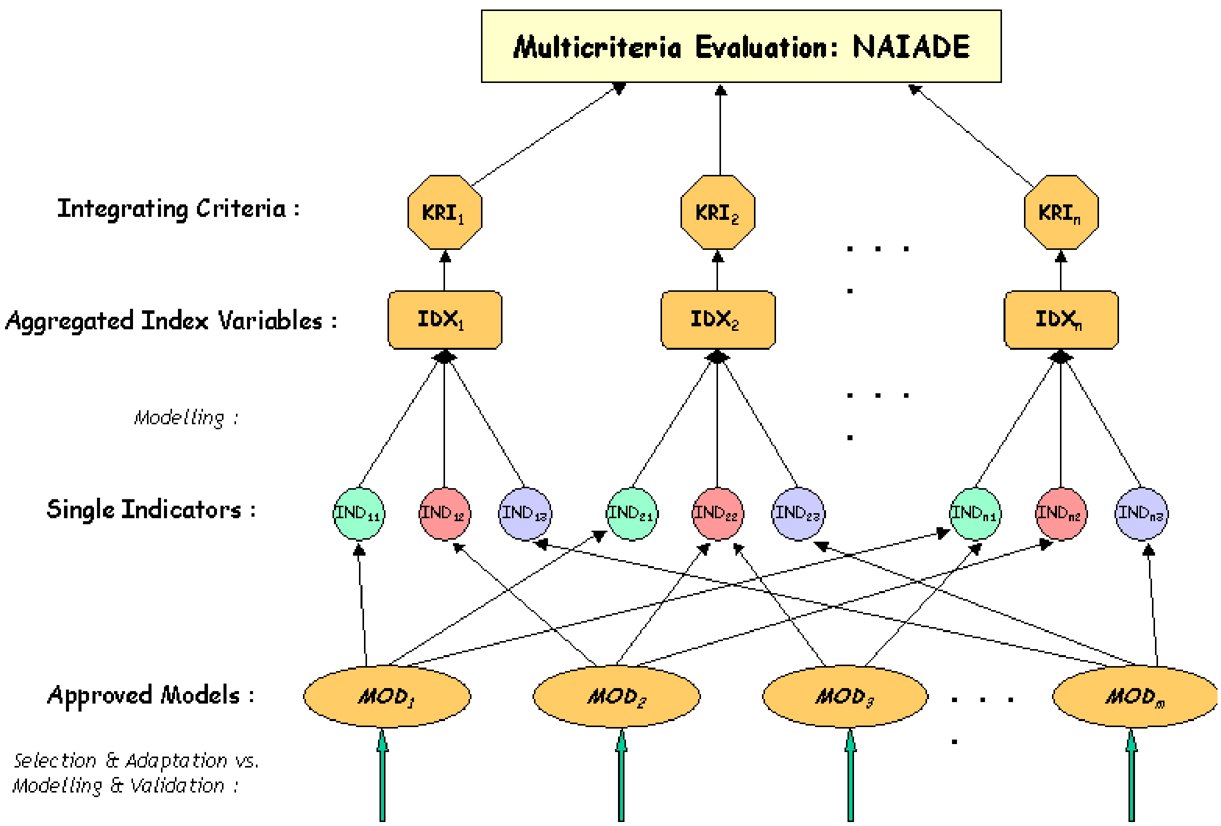

Figure 3: Structure for evaluations

It follows a list of index variables modelled to be used for the definition of criteria:

Aggregated Index Variable	Combined Single indicators
Water Supply Security Index	Deficit probabilities for Minimal discharges, Demands of PPs, WPs and lockage
Waters Quality Class Index	Threshold values (LAWA, 2002) for Chemical compounds and Trophy
Bathing Site Water Quality	TP, Chlorophyll-a, Blue-green algae, Secchi depth, Pathogenic bacteria, Potential bathing frequency

Episodic Fish Mortality	O_2-provisions, pH-value & NH4 through Exceptional loads by Canal overflows Caused by Heavy rain events
Urban Climate	Temperature distribution, Air moisture and Circulation in the urban area
Monetary Index	Balances for costs and benefits for alternatives

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Table 2: Index variables with assigned single indicators

***MOD*: Model set up**

The integrative character of this method becomes immediately transparent looking at Fig. 4. This scheme may serve as a vivid guidance for the impact analyses (Wenzel et al., 2002). It shows not alone the manifold of special purpose models (ellipses) used for these analyses, but also their working connections, the principal information passed between them (rectangles), two main clusters for the management fields (squares), and some complex index variables (circles) as prerequisites for the definition of evaluation criteria. The models in the left upper corner represent two components of Global change: Climate change and urbanization trends.

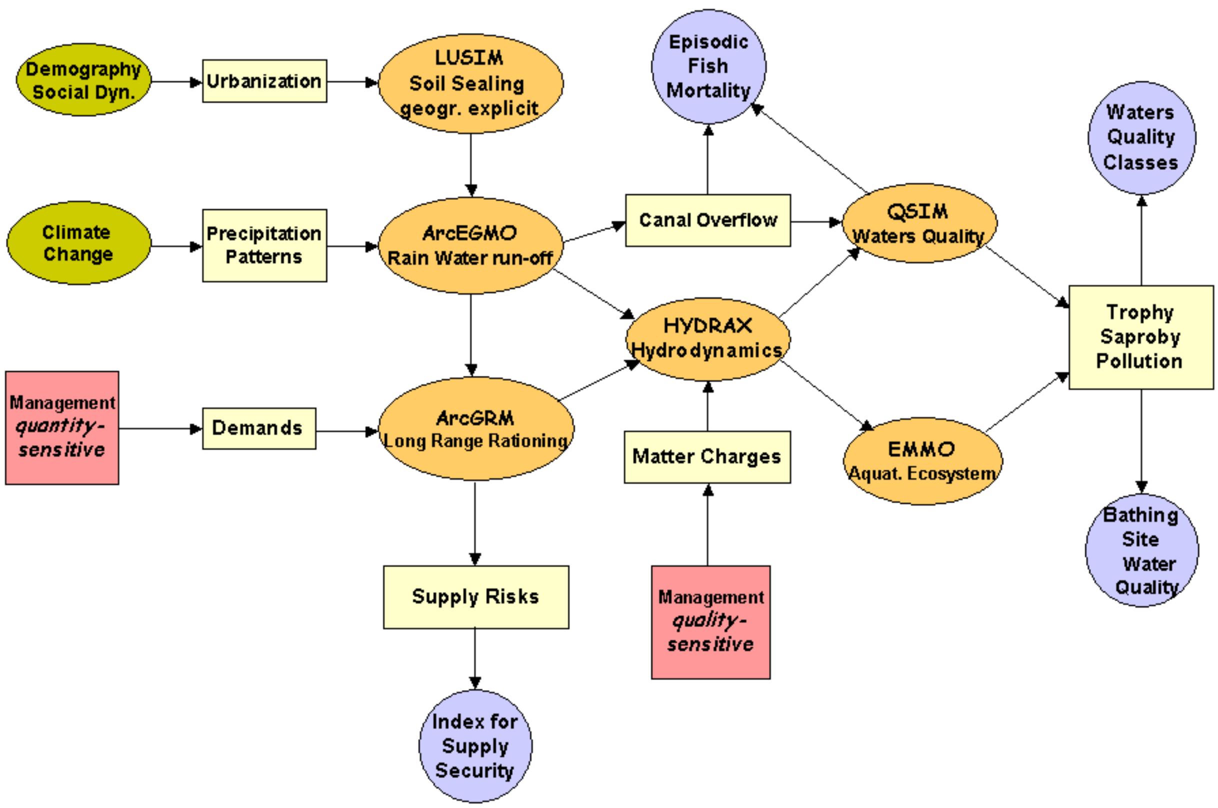

Figure 4: Integrated model for Berlin water quantity and quality investigations

3.4 Definition of scenarios

***EXO*: Quantification of external drivers**

Above the human control actions there are also drivers and changes, which cannot be influenced anthropogenic, immediately and purposefully. For example, this is true even for given budgets where we can only decide about spending and distribution.

However, the most important external drivers are connected here with Global change. In particular, two components are important for the water balances of the region: Climate change and Urbanization. They are incorporated within the integrated model of Fig. 4 in the left upper corner. The most sensible climate parameter is precipitation and the most water-sensible factor of urbanization is soil sealing. Both are changing the run-off conditions in the region and, therewith, water availability and spatial distribution.

We use a climate change scenario with a temperature growth of 1.5 K represented by 100 statistically distributed realizations of precipitation time series, the spatial heterogeneity of which is correlated with past measurements of a number of climate stations distributed in the region (Gerstengarbe & Werner, 2003).

Urbanization is implemented through a soil-sealing trend, which is modified by region-specific anticipation of future population growth and building characteristics. In order to make the given trend geographically explicit according to certain rules, a special purpose model has been developed and applied (Ströbl et al., 2003).

***ALT*: Design of alternatives**

In step 2 we selected 6 sectors or management fields and 14 quantitative actions or management options on these fields (Senatsverwaltung für Stadtentwicklung, 2001). We consider now all possible combinations of such actions and meet no difficulties to select of them the meaningful and most interesting alternative strategies. Using the introduced symbols, we want to compare the following 4 Berlin-specific alternatives:

***ALT1**: WP0,PP0,RW0,EP0,FR0,EN0 - Business as usual*
***ALT2**: WP1,PP0,RW1,EP1,FR0,EN1 - Moderate Options*
***ALT3**: WP1,PP0,RW1,EP0,FR0,EN2 - Redistribution of water for Biotopes*
***ALT4**: WP1,PP2,RW1,EP0,FR0,EN2 - Improved purification & Biotope protection*

ALT5 – ***ALT8*** are the same as ***ALT1 – ALT4***, but with the transfer of Oder-water *(FR1* instead of *FR0).*

In addition, the 4 Berlin-alternatives are superimposed with 2 scenarios in the Upper-Spree region, namely, *Flooding of abandoned mining holes* and *Reduced affluxes* (Kaltofen et al., 2003). Thus, we have altogether the following ensemble of alternatives to compare:

1. Basic-Scenario **ALT1 – ALT4**
2. Oder-water transfer **ALT5 – ALT8**
3. Flooding of abandoned holes **ALT9 – ALT12**
4. Reduced affluxes **ALT13 – ALT16.**

3.5 Impact Analysis

Impact analysis consists of the calculation or estimation of the values or trajectories for the selected single indicators applying the appropriate pathways of the integrated model (Fig. 4) or, otherwise, by the acquisition of the corresponding expert knowledge, the collecting of needed data by literature review or adaptation from appropriate databases. This has to be done for all alternatives to compare with the intention to fill the impact-matrix as an inevitable prerequisite for NAIADE multi-criteria analyses.
For details see Wenzel (2004).

3.6 Evaluation of alternatives

If the trajectories for the single indicators are available for all the alternatives to compare, we proceed with the calculations for aggregating index variables. Two examples are given in the following.

***IDX_1*: Index of bathing site water quality**
The normative frame for bathing sites is scheduled by the *Guidelines of the European Council* (Richtlinie des Rates, 1975). We consider the two most important topics of them, namely, pathogenic bacteria (Escherichia coli *EC* and/or Coliform bacteria *CB*) and trophy (determined by total phosphorus *TP*, Chlorophyll-a *CHLa* and/or secchi depth parameters). So-called normative G- and I-values (Guiding and Imperative, resp.) are defined for both dimensions. Those can be used for standardization of the corresponding water quality index to interval (0,1).
Recently, Blue-green algae toxicity has become important and to form a third dimension. This factor could be standardized too through normative values for the algae biomass or abundance (BA).

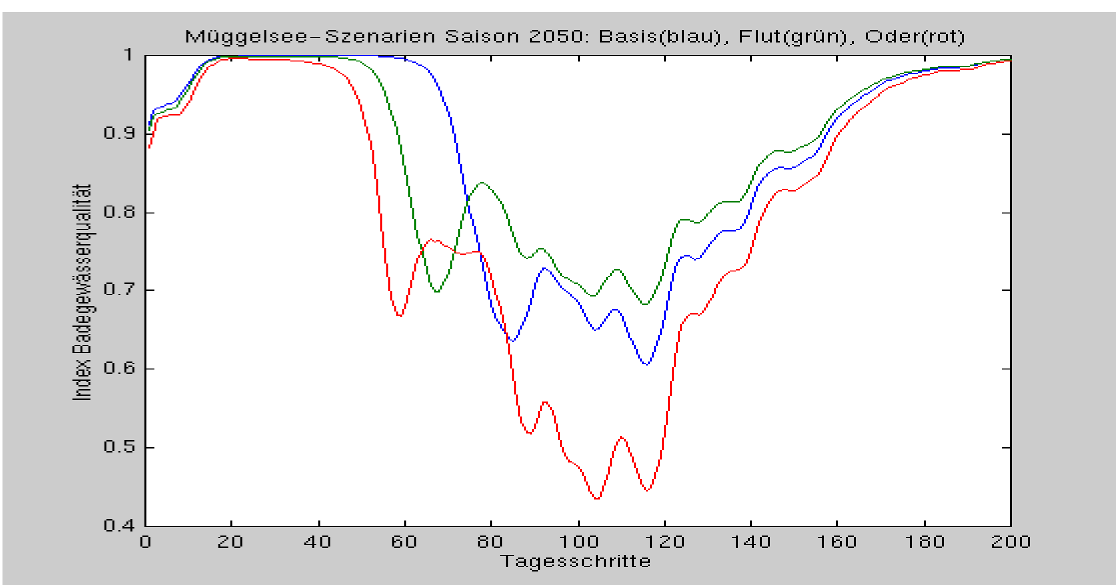

Figure 5: Müggelsee-trajectories of bathing site water quality for 3 scenarios

Using all the available information for calibrations, the index is put together of the following three terms:

$$BQ = (1-BQ1)/3 + (1-BQ2)/3 + (1-BQ3)/3$$

$$BQ1 = CHLa / 150\ g/l;\ BQ2 = 0.113*BA\ mg/l;\ BQ3 = \log(EC) / 4.$$

This index is site-specific and can be aggregated, for example, by integration and combination with other sites, where the bathing frequency is used as a weight that expresses an economic / monetary value.

***IDX_2*: Index for supply security**

The dominating types of demand facilities in Berlin are water plants (WP) and locks, electrical power plants (EP), and gauges with minimal discharge demand (GM). We calculate the deficit probabilities per month *W(a, month)* by applying the model ArcGRM for each single aggregate *a* of each type.

An integration in time yields for any year of a 5-years period (pentade):

$$W(a,year) = W(a,pentade).$$

It follows integration over the aggregates *a* with individual weights *q(a):*

$$V(p) = (\Sigma q(a) * W(a,p)) / Q \qquad \text{with } Q = \Sigma q(a)$$

The weight for a gauge *q(a)* is the demanded local discharge $Q_{min}(a)$ in m^3/s , while those for the EP or WP are identified with the optimal demanded quantities.

For EP the deficit probability corresponds to the water quantity that is multiple used when taken from the currently available water pile.

***AvC*: Multi-criteria analyses**

The calculations of the index variables for all alternatives provide the elements of the impact matrices. And those are the input information of multi-criteria analyses for optimisation purposes under assistance of the NAIADE-system (Munda, 1995).

We show two special cases for illustration.

In the first case, we consider the four internal Berlin-alternatives without and with Oder-water transfer (*ALT1 – ALT8*) and the three components of supply security as criteria. As for pure water quantity criteria holds *ALT3* = *ALT4* and *ALT7* = *ALT8*, the corresponding impact matrix has the following form:

Matrix Type: Impact — Case study: Berlin Water Case Study

Criteria \ Alternatives	ALT1	ALT2	ALT3	ALT5	ALT6	ALT7
Gauges Supply-security	0.8058	0.8112	0.7942	0.8302	0.8391	0.8186
Waterplant Supply-secur.	0.9484	0.96641	0.9497	0.9722	0.9873	0.975
Powerplant Supply-secur.	0.754	0.9949	0.7379	0.8252	0.9949	0.8034

Figure 6: Impact-matrix with supply security

The following rankings are delivered by multi-criteria analysis:

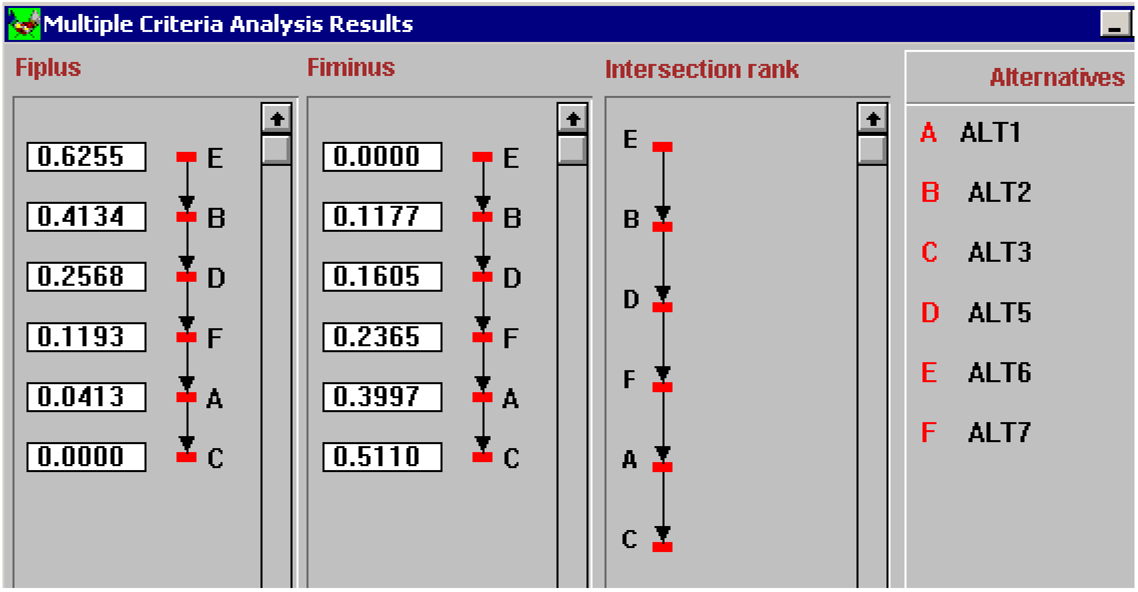

Figure 7: Ranking with supply security

The moderate control measures (ALT2) are winning, even more with additional Oder-water transfer (ALT6).
The second case considers for ALT1 – ALT4 in addition the water quality criteria of trophy and of matter compounds in pentade 1 (2003-2007) for both, Spree-river and Teltowkanal (Tek):

Matter Type: Impact — Case study: Berlin Water Case Study

Criteria \ Alternatives	ALT1	ALT2	ALT3	ALT4
Gauges Supply-secur.	0.917	0.91497	0.8823	0.9349
Vaterplant Supply-secu	0.9884	0.9904	0.9455	0.944
'owerplant Supply-secu	0.9349	0.9487	0.9089	0.9487
Compounds-Index Spre	0.6342	0.6436	0.6377	0.6425
Compounds-Index Tek	0.535	0.5472	0.5405	0.5412
Trophy-Index Spree	0.4976	0.4863	0.4939	0.4889
Trophy-Index Tek	0.4895	0.4902	0.4894	0.4836

Figure 8: Impact-matrix with supply security and water quality

We show here the results for pentade 1:

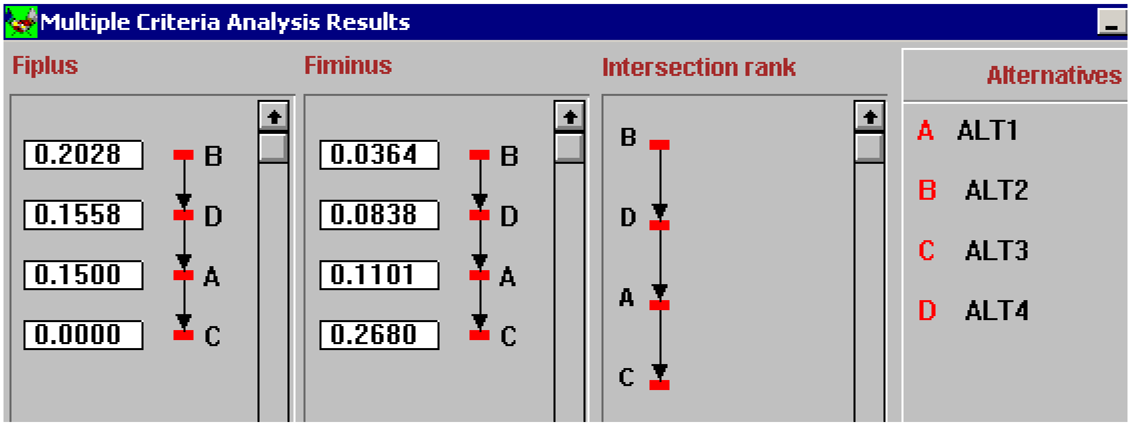

Figure 9: Ranking for supply security and water quality (pentade 1)

Again ALT2 is the best one, however, ALT4 improved its position and follows now immediately, i.e. the environment protection measures are significantly effective.
For pentade 10 (2048-2052) ALT4 was replaced by ALT5 (Business as usual with Oder-water transfer). We show only the results:

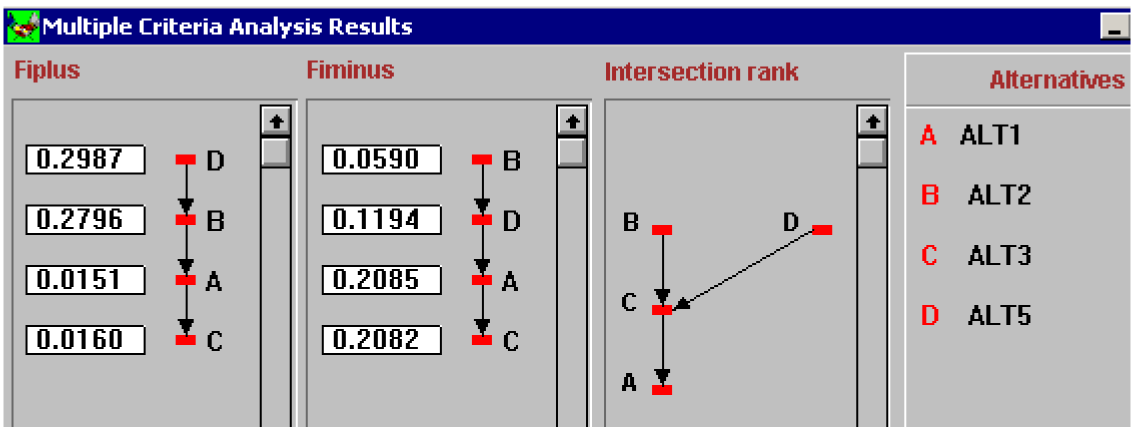

Figure 10: Ranking for supply security and water quality (pentade 10)

Despite of the simple configuration, this result shows already a more complex form of order: Namely, first and second column have different order. Consequently, the intersection rank is no more of linear order. However, Fiplus represents an optimisation and declares ALT5 (Oder-water transfer) the best decision. Fiminus represents a pessimisation, i.e. for catastrophe prevention is ALT2 a better solution. The reason is that the water quality deteriorates with the Oder-water transfer.

3.7 Negotiation for compromise

***AvS*: Equity-analysis**

This step is dedicated to conflict analysis, negotiation and compromise searching. For this purpose the stakeholders are asked to subjectively evaluate every single alternative. We use for this goal NAIADE equity-analysis (Munda, 1995) and propose for the evaluations its intrinsic linguistic scale with the following fuzzy-variables:

0 *Extremely Bad*
Very Bad
0.08
Bad
0.24
More or Less Bad
0.41
Moderate
0.59
More or Less Good
0.76
Good
0.92
Very Good
1 *Perfect*

The numbers mark the points of overlapping for neighbouring functions. The result of all stakeholder evaluations is then established as equity-matrix:

Matrix Type: Equity   Case study: Greater Berlin water household

Alternatives / Groups	ALT1	ALT2	ALT3	ALT4	ALT5	ALT6	ALT7	ALT8
Urban development	Bad	Good	Good	Very Good	Very Bad	Bad	Moderate	Moderate
Environment policy	Very Bad	e or Less G	Very Good	Perfect	Very Bad	Bad	re or Less E	Good
Health care	Bad	re or Less E	Moderate	Good	Bad	Moderate	e or Less G	Good
Water supply	Moderate	Moderate	Moderate	Moderate	Very Good	Good	Good	Good
Energy supply	e or Less G	Moderate	Moderate	Moderate	Very Good	Very Good	Very Good	Very Good
Navigation	Moderate	Bad	Bad	Bad	Very Good	Good	Good	Good
Envir. protection	Very Bad	Bad	Good	Very Good	xtremely Ba	Very Bad	Moderate	Moderate
Bathing outdoor	Bad	re or Less E	Moderate	Good	re or Less E	re or Less E	Good	Very Bad
Fishermen	Very Bad	Bad	Moderate	Moderate	Good	Good	Very Good	Very Good

Figure 11: Equity matrix Berlin

NAIADE equity-analysis uses the matrix as input and delivers a coalitions dendrogram:

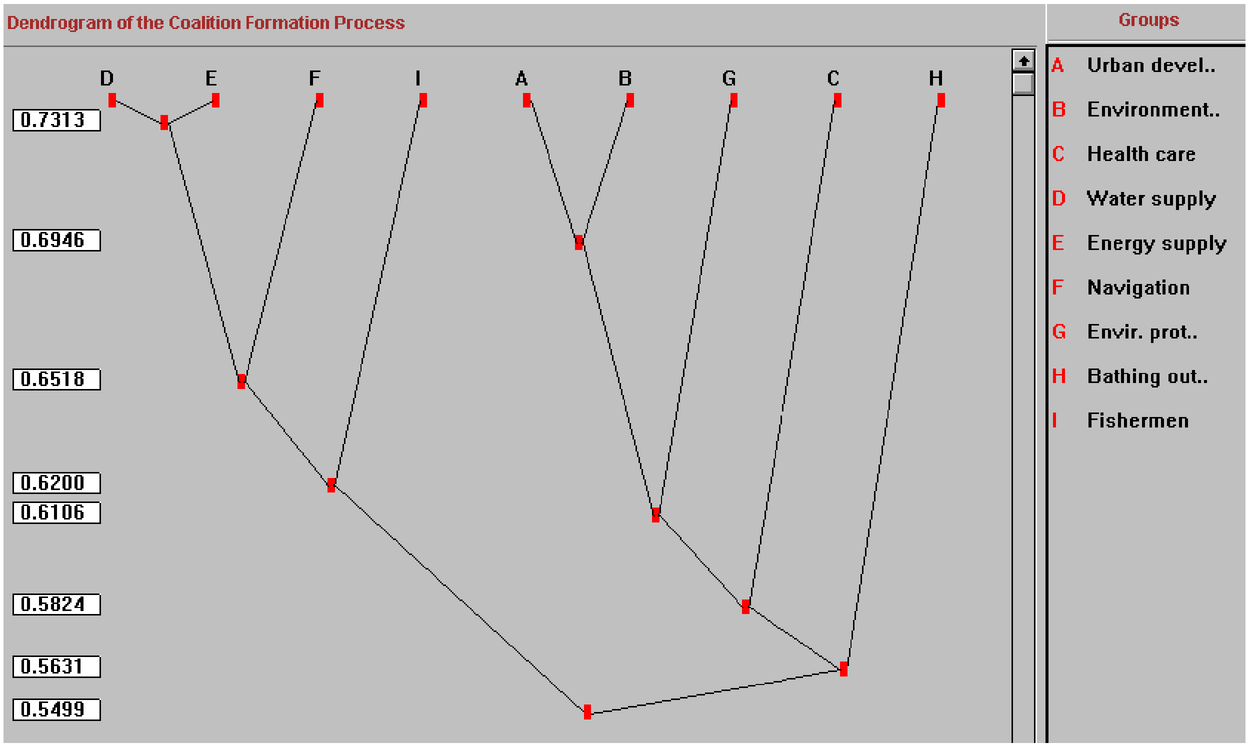

Figure 12: Coalitions dendrogram

***NEG*: Negotiations**

The next step organizes negotiations between the water suppliers and the energy suppliers, as they are already close to a common evaluation. If they find a compromise, then 2 lines of the equity-matrix may be replaced by only 1 and equity analysis repeats with a matrix of lower dimension. This iterative process may end in different way:

- The stakeholders find – iteration by iteration – a compromise evaluation that corresponds to a compromise ranking of alternatives.
- A compromise among the stakeholders with respect to the present ensemble of alternatives cannot be found.

In the latter case, negotiations should concern not only the evaluation of alternatives but also the mitigation of inconvenient effects by their modification or even the definition and inclusion of new alternatives. Then this iteration requires in addition new impact analyses.

Thus, the differences between stakeholders can be stepwise reduced or, if possible, removed. The decision maker receives in both cases a richer information base for his decisions.

Both rankings, the optimal and the compromise, form together a quintessence of the present knowledge about the system. Its simple and handy character is welcome and intended. However, this should not disguise the fact that the complexity of the investigated system was made much more transparent (corresponding to the saturation level of the original epistemic structure) and that we have access on every detail within this structured procedure, which is always ready for iterations under modified conditions.

Therefore, limitations are given by the resources needed for its application rather than by the method itself.

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