The Danube Water Quality Model and Its Application in the Danube River Basin

Jos van Gils

Abstract The Danube Water Quality Model (DWQM) was developed in the framework of the GEF project "Danube River Basin Pollution Reduction Programme" (1999) and updated in a large international research project called "Nutrient Management in the Danube Basin and its Impact on the Black Sea" (acronym *daNUbs*, 2001–2005). The DWQM simulates the water quality in the Danube River and its main tributaries as a function of space and time, dependent on the river morphology and hydrology and on emissions calculated by the model MONERIS. The specific goal of the DWQM is to simulate the nutrient loads to the Black Sea in support to the management of the nutrients nitrogen (N) and phosphorus (P) in the Danube River Basin and to distribute them over time and over the different nutrient species. Both distributions are decisive for the assessment of the impact of the Danube outflow on the north-western shelf of the Black Sea. This chapter discusses the set-up of the DWQM and its application to the conditions around the year 2000, which served both to enhance our understanding and to calibrate and validate the DWQM. The validated DWQM has been used to assess five scenarios for future management alternatives, varying from "business as usual" to "deep green". Where appropriate, we refer to the underlying scientific papers and reports.

Keywords Danube River, *daNUbs*, Modelling, Nutrient management scenarios

Contents

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1 Introduction

The Danube Water Quality Model (DWQM) goes back to the late 1990s, when the first version was developed in the framework of the GEF project "Danube River Basin Pollution Reduction Programme" [1, 2]. The experience gained during this project was used to formulate a large international research project called "Nutrient Management in the Danube Basin and its Impact on the Black Sea" (also known by its acronym "*daNUbs*") [3]. This project ran from 2001 to 2005, and it was financed by the EU Fifth Framework Programme and 18 participating European research partners.

Both the GEF project and *daNUbs* addressed the management of the nutrients nitrogen (N) and phosphorus (P) in the Danube River Basin. At the time, nutrient emissions in the preceding decades had led to severe ecological problems: the deterioration of groundwater resources and the eutrophication of rivers, lakes and especially the Black Sea ([4] and references therein). These problems are directly related to social and economic issues (e.g. drinking water supply, tourism and fishery as affected sectors; agriculture, nutrition, industry and wastewater management as drivers). We refer to the chapters by Popovici [5] and by Hamchevici and Udrea [6] in this book for further backgrounds. In order to recommend proper management for the protection of the water system in the Danube Basin and the Black Sea, *daNUbs* provided an interdisciplinary analysis of the Danube catchment area, the Danube River system and the mixing zone of the Danube River in the north-western Black Sea.

One of the cornerstones of the analysis provided by *daNUbs* was the use of mathematical modelling, for two reasons. First, the set-up, calibration and validation of mathematical models help to find out to what degree the available information and knowledge are consistent. It also helps to determine how far our understanding of the system under study reaches and to determine data and knowledge gaps. Next to learning to what degree the researchers understand the behaviour of the Danube River Basin and the north-western Black Sea ("diagnosis"), *daNUbs* also used models to study possible future lines of developments, formulated as scenarios ("prognosis").

The issue of nutrient management in the Danube River Basin shows a high level of complexity, including the natural and socio-economic features of the basin, resulting nutrient emissions to the surface waters, in-stream transformation, storage and losses, conveyance of nutrients towards the Danube Delta and the Black Sea. At the time that the *daNUbs* project was formulated, it was decided to cover this complexity by two connected models, MONERIS and the DWQM, each with their own specific strong points.

MONERIS (MOdelling Nutrient Emissions in RIver Systems) can be characterised as a lumped catchment model, covering the whole basin (land + water) divided in sub-catchments. MONERIS has been developed during the 1980s and 1990s and has been applied and further developed for a wide range of rivers, in Europe and outside Europe. The model is based on data regarding the river flow and the water quality as well as on digital maps and extensive statistical information about the relevant socio-economic drivers, such as population density, wastewater management, livestock, fertiliser use, etc. It uses semiempirical relations to calculate the multi-annually averaged emissions of N and P to the surface waters, distributed over different pathways, as well as the in-stream retention in the small-scale surface water network.

The Danube Water Quality Model (DWQM) covers the Danube River itself and its main tributaries. It is based on generic programmes to calculate the water flow and the water quality. The DWQM calculates the in-stream nutrient loads and the storage and losses in the Danube River and its main tributaries. It is based on data regarding the yearly point and diffuse emissions to the surface water from MONERIS as well as on daily hydrological data for different stations in the Danube basin. Eventually, it calculates the nutrient fluxes towards the Danube Delta.

Below, we will discuss the highlights of the development and the application of the DWQM. A full record is provided by the relevant *daNUbs* reports [7–9].

2 Danube Basin Water Quality Model Set-Up

2.1 Objectives

The envisioned role of the DWQM within *daNUbs* led to the following objectives: (1) the dynamic modelling of the water quality in the modelled river stretches, based on emission estimates generated by MONERIS; (2) the analysis of the in-stream retention processes on a spatially varying basis, in order to study the role of large wetlands and reservoirs (Gabcikovo, Iron Gates, Danube Delta); and (3) the modelling of the outflow to the Black Sea on a day-to-day basis, in terms of the water discharges and the concentrations of the relevant water quality parameters. The modelling of organic pollution and dissolved oxygen was not within the scope of the DWQM.

2.2 General Structure and Model Formulations

The DWQM consists of two modules: the channel flow (CF) module that calculates water levels and water flows as a function of space and time and the water quality (WQ) module that calculates the concentration of relevant water quality variables as a function of space and time. A preprocessor prepares the necessary input data on the basis of hydrological data and the output from MONERIS. Figure 1 provides an overview.

The CF module uses the so-called shallow water equations to calculate the water level and the water flow (in m^3/s) in the river network as a function of time (for an account of the equations, see [10]). The WQ module uses the advection diffusion equation [11] to calculate the concentrations of the relevant water quality variables. These include four nitrogen species (nitrates NO_3^-, ammonium NH_4^+, particular organic nitrogen PON, dissolved organic nitrogen DON), three phosphorus species (*ortho*phosphates PO_4^{3-}, particulate inorganic phosphorus PIP, particulate organic phosphorus POP), two silica species (dissolved silicates, opal silicate), phytoplankton, dead organic carbon and inorganic suspended matter. The terms considered in the water quality model equations are demonstrated in Fig. 2, for a schematic representation of river segment i. They include the longitudinal river fluxes of water and substances, the lateral inflow of water and substances from the Danube sub-catchments linked to the river as well as decay and transformation processes within the river.

The model contains all relevant processes for the modelled variables [11]. Figure 2 shows a schematic representation of the relevant processes for the nitrogen and phosphorus species. Of particular relevance are storage and loss processes, which remove N and P from the water column and prevent or reduce the downstream transport. For N, the most relevant process is denitrification: a loss process which takes place in aquatic sediments. It is driven by the oxidation of organic

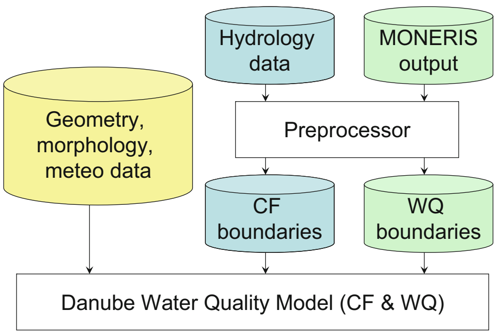
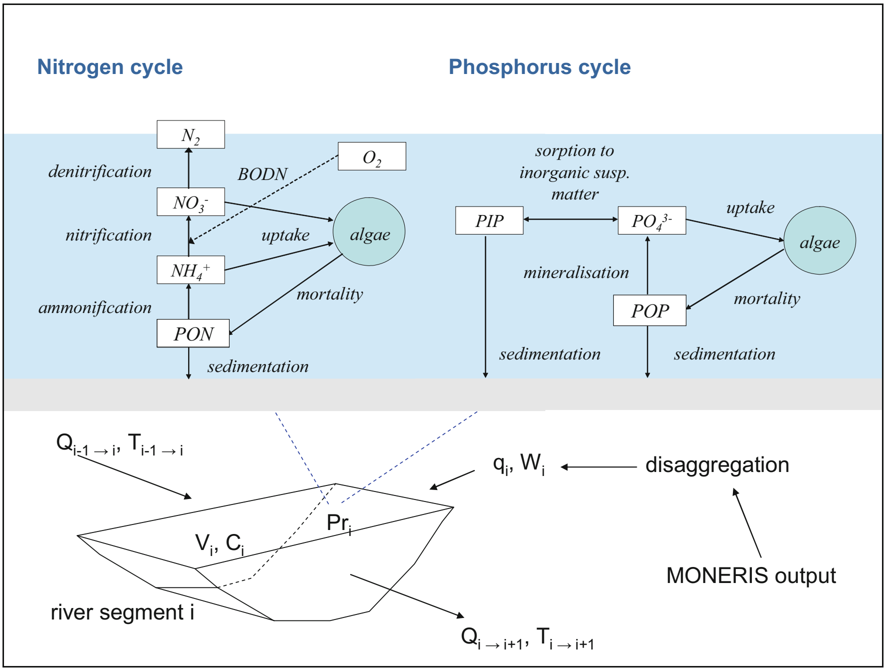


Fig. 1 General structure of the DWQM



N_2	nitrogen gas	DO	dissolved oxygen
NO_3^-	nitrates	PIP	particulate inorganic phosphorus
NH_4^+	ammonium	PO_4^{3-}	ortho-phosphates
PON	particulate organic nitrogen	POP	particulate organic phosphorus
V	water volume (m^3)	C	concentration (g/m3)
Q	river water flux (m^3/s)	T	river substance flux, = QC (g/s)
q	lateral water inflow (m^3/s)	W	lateral substance flux (g/s)
Pr	decay and transformation processes within the river segment (g/s)		
i-1	upstream segment	i+1	downstream segment

Fig. 2 Schematic overview of the water quality model formulations

carbon at a depth where dissolved oxygen is no longer available as an oxidator and nitrates take over this role. As a result, N_2 (and to some extent N_2O) escapes to the atmosphere. For P, the most relevant process is storage of PIP and POP in aquatic sediments in areas of net deposition (e.g. wetlands and floodplains).

2.3 Emission Data

The DWQM relies on MONERIS to calculate the (multi-annually averaged) emissions of nitrogen and phosphorus towards the surface waters. MONERIS calculates these emissions for all sub-catchments in its schematisation. The application to the Danube Basin has about 400 sub-catchments (see Fig. 3) and has been validated on the basis of historical data [12, 13].

The emissions are calculated taking into account seven different pathways to reach the surface waters, in particular: (1) point sources (mostly wastewater treatment plants (WWTPs) and some industry), (2) urban area run-off, (3) atmospheric deposition, (4) tile drainage, (5) groundwater inflows, (6) surface run-off and (7) erosion. Figure 4 shows the relative distribution of the emissions of N and P over these seven pathways. For nitrogen, the most important pathways are the groundwater inflows and the WWTPs. For phosphorus, the most important pathways are the WWTPs and the erosion.

While calculating the emissions of nutrients to the surface water, MONERIS already takes into account the loss of nitrogen in the soil and groundwater mainly due to denitrification. Averaged over larger areas (14 subbasins), the retention in the soil and the groundwater varies between 62% (Sava) and 99% (Delta Liman). MONERIS also addresses the storage and losses of nutrients in the smaller surface waters which are not explicitly included in the DWQM. Averaged over larger areas (14 subbasins), the retention in the smaller surface waters varies between <40% (Germany, Austria, Sava, Drava) and >80% (Delta Liman).

All together, the MONERIS sub-catchments cover the whole catchment. For every sub-catchment we assume that we know at what point the emissions from this

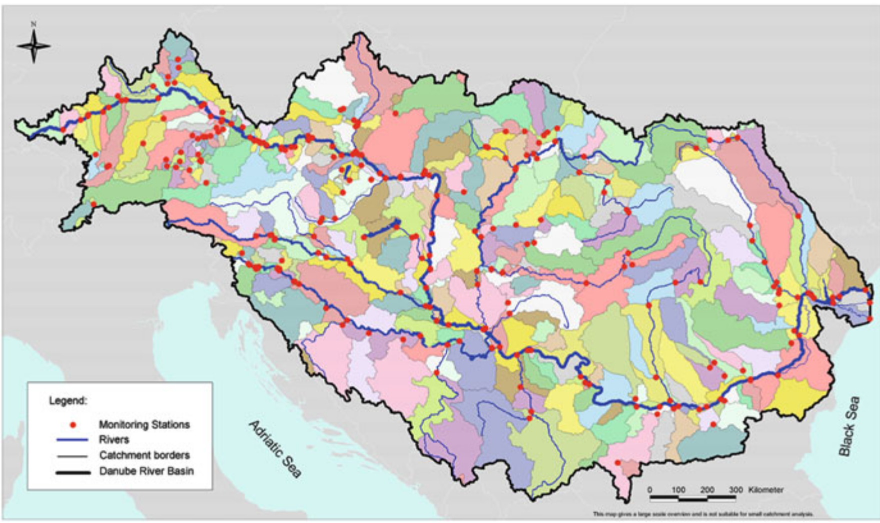


Fig. 3 Overview of the schematisation of the Danube Basin in MONERIS

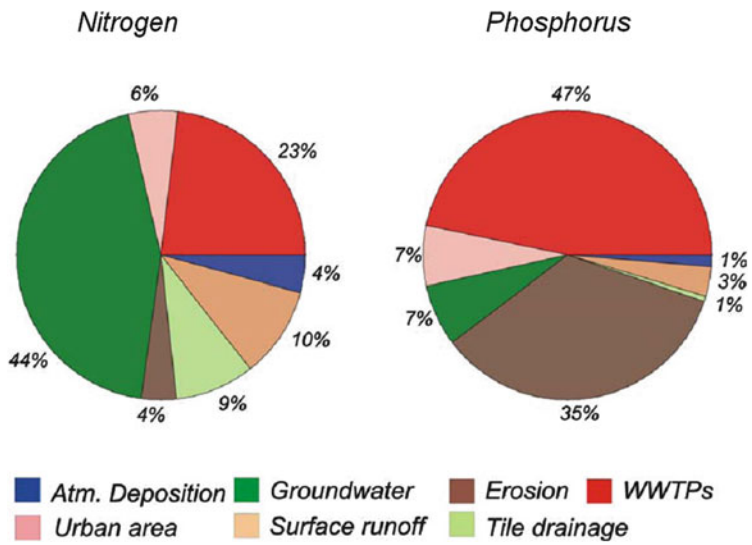


Fig. 4 Relative distribution of nutrient emissions from different pathways for the total Danube Basin (1998–2000)

sub-catchment reach the river network schematised in the DWQM. This point is called the connection point. Every sub-catchment is connected to one connection point, while one connection point can be the recipient of one or more sub-catchments.

2.4 DWQM River Basin Geometry and Morphology

The DWQM derives information about the alignment of the Danube and its main tributaries, the cross sections and the major river structures from the information collected for the set-up of the Danube Basin Alarm Model [14]. Figure 5 provides an overview of the modelled river branches. This figure also shows the connection points to the MONERIS sub-catchments, the major structures and the locations of the defined cross sections.

Fig. 5 The schematisation of the Danube River and its main tributaries in the DWQM, selected hydrological stations

2.5 Creating CF and WQ Boundaries

The output from MONERIS provides the multi-annually averaged inflows of water and substances from the Danube catchment area at the connection points to the Danube River and its main tributaries. A core part of the DWQM is the disaggregation of these inflows over time. To disaggregate the water inflows, the DWQM uses the monitored water discharge time series at selected stations (Wolfsthal, Hercegszanto, Bazias, Tiszasziget and Reni; see Fig. 5). These discharge time series characterise the hydrological regime of the river as well as the spatial variability of this regime. The observed water discharge time series are used to distribute the water inflows at the connection points over time, without changing the average inflows per point. The result is provided to the CF module as input and allows it to accurately simulate the discharge as a function of time throughout the river network.

To disaggregate the inflows of N and P at every individual connection point, the DWQM divided the inflows into three categories:

- All inflows associated with MONERIS pathways with a point source character are disaggregated assuming a constant load in the river.
- All inflows associated with MONERIS pathways with a groundwater/base flow character are disaggregated assuming a constant concentration in the river.
- All inflows associated with MONERIS pathways with a surface run-off/erosion character are disaggregated assuming a concentration proportional to the river flow.

The DWQM uses the disaggregated water inflows to calculate the disaggregated inflows of N and P according to the above assumptions. On top, the DWQM assumes that the retention of nitrogen in the smaller surface waters not included in the DWQM (which is also calculated by MONERIS) varies seasonally with a sinusoidal pattern, with zero retention on 31 January and maximum retention on 31 July. The result is provided to the WQ module as input. The formulas are provided by Constantinescu and van Gils [7] and van Gils [8] respectively.

2.6 Water Quality Monitoring Data

The set-up of the DWQM also relied on the analysis of water quality data from the Danube Basin. The Trans-National Monitoring Network of the International Commission for the Protection of the Danube River (TNMN) proved an extremely valuable data set, because for the years 1996–2002, it provides continuous (>12/year) data for stations throughout the basin (>61). Very useful also were the results from the first Joint Danube Survey (JDS1, August–September 2001), which provides homogeneous data along the whole river satisfying very high quality standards. The model set-up was further supported by data collected during dedicated *daNUbs* surveys and by data from various other sources, compiled by van Gils [9].

3 Modelling the Existing Situation

By simulating different years from the period around 2000 (1997–2003), the developers demonstrated the capabilities of the combined models MONERIS and DWQM to represent the existing situation. Below, we will first present selected results from the analysis of field data, which provide the basis for "checking" the model. Next, we will present some highlights from the model validation.

3.1 Selected Results from Data Analysis

The 1997–2001 data from the TNMN have been used to compile overviews of the in-stream transports ("loads") of nitrogen and phosphorus in the Danube and the main tributaries. Figure 6 shows the results for dissolved inorganic nitrogen (DIN, sum of ammonium, nitrites and nitrates). We note that in 1997–2001 the stations within Serbia were not yet participating in the TNMN. Therefore, the load from the Sava had to be calculated from the change in the in-stream load along the relevant Danube section, assuming that the net retention in the Iron Gates area (yellow section in Fig. 6) is negligible. We note that there were insufficient data for organic nitrogen to compile a similar picture for total nitrogen. For total phosphorus (Fig. 7), the available field data provided ambiguous results. Firstly, the results from pairs of stations on both sides of the river at the same longitudinal position

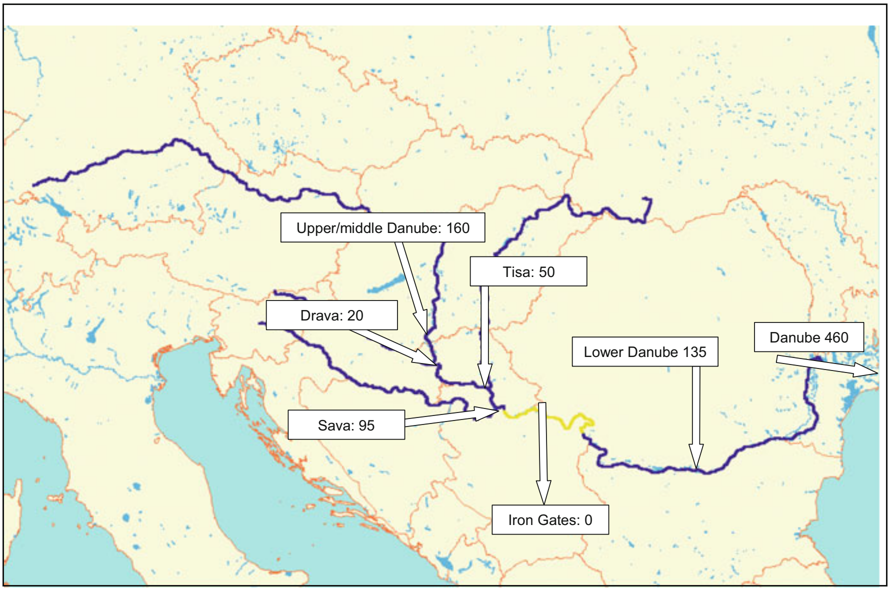


Fig. 6 DIN in-stream loads (kt/year) of the Danube River (based on data from 1997 to 2001)

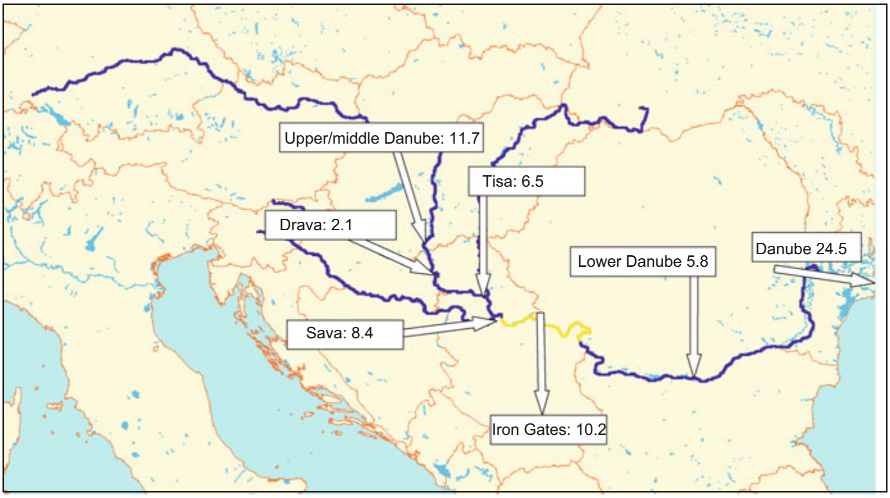
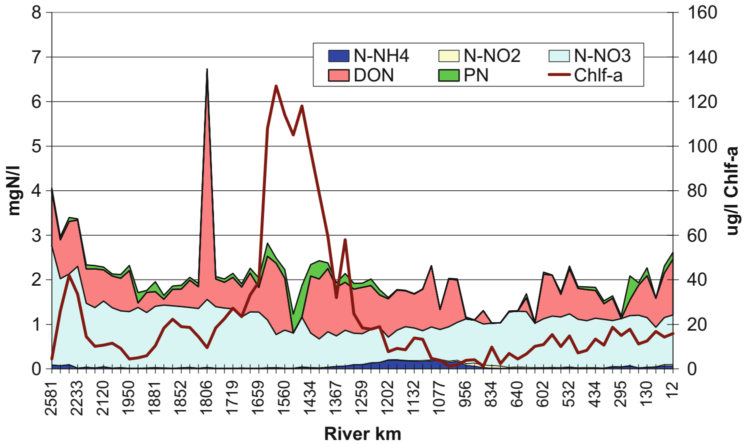


Fig. 7 Estimated total phosphorus in-stream loads (kt/year) of the Danube River (based on data from 1997 to 2001)

were inconsistent, both in the middle and lower river sections. Furthermore, the loads at stations upstream of the Iron Gates section were significantly lower than expected based on our understanding of the Danube River system. Finally, in 2000–2001 a strong decrease of the calculated river load downstream of Pristol was observed, which was not there in the preceding years 1996–1999. Therefore, the phosphorus load information had to be interpreted on the basis of expert judgement. Again, the load from the Sava had to be calculated from the change in the in-stream load along the relevant Danube section, while the retention of phosphorus in the Iron Gates area was estimated as 1/3 of the incoming load (between Smederevo and Kladovo [15]).

The data from the first Joint Danube Survey provided a valuable insight in the longitudinal concentration gradients of nitrogen and phosphorus and the speciation of these nutrients. Figures 8 and 9 show profiles along the Danube of the cumulative concentrations of N and P species, respectively. For interpretation purposes, Fig. 8 shows the concentration of chlorophyll a, which is an indicator for the concentration of phytoplankton. For N, nitrates are the dominant species. The total of nitrates, ammonium and nitrites represents a median fraction of 62%. Ammonium is only present in a noticeable amount downstream of the area of algae bloom (1,600–1,400 km), where it is formed as an intermediate product during the recycling of organic matter to nitrates. The median fraction of organic nitrogen is 38%. The share of particulate organic nitrogen is very small: the median fraction is 3%. This means that nitrogen is present almost completely in dissolved forms.

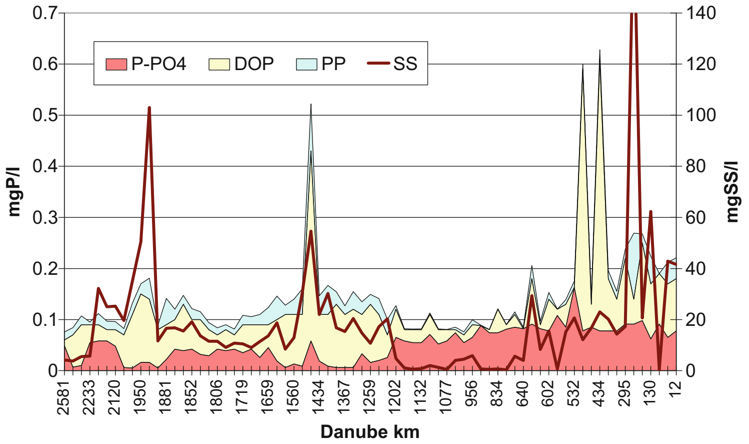
For interpretation purposes, Fig. 9 shows the concentration of suspended solid. For P, phosphates represent a relevant part of the total (median 37%), with other dissolved phosphorus (DOP) representing a similar fraction (median 46%).



N-NH4 = ammonium N-NO2 = nitrites N-NO3 = nitrates

DON = dissolved organic nitrogen PN = particular nitrogen Chlf-a = chlorophyll-a

Fig. 8 Profile of cumulative concentrations of N species along the Danube (Joint Danube Survey 1, August–September 2001)



P-PO4 = ortho-phosphates DOP = dissolved organic phosphates

PP = particular phosphates SS = suspended solids

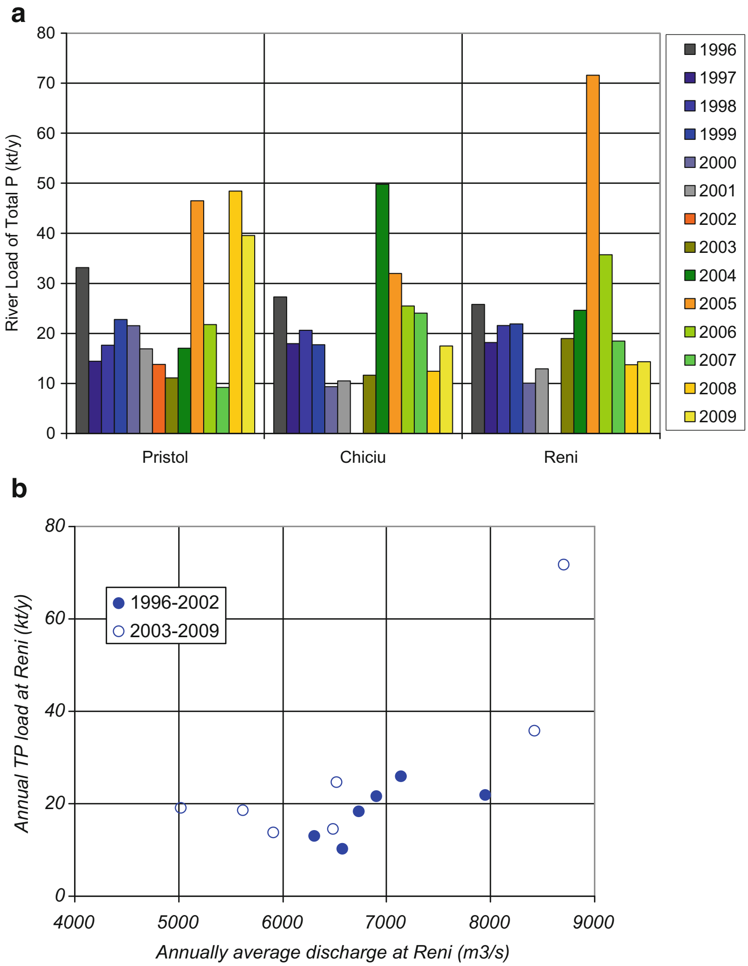
Fig. 9 Profile of cumulative concentrations of P species along the Danube (Joint Danube Survey 1, August–September 2001)

The share of particulate P is smaller (median 13%). It can be noted that the particulate fraction and SS almost disappear in the Iron Gates section downstream of 1,200 km.

We note that the JDS results are probably not representative for the whole year. The JDS represents a summer situation when algal activity is at its maximum and the concentrations of suspended solids are relatively low.

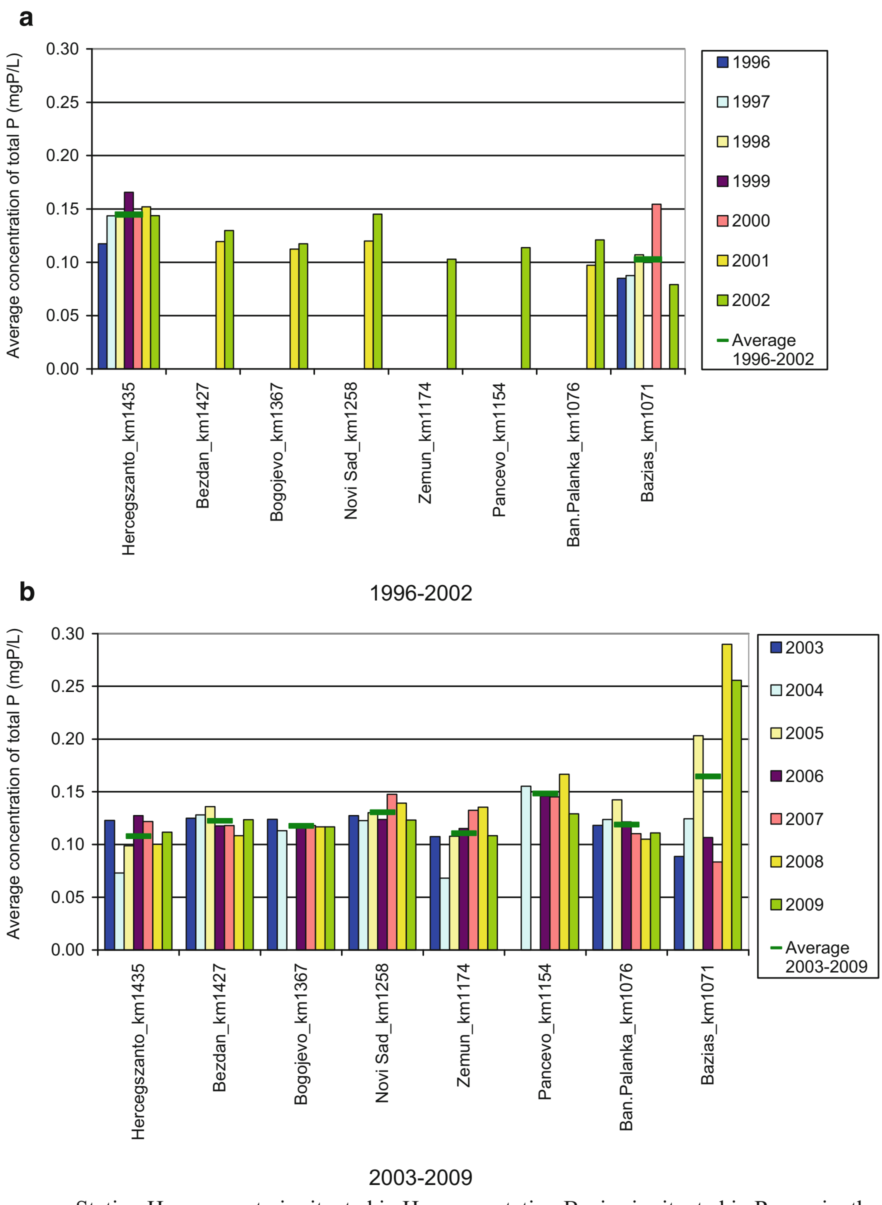
Since the finalisation of the *daNUbs* project, new data have become available to verify the expert judgements made at that time. In particular, the ongoing harmonised and basin-wide TNMN provides highly valuable additional data and information. Figure 10a shows the annual in-stream loads of phosphorus at three stations along the lower Danube (Pristol at 834 km, Chiciu at 375 km and Reni at 132 km), calculated from observed water quality data and discharge data. The loads for 1996–2001 have been copied from van Gils [9], while data for 2002–2009 have been derived from the TNMN Yearbooks [16]. Figure 10a shows the apparent strong decrease, both in space and in time, of the calculated river load downstream of Pristol in 2000–2001, as compared to the preceding years 1996–1999, which was observed during *daNUbs*. The new data for 2002–2009, however, illustrate that these spatial and temporal trends are not persistent, which was indeed the assumption made during *daNUbs*. Figure 10a shows an extremely strong interannual variability, which is partly correlated to the variable water flow, as illustrated in Fig. 10b.

Another assumption made during *daNUbs* was that the observed concentrations at the station Bazias (Danube 1,071 km) were for some reason not representative for the Danube in-stream load of phosphorus upstream of the river section affected by the Iron Gates dams. In particular, to be representative these concentrations should have been higher. Figure 11 shows annually averaged observed concentrations of total phosphorus, calculated from TNMN data [16], along the river stretch between 1,435 and 1,071 km, for 1996–2002 (a) and for 2003–2009 (b). We note that the most upstream station Hercegszanto is situated in Hungary, that the most downstream station Bazias is situated in Romania and that the stations in between are all on the Serbian territory. We also note that the data for the Serbian stations as well as the data for 2003–2009 were not available at the time that the *daNUbs* project was carried out. The results illustrate the apparent decrease of the concentration in Bazias in 1996–2002 relative to the station Hercegszanto (Fig. 11a), which was assumed unrealistic in the *daNUbs* project. The results for 2003–2009 (Fig. 11b) suggest that this decrease is not there: the average value over 2003–2009 increases. The Serbian stations in between suggest that there is no consistent spatial gradient along the middle Danube. These observations confirm the assumptions made during *daNUbs*.



Loads for 1996-2001 have been copied from van Gils et al. (2004a). Data for 2002-2009 have been derived from the TNMN Yearbooks (e.g. ICPDR, 2009).

Fig. 10 Annual in-stream loads of phosphorus over the period 1996–2009, calculated on the basis of water quality monitoring data: (**a**) at three stations along the lower Danube (Pristol (834 km), Chiciu (375 km) and Reni (132 km)); (**b**) at Reni, plotted against the annually averaged water discharge



Station Hercegszanto is situated in Hungary; station Bazias is situated in Romania; the remaining stations are on Serbian territory.

Fig. 11 Annually averaged observed concentrations of total phosphorus at a sequence of stations along the middle Danube. (**a**) 1996–2002. (**b**) 2003–2009

3.2 Model Calibration and Validation

The DWQM needs to be able to represent the transport and retention of nutrients in the Danube river and its main tributaries with a sufficient accuracy. The developers validated this by comparing simulation results to field data. This validation was carried out on the basis of a list of concrete criteria, directly related to the ability of the DWQM to meet its objectives. Certain model formulations are of a (semi) empirical nature and contain parameters which may have to be tuned to the characteristics of the Danube River and its main tributaries. This process is called calibration. The number of parameters potentially subject to calibration is very large, and it is not possible to pay explicit attention to all of them [8]. The calibration effort was therefore concentrated on those parameters which affect the behaviour of the model the strongest, in view of the concrete criteria for validation mentioned above. Sensitivity analyses served as a supportive tool to find such parameters.

Among other things, the developers quantified the “goodness of fit” between the model results and the field data. This provides an objective and reproducible evaluation of the ability of the model to reproduce the field data. However, it was not possible to rely on this information only, for different reasons. In the first place, our ability to define a representative criterion for goodness of fit is limited, taking into account the complexity of the study area and the model formulations. Furthermore, the quality of the field data was sometimes limited. Therefore, qualitative and necessarily subjective judgements on the quality of the model have also been used, on the basis of simultaneous graphical presentation forms of field data and simulation results.

The first validation criterion reads: *the model should be able to adequately reproduce the (temporal and spatial variability of the) river hydraulics, insofar as it determines the water quality and the pollution loads to the Black Sea.* This criterion deals with the river discharge since it influences the diffuse emissions and the dilution of pollutants. The river velocity is important because it determines the residence time of the water in the river system. Together with the river depth and the bottom roughness, the velocity controls the shear stress, which determines the sedimentation and resuspension of particles. Finally, the river depth determines the relative importance of surface- and sediment-related processes, as well as the available light for phytoplankton growth. The model validation revealed that the dynamics of the river discharge is adequately reproduced, and the model generates a realistic behaviour with respect to the water depth and the water velocity.

The second validation criterion reads: *the model should be able to adequately reproduce the (temporal and spatial variability of the) concentrations of total nutrients.* This criterion deals primarily with the emissions and their disaggregation over time. Also the losses and storage of nutrients play a role. This aspect of the model validation could only partly be completed, due to data gaps: for nitrogen, we have to rely on data of dissolved inorganic nitrogen (DIN) only, while for phosphorus, the data show ambiguities (see Sect. 3.1 above). Assuming that our expert judgements to overcome these gaps are correct, the DWQM is reproducing the

Table 1 Simulated overall nutrient balances for the Danube Basin (multi-annual average, around the year 2000)

	N (kt/year)	N (%)	P (kt/year)	P (%)
Emissions to surface waters	687	100	67.8	100
Retention "small waters"	236	34	36.1	53
Inflow to DWQM	451	66	31.7	47
Retention in DWQM	16	2	7.6 (Iron Gates)	11
Outflow to delta	435	63	24.1	36

concentrations of total N and total P well. This conclusion was based among other things on thorough sensitivity analyses and subsequent parameter calibration, the evaluation of the formal goodness of fit and visual inspection of different types of graphical presentations comparing model results and measured concentrations.

Table 1 shows the overall nutrient balances derived from the validated model simulations. The table shows the total emissions to the surface waters and the retention of small surface waters not included in the DWQM, as calculated by MONERIS. The table also shows the remaining inflows to the Danube and its main tributaries, the retention along the larger rivers and the resulting outflow towards the Danube Delta. For nitrogen, about 63% of the emissions reach the Delta. The nitrogen retention is taking place almost exclusively in the small water courses not included in the DWQM. For phosphorus, about 36% of the emissions reach the Delta. In this case, there is significant retention along the Danube itself. The Iron Gates section of the Danube (yellow colour in Fig. 7) traps roughly 50% of the incoming inorganic particles (the model has been calibrated to reproduce the literature dedicated to this subject). Since phosphates sorb to these particles, also P is trapped in the Iron Gates section.

For P, another form of retention is taking place in floodplains. A clear example is the Gabcikovo section along the Slovak–Hungarian border. A *daNUbs* survey in the area during the major August 2002 flood demonstrated a substantial retention of suspended solids and phosphorus, due to the sedimentation of particles in the floodplains and old Danube branches (van Gils [9]). Because of the limited availability of detailed cross-sectional data, the model does not explicitly represent the floodplains along the Danube and the main tributaries and therefore cannot resolve this retention mechanism. We note that the frequency of the 1996–2001 TNMN water quality monitoring also does not resolve flood events responsible for this retention mechanism. Therefore, the retention may not show in the field data either.

This process is not only relevant along the main river but also in the smaller order tributaries. With every high-water period, sediment is deposited with P attached to it. This deposition process is probably partly counteracted by resuspension during the next flood and deposition further downstream. The literature provides evidence however that the river floodplains experience a net sedimentation.

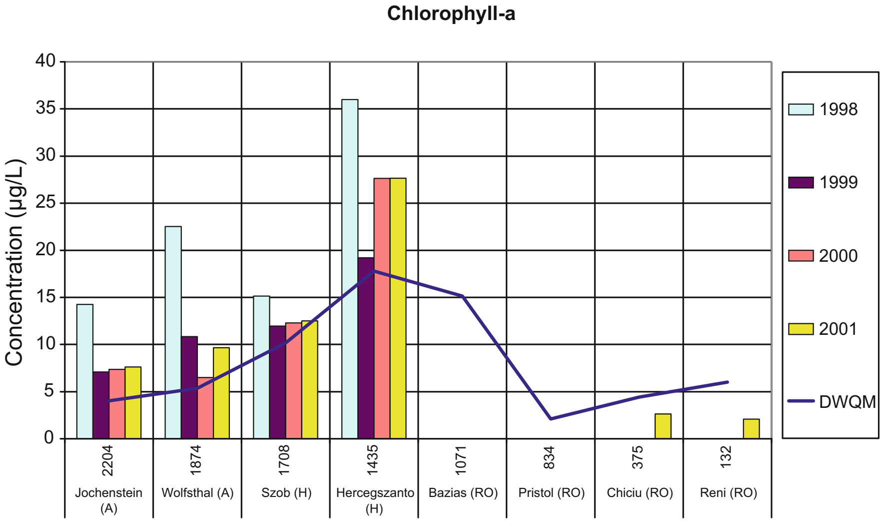
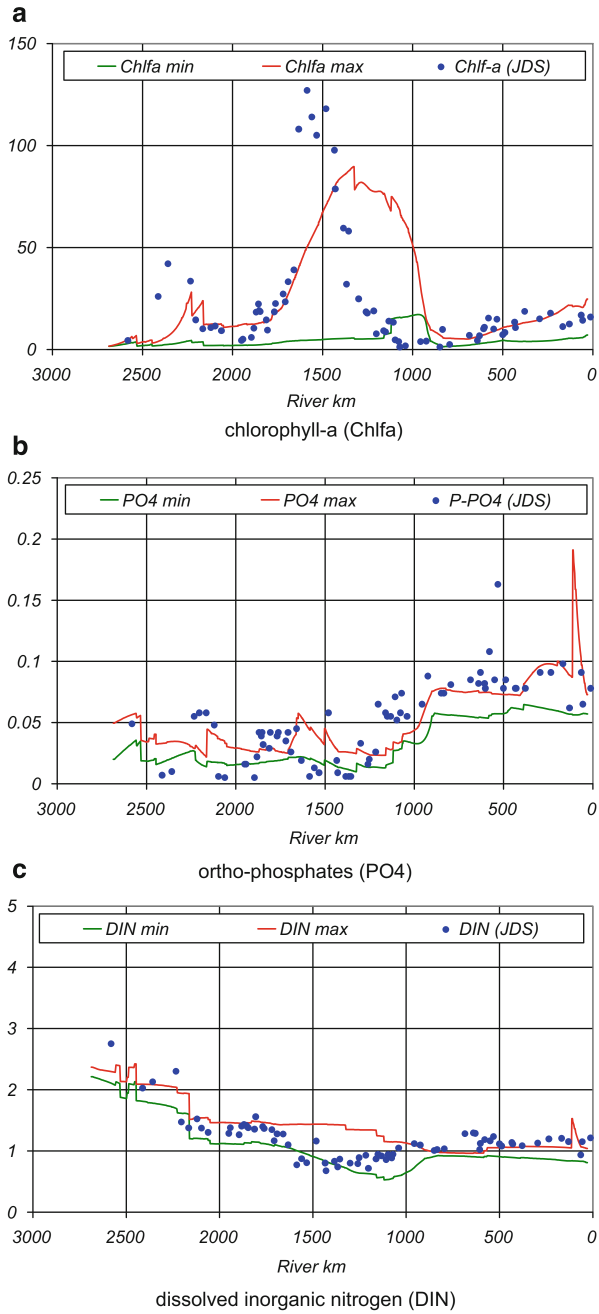


Fig. 12 Comparison of annually averaged simulated concentrations of chlorophyll a (µg/L) with annual averages of observed concentrations from the TNMN at selected stations

The third validation criterion reads: *the model should be able to adequately reproduce the (temporal and spatial variability of the) concentrations of the different nutrient species*. This criterion deals with the cycling of the nutrients induced by phytoplankton growth, the mineralisation of organic matter and the different processes related to inorganic nutrients. Since the phytoplankton dynamics of a river system are controlled by the water clarity which determines the light availability in the water column, also the suspended sediment dynamics and the particle light extinction characteristics are relevant. The model was calibrated to reproduce the available field data for chlorophyll a (see Figs. 12 and 13a).

Figure 13b, c shows that the model is able to reproduce the observed concentrations of *ortho*phosphates and dissolved inorganic nitrogen during JDS1 quite well. The DWQM does not reproduce the TNMN data for ammonium very well. These data show a sudden increase of the concentration of ammonium from Bazias (Danube 1,071 rkm) onwards, while the model shows only minor variations in the downstream direction. Note that the JDS results do not show such a gradient (Fig. 8). If the spatial gradient in the field data is realistic, we do not know what causes it and therefore cannot make the model reproduce it.

Fig. 13 Observed concentrations along the Danube during JDS1 (*blue dots*) and simulated concentrations during the survey period (*green*, minimum value; *red*, maximum value) for various parameters: chlorophyll a as μg/L (**a**), *ortho*phosphates as mgP/L (**b**) and dissolved inorganic nitrogen as mgN/L (**c**)



4 Prognosis of Future Situation

During the *daNUbs* project, the MONERIS and DWQM models have been used to make a prognosis of the expected water quality in the Danube outflow (for further assessment by Black Sea researchers). This has been done for five different scenarios varying from a "business as usual" to a "deep green" scenario. A detailed description of this exercise is provided by van Gils et al. [17].

Figure 14 provides the calculated Danube River loads towards the Danube Delta, for the present situation (year 2000, Sc0) and the scenarios Sc1 to Sc5. The results show that the loads may increase or decrease as compared to the present situations, dependent on the assumed socio-economic development of the Danube countries in each of the scenarios. It is also clear that the phosphorus loads show a stronger response to socio-economic changes than the nitrogen loads. The error bars in Fig. 14 show the variability of the loads, induced by differences in the river hydrology. This variability is significant. For phosphorus, the variability induced by socio-economic factors dominates the hydrological variability, but for nitrogen both are of the same order. This means that the effect of pollution reduction measures on the Danube nitrogen loads can be hidden by natural hydrology-induced variability.

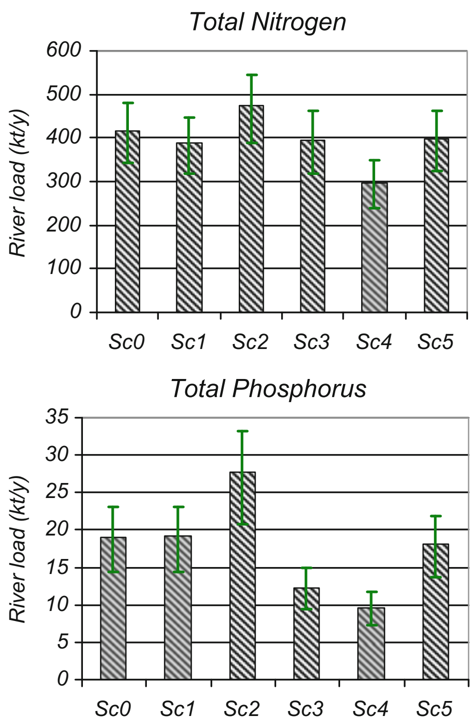


Fig. 14 Calculated Danube River loads towards the Danube Delta, for the present situation (Sc0) and the scenarios Sc1 to Sc5. The *error bars* show the variability of the loads, induced by differences in the river hydrology

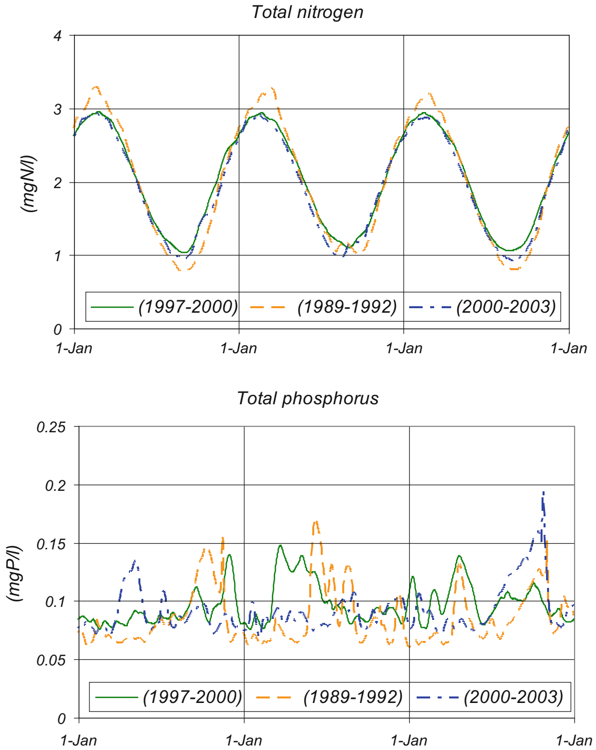


Fig. 15 Disaggregation over time of the concentration of total N and total P for scenario 5, for a period with low river discharges (1989–1992), a period with intermediate discharges (2000–2003) and a period with high river discharges (1997–2000)

Figure 15 shows simulated time series at the Danube outflow point for a period of 3 years assuming scenario 5 (a "policy" scenario representing the implementation of the Water Framework Directive and other EU water-related legislation throughout the Danube Basin). Again, the impact of the river hydrology is shown, by using three different historical periods as hydrological forcing for the model simulations.

5 Closing Remarks

The work that formed the basis for the present chapter has been carried out in the period 2002–2006. Meanwhile, new data have become available, and scientists and water managers have continued their efforts to improve the quality of the available data. Thus, a renewed effort to evaluate and if possible improve the work presented here done would be possible. Based on the *daNUbs* experience, the modelling could be further improved with respect to (a) the production, transport and retention of sediment; (b) the explicit modelling of floodplains as a sink of sediment and phosphorus (on all spatial scales); and (c) the consistent treatment of the temporal and spatial scales (which implies integrating the MONERIS and DWQM models and their underlying concepts).

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