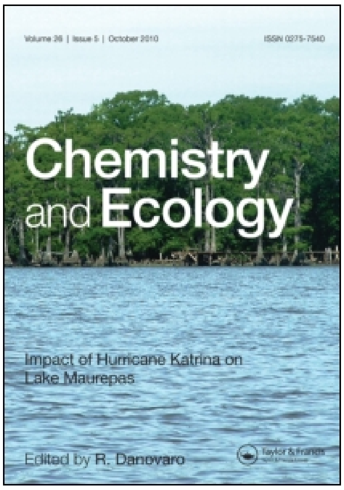

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daNUbs: Lessons learned for nutrient management in the Danube Basin and its relation to Black Sea euthrophication

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The results of the daNUbs-project deliver a basis for a proper management of nutrients in the Danube Basin. The understanding of the sources, pathways, and sinks of nutrients in the Basin and their effects on the Western ad North-Western Black Sea (WBS) ecosystem has been improved. Quantitative models on the emission of nutrients, their transport along the rivers, and their impact on the WBS have been further developed and combined. Phosphorus loads discharged by the Danube are 30–50% lower than in the 1980s (dissolved P even to a higher extent). Nitrogen emissions have decreased considerably as well. The lower nutrient discharges from the Danube have led to a significant improvement in the WBS ecosystem. Current low discharges of N and P to the WBS are the result of (1) improved nutrient removal from waste water in Germany, Austria, and Czech Republic, (2) reduced P-discharges from detergents and (3) the consequences of the economic crisis in central and eastern European countries following the political changes of 1989/1990. As the decrease is partly due to the economic breakdown in the formerly communist countries, economic development in these countries has to go along with proper nutrient management. Otherwise, the situation in the WBS ecosystem will deteriorate again.

Keywords: Black Sea protection; Danube River Basin; Eutrophication; Integrated river basin management; Nutrient management

1. Introduction

Problems related to eutrophication of marine estuaries due to excessive discharge of nutrients (mainly nitrogen and phosphorus) by large rivers are recognized in many regions of the world. Often, high nutrient discharges stem from diffuse sources linked to land use and agriculture. The daNUbs research project within the 5th European Research Framework Programme dealt with this problem in the Danube River Basin and the Western and North-Western Black Sea (WBS), which is highly influenced by the discharge of the river Danube. The project was performed by an international and multidisciplinary research team with 17 scientific institutions in seven European countries and in close cooperation with the International Commission for the Protection of the Danube River (ICPDR). The project was carried out from February 2001 to March 2005 (figure 1).

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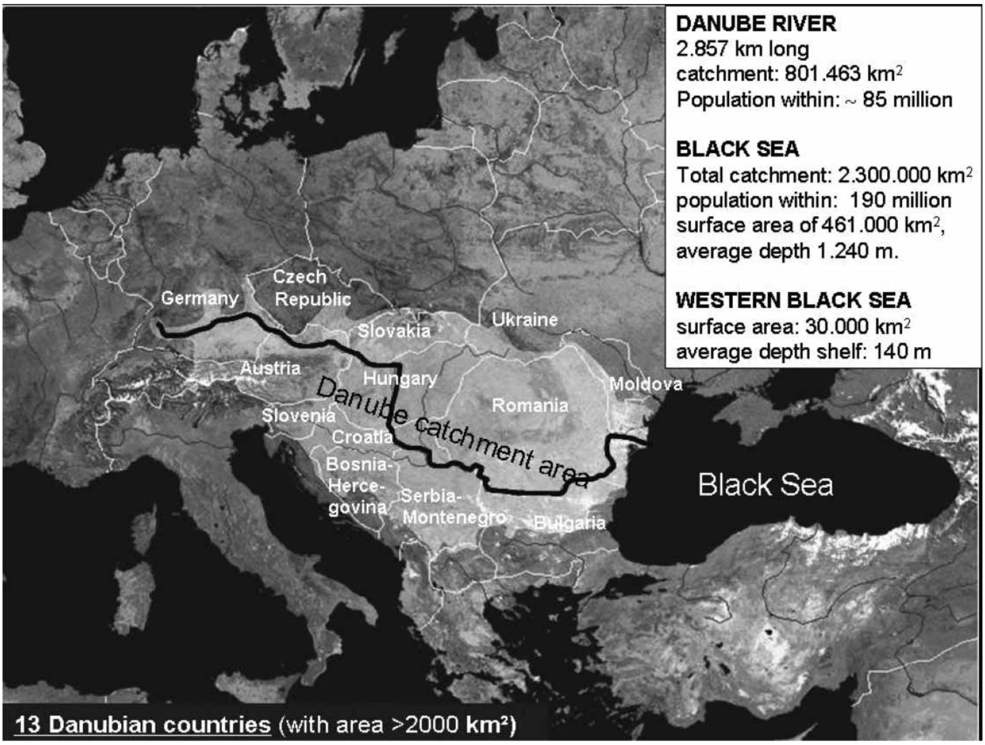

Figure 1. Danube, Danube Basin and Black Sea.

1.1 *Project characterization*

The motivation for the daNUbs project can be characterized by the following aims (figure 2):

- improvement in the understanding of the fate of nutrients (N, P) from their sources (especially the diffuse sources) to the WBS in order to enhance existing mathematical models (MONERIS, Danube Water Quality Model, Danube Delta Model);

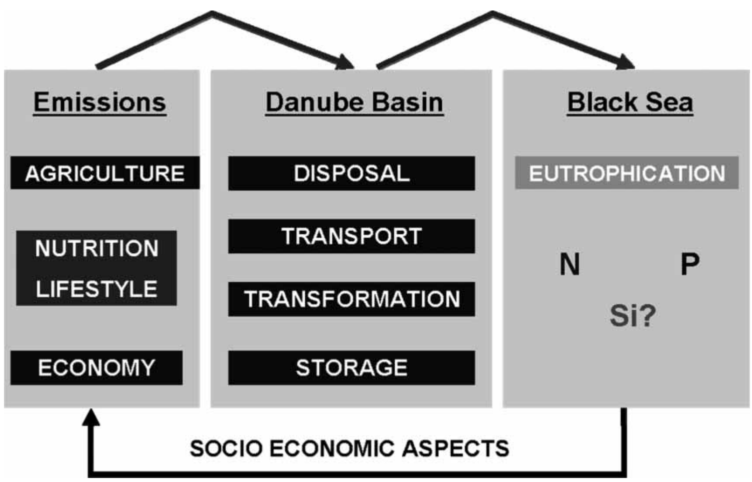

Figure 2. Concept of the daNUbs research project.

- improvement in the understanding of the role of river discharge for the eutrophication process in the WBS in order to derive information on the nutrient load which leads to a sustainable quality of the WBS along the coast;
- development of technical and operational measures able to reduce excessive discharge of nutrients with special emphasis on waste-water-treatment requirements, agriculture, and land use;
- development of different scenarios linked to political and socio-economic tools which can be applied in order to achieve a good status of all waters in the Danube Basin in accordance with the EU Water Framework Directive (WFD);
- development of monitoring procedures in order to check the effect of the measures implemented.

2. Material and methods

2.1 *Project methodology*

The basis for the following considerations is an assessment of all anthropogenic and natural sources of the nutrients nitrogen and phosphorus which are relevant for water-quality management. This assessment requires information on the flow of goods as well as the nutrient content related in natural environments and in the human society. Important data sources are the national statistical authorities and administrative bodies on a national level (e.g. ministries) or county level. To a large extent, data are aggregated on a national or other administrative level and not on a catchment level. Especially for agriculture, a more detailed spatial attribution of nutrient data is advantageous but not available everywhere. If no (regional) information is available, information from comparable regions is transferred, or expert knowledge has to be considered. The results of the assessment of the sources of nutrients were used as input data for the MONERIS model (MOdelling Nutrient Emissions in River Systems) [1, 2].

The MONERIS model describes the transport and transformation of nutrients from their sources to the river system as well as in the river system. This model takes into account the local geologic and morphologic conditions (GIS based digitalized maps), soil type, land use, crop production, livestock densities, urban settlements, waste-water-treatment plants, etc., and also the climatic conditions are reflected. The calibration of many parameters of this model was derived from the application of the model to a series of different European catchments with different characteristics and good data availability. In order to check the applicability of the model under the specific climatic and hydrological conditions of the Danube Basin, investigations in five case study regions (400–4000 km^2) within the Danube catchment were performed where data availability was higher and additional data collection could be realized within the frame of the daNUbs project [3]. With the calibrated model, the historic development of nutrient discharges of the Danube River as 5 yr averages was simulated and compared with the historical data on nutrient discharges in the Danube Basin. However, it has to be considered that the historical data do not always meet the same quality criteria as the present ones.

As a consequence of the economic breakdown in 1989 in Eastern Europe, there was a dramatic change in agricultural practice (fertilizer application, manure management, etc.), the use of detergents and industrial activity. The resulting change in nutrient discharge allowed a more significant test of the calibrated model as compared with more steady-state conditions (figure 3).

The discharged N-load (especially those for dissolved species) is strongly influenced by the annual water discharge of the Danube River which can vary in a broad range (below 140 km^3 to almost 300 km^3, average 206 km^3 per year). The interpretation of the calculated nutrient

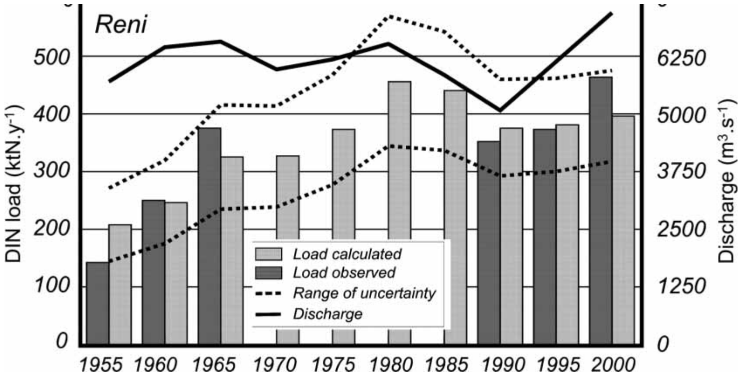

Figure 3. Deviation N-load calculated to load observed at Reni station (directly upstream of the Danube Delta) for 1955–2000 [2].

load in respect of trends over time has to take this fact into account. MONERIS model results are attributed to a 5 yr moving average which reflects the slow response of the basin to changes in anthropogenic and climatic conditions.

The Danube Water Quality Model (DWQM) [4] describes the transport, transformation, and storage processes in the large rivers, where the influence of the riparian morphology plays a minor role, while eutrophication, sedimentation, storage, and remobilization are important. Special emphasis in this model is attributed to the effects of dams for hydropower production on the transport of sediments and nutrients. The largest reservoir within the Danube Basin is the Iron Gate Dam at the end of the middle section of the Danube River. There, an important storage process takes place. This reservoir will remain a sink also during the next decades. Especially for particulate phosphorus, this storage process is important.

One of the interesting developments within the daNUbs project is the transformation of the 5 yr moving yearly average of the MONERIS Model output to the dynamic DWQM able to describe the daily load variations caused by the flow situation in the large rivers.

The output of the DWQM is used as input to a separate detailed Danube Delta Model (DDM) [5] describing the influence of the Delta on the nutrient discharges to the WBS. With this combined model approach, it is possible to simulate the effects of changes of nutrient management in the Danube Basin on the nutrient discharge to the WBS with adequate accuracy for strategic decisions.

Using historic data, it was possible to simulate the effect of the economic crises in the CEE countries starting in the years 1989/1990 on N and P discharge to the WBS. N-discharges from diffuse sources started to decrease due to reduced market fertiliser application. However, the response in nitrogen discharge reduction was retarded, as (1) the main pathway of diffuse N-input is via groundwater, which can have a long retention time (up to >30 yr), and (2) the water discharge in the late 1990s was relatively high (figure 3).

Several cruises were carried out to investigate the actual state of the marine ecology. The results were related to chemical–physical analytical data in order to identify the impact of the Danube discharge on the WBS. All this information was compared with the existing historical data, and the most important indicators for the evaluation of the status were derived. At the same time, a group of modelling experts applied and adapted existing quantitative physical and biological models using the output of the DDM as input to the marine models. The detailed WBS Models had to be embedded into an existing Black Sea Model in order to obtain the correct boundary conditions [6]. As the mixing conditions between Danube and Black Sea strongly depend on climatic conditions (wind speed and direction, temperature, solar radiation, etc.), it is necessary to use dynamic models able to simulate the effect of short-term changes in weather conditions. The model results were compared with chlorophyll *a* data derived from satellite images (SeaWiFS) and with results obtained by the marine ecologists during their cruises [7]. With these models, different scenarios were simulated using specific historic climatic conditions as background.

Using the information on the various factors and processes, different scenarios can be developed in respect to economical, political, and technological tools. As a result, nutrient discharges to the receiving sea are obtained. It is also possible to use 'bearable nutrient loads for WBS' as a base for the scenario calculations, even if it is complex to assess these loads. Therefore, a decision has to be made for the implementation of a combined approach strategy including the:

- precautionary principle (legal framework on minimum criteria, e.g. Urban Waste Water Directive (UWWD), good agricultural practice, enhanced by economical incentives, etc.) and
- environmental quality criteria for additional measures based on cost-effectiveness.

3. Results and discussion

3.1 *Driving forces of nutrient discharges and natural factors for transport and losses*

Data quality assessment is always an important task, even more in a transnational catchment like the Danube catchment. The most reliable water quality data are those for dissolved (inorganic) nutrients. Data are much less reliable in regard to particulate and organically bound nutrients. The assessment of data has to consider that the measured values are already the result of various processes and their related history like (i) natural nutrient input, (ii) anthropogenic input, (iii) primary production (sunlight, climatic conditions), (iv) release of nutrients from breakdown of organic solids (including denitrification), (v) transport phenomena, intermediate storage and (vi) 'final' storage in sediments (e.g. riparian zones, deep sea). All these processes are subject to strong variations over time (day, season, year, decades) and are heavily influenced by specific local and regional conditions. As a basic consequence: the interpretation of measured concentrations and calculated fluxes (loads) without understanding the processes involved is limited and can be even completely misleading.

The main anthropogenic driving forces for N and P discharge to the Black Sea are (figure 4):

- agriculture;
- waste-water management (sewerage and wastewater treatment);
- air pollution by combustion process (traffic, energy conversion, etc.) with NO_x.

Within the agricultural production process, the following activities strongly influence nutrient emissions to the water system:

- fertilizer management in plant production;
- production of animal protein and fat (meat, milk, and eggs);
- soil-quality management, erosion abatement, etc.;
- agricultural policy (financial support) at national, EU, and WTO levels.

Noticeable regional differences in the (area-specific) nutrient emissions from anthropogenic sources and from the natural background can be identified. These emissions can be modified heavily by natural conditions like geology/soils or precipitation and cause further regional

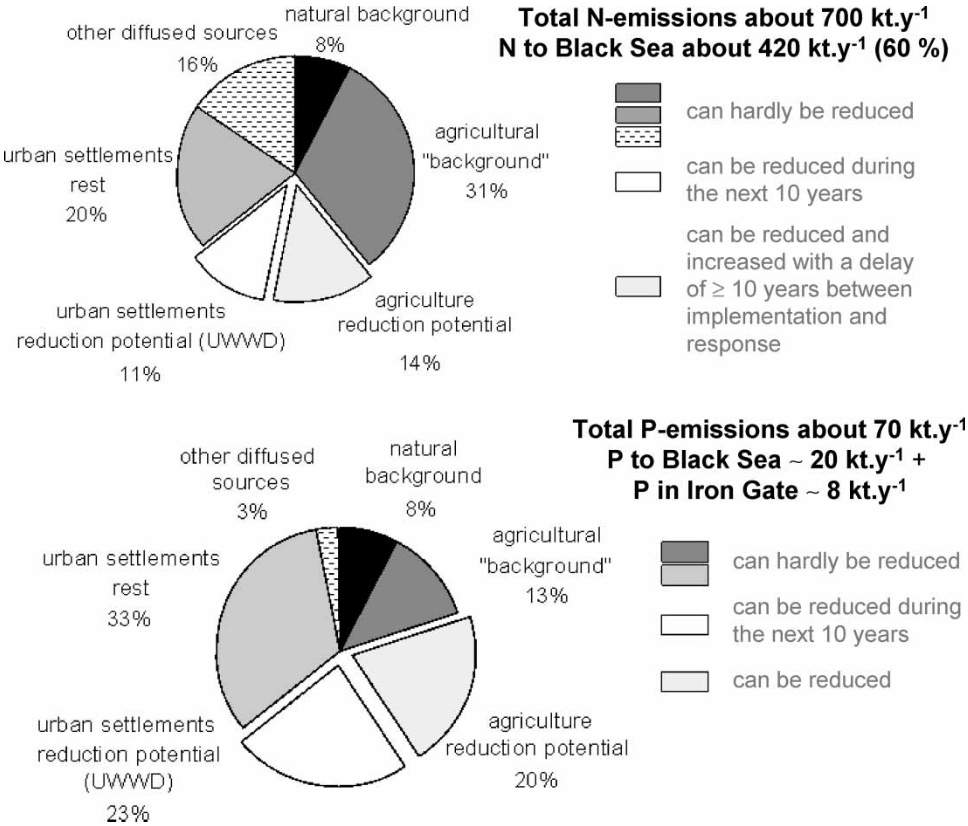

Figure 4. Sources of nutrient emissions 1998–2000 into the Danube River [7].

differences. These modifications by the natural conditions can even be more pronounced than the N-surpluses of agriculture in different regions.

Important natural factors influencing nutrient emissions to river water system are:

- soil geology;
- climatic conditions (precipitation, etc.);
- slope;
- residence time in groundwater.

These regional differences mean that the goals (1) protection of local groundwater or surface waters and (2) protection of the WBS can require completely different measures. For instance, it can be shown that regions with high nitrate concentrations in groundwater are of minor importance with respect to nitrogen emissions to the Danube and the Black Sea due to high denitrification rates in groundwater, while regions without problems with high nitrate concentrations in groundwater due to high dilution may have significant contributions to the emissions to the river Danube and the Black Sea [3].

Driving forces for transport, retention, and losses of nutrients can be specified as follows:

- the denitrification mainly in soil and groundwater (residence time), in zones of interaction between groundwater and river water (littoral areas), and in small to medium-sized rivers [8];

- erosion together with over-fertilization strongly contributing to transport of particulate nutrient loads (also, their role for eutrophication is still not very well understood);
- sedimentation of particulate nutrient loads in small and medium-sized rivers, and re-mobilization of these nutrient loads at high flow conditions with partial transport and sedimentation at flooding areas [9];
- the large dam at Iron Gate representing an important sink for phosphorus, even for decades to come [4].

  Large rivers including wetlands along these rivers and the Danube Delta have little influence on N transport and loss [4, 6].

3.2 *Status of the Western and North-Western Black Sea Coastal Area (WBS)*

Starting in the early 1970s, the yearly loads of phosphorus and nitrogen components discharged by the Danube River into the Black Sea have increased considerably. These nutrients are mainly responsible for the primary productivity (algae growth) in the marine environment. In the mid-1980s, N and P discharge reached a historic peak, with the result that the mass production of phytoplankton had severe deleterious effects on the shallow water ecosystem of the WBS including hypoxia near the bottom water layers [10]. By the end of the 1990s, almost no anoxic conditions were observed in this region, which has been regularly investigated by the Romanian monitoring programme and since 2001 within the daNUbs-project.

In the WBS waters off the Danube Delta, the N/P ratio increased during the early 1990s and reached its optimum value of 16 (Redfield ratio) in 1997. Since this year phosphorus has become the limiting nutrient for phytoplankton growth in the WBS, while in Black Sea offshore waters and in the Bulgarian shelf area, still influenced by river Danube discharge, N is the limiting nutrient for primary production.

A further indicator for the improvement of the ecologic status of WBS is the increase in macrobenthic organisms from 22 to 38 species in the Romanian waters off the Danube delta from 1998 to 2002 [11] (figure 5).

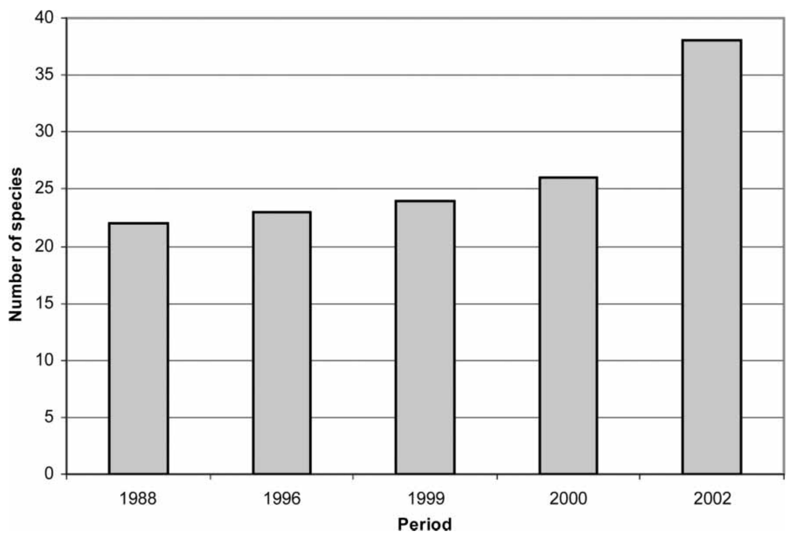

Figure 5. Development of number of macrobenthic species in the Romanian waters off the Danube delta from 1988–2002 [11].

Another indicator of improvement is the decrease in phytoplankton blooms observed from ocean colour registering satellite sensors in previous years compared with the extension of strong phytoplankton blooms in the 1980s [11].

Investigations conducted in the frame of the daNUbs project [7] in September 2002 showed the presence of healthy growing epibenthic organisms especially *Mytilus galloprovinzialis* and *Ciona intestinalis* on a station grid, extending 50 km off the Danube delta. The healthy development of these species indicates that there were no recent longer-lasting anoxic conditions in front of the Danube delta.

Extremely long-lasting calm and warm weather periods may still lead to the development of strong pycnoclines and stagnation in the shallow shelf water areas strongly influenced by Danube discharge. Under these exceptional conditions, occasional anoxic conditions at the bottom can still occur, as observed for example during September 2001 in front of the Delta.

The decreased nutrient discharge can be deemed the main cause of the improvement of the shallow water ecosystem in the WBS. However, it is hypothesized, and there are data indicating, that climate change and especially the increased winter temperature as indicated in the north Atlantic oscillation may lead to a decrease in convection and consequently to a decreased vertical nutrient transport [12].

Besides the positive effects of reduced eutrophication in the Black Sea, there is still the severe demand for a regeneration of the pelagic food web. Up to now, the gelatinous zooplankton, and predominately the medusa *Aurelia aurita*, as well as the ctenophore *Mnemiopsis leydii*, which has been introduced into the Black Sea with bulk water in the early 1980s are dominating the zooplankton community and apparently do not allow fish stocks to recover. In this respect, overfishing plays an important role as well.

3.3 *Reasons for improvement*

As mentioned before, at the beginning of the 1990s nutrient emissions started to decrease considerably, which was associated with economic breakdown in the central and eastern European countries (CEE countries) in the middle and downstream section of the Danube Basin. Market fertilizer applications dropped to almost zero, and the fertilizer industry and industrial animal production almost disappeared. The response of nutrient discharges to WBS was different for nitrogen and phosphorus as well as for dissolved and particulate nutrient species. The principal result was a decrease in dissolved P, whereby the consequences of economic collapse in the CEE countries coincided with improved nutrient removal at waste-water-treatment plants in western Danubian countries (mainly Germany and Austria) and a reduction in phosphorus in detergents in the whole Basin (see figure 6). In more detail, the positive development can be related to:

- economic crises in CEE countries since 1989;
- change in agriculture from economically driven production to nutritional survival of the population, and closure of large animal production plants and of the fertilizer industry (market fertilizer application close to zero) in the CEE countries;
- use of P-free detergents in Germany, Austria, and, increasingly, CEE countries;
- N and P removal at municipal treatment plants in Germany, Austria, and Czech Republic;
- improved agricultural practice.

The actual situation is characterized by a non-sustainable economic situation in the CEE countries. The economic development can result in an important increase in nutrient discharges form diffuse (agricultural development) and point sources (sewerage development without adequate waste water treatment with nutrient removal). Therefore, it is very important to

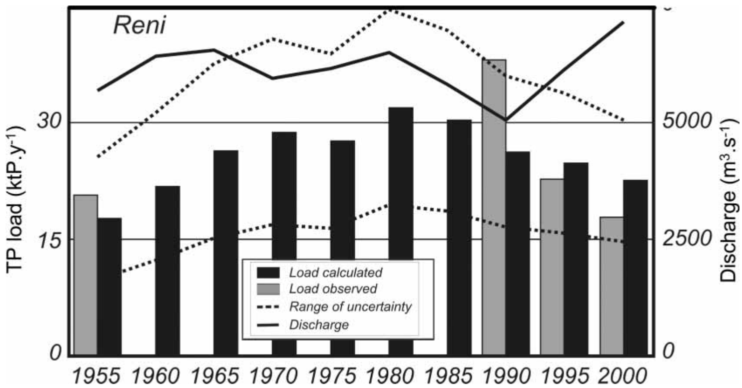

Figure 6. Deviation P-load calculated to load observed at Reni station (directly upstream of the Danube Delta) for 1955–2000 [2].

develop quickly a common nutrient management policy which enables economic growth without compromising water quality in the Danube Basin and the WBS. Changes in climate will probably intensify the pressure.

4. Conclusions

Good data quality and adequate data availability are basic requirements for the development of rational water-quality-management strategies. Understanding the transport, storage, and transformation processes of 'pollutants' from their source to the receiving sea and their effects on aquatic ecosystems (and other environmental compartments) is necessary for data interpretation. Mathematical modelling is a useful tool to improve the application of our knowledge and experience (understanding) to answer specific questions for complex systems as well as to validate our knowledge and/or evaluate data quality. However, model results can never be 'better' than our understanding and the quality of the data we use for calibration.

A consistent methodology is needed to trace 'pollution' loads (sources, pathways, storage, and losses) from their source to the Black Sea consisting of mass balances and dynamic models combining the hydraulic, hydrological, and biological processes in the catchment, the rivers, and the Black Sea.

There is a considerable time lag of emissions in the catchment and the related effect on water quality (which can be as long as several decades!). As a consequence, a Black Sea quality-management strategy can never be developed from Black Sea data alone, even when the monitoring programme is extended and improved. Pollution has to be monitored as close to the sources as possible, exploiting statistical databases and using a mass balance methodology. Water-quality management on a catchment scale needs a long-lasting strategy for sustainable development with a perspective of about 30 yr for stable success.

The precautionary and the environmental standard principles will have to be combined in order to achieve optimal cost and environmental effectiveness. Decision making needs the consent of stakeholders, even if there are sound scientific analyses and reliable modelling results.

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