The Danube Water Quality Model and its role in the Danube River Basin Pollution Reduction Programme.

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Abstract: The Danube River Basin Pollution Reduction Programme is a project carried out by UNDP/GEF in 1997-1999. It studied among other things the current state of the Danube Basin and a concrete set of proposed measures aimed at reducing the trans-boundary transports of pollution. The work in this project was supported by the Danube Water Quality Model (DWQM). In particular, this model was used to quantify the Danube in-stream loads of N and P in the current conditions, and the effects on these loads of the implementation of the Pollution Reduction Programme. The current paper describes the objectives, the set-up, the validation and the application as well as the limits of the DWQM.

Keywords: Danube, nutrients, water management, modelling, in-stream loads, retention.

Das Donau Wasserqualitäts-Modell und seine Rolle in das Programm zur Verringerung der Wasserverschmutzung der Donau.

Zusammenfassung: Das Programm zur Verringerung der Wasserverschmutzung der Donau ist ein Projekt, welches von 1997 bis 1999 mit finanzieller und technischer Hilfe des UNDP/GEF durchgeführt wurde. In diesem Projekt wurde die Situation der Wasserverschmutzung im Donaueinzugsgebiet, ihre Ursachen und ihre Folgen studiert und Maßnahmen vorgeschlagen um grenzübergreifende Gewässerverschmutzung zu reduzieren. Das Donau Wasserqualitäts-Modell (DWQM) wurde hierbei zur Erarbeitung einer Vergleichsanalyse eingesetzt. Das Modell wurde dazu benutzt, Nährstofffrachten in Fliessgewässern sowie die Auswirkungen von Maßnahmen zur Verringerung der Wasserverschmutzung darzustellen. Der vorliegende Bericht beschreibt die Ziele, die Voraussetzungen, die Erstellung, die Modelleichung und die Einsatzmöglichkeiten sowie auch die Grenzen der Anwendbarkeit des Modells.

Schlüsselworte: Donau, Nährstoffe, Wasserwirtschaft, Modellentwicklung, Frachten in Fliessgewässern, Rückhalt.

1. Introduction

<u>The Danube River Protection Convention</u>, created in the framework of the ECE-Convention for the protection of trans-boundary waters (Helsinki Convention 1992), became with its entry into force on 22 October 1998 the overall legal instrument for co-operation and trans-boundary water management in the Danube River Basin. The overall objective of the DRPC is to achieve and maintain the sustainable development and use of water resources in the Danube River Basin. The Contracting Parties are recommended to aim at an intensified regional co-operation, a due balance between ecology and economy, an integrated implementation as well as goal-oriented policies and strategies, executive structures and tools. In order to achieve substantial progress in the protection and sustainable use of the water resources, the following overall strategic goals and targets are defined:

- to maintain and improve the status of water resources as to quality and quantity;
- to prevent, reduce and control water pollution, including accidental pollution, in particular where hazardous substances and nutrients are involved;
- to improve the aquatic ecosystems and biodiversity;
- to contribute to the protection of the Black Sea from land-based pollution.

National and regional policies are based on common principles related to the protection and use of natural resources, in particular on the Precautionary and the Polluter Pays Principles, the best available technology (BAT) and the best environmental practice (BEP). The same applies to the Convention. Most of the Contracting Parties have developed a water management policy as a part of their national policy. Sector policies for reducing point sources of pollution are mostly in place whereas specific policies for reducing diffuse sources of pollution are partly under development; policies regarding wetland rehabilitation are emerging.

The protection of the Black Sea and its ecosystems from land-based pollution constitutes a multifaceted regional framework objective. Its realisation is to a considerable degree depending on the implementation of relevant objectives and policies in the Danube River Basin, in particular regarding eutrophication caused by nutrient discharges. Hence the Commissions responsible for the protection of the Danube River (ICPDR) and the protection of the Black Sea (ICPBS) jointly declare their policies and willingness to co-operate for achieving common strategic goals as specified in a “Memorandum of Understanding” which shall be adopted in the year 2000. These goals particularly address assessment and urgent control measures regarding nutrients and hazardous substances. A defined ecological status is intended to be maintained and at a long-term scale recovered through ensuring appropriate practices and measures.

In the frame of the Danube Environmental Programme, the UNDP Global Environment Fund and the EU through its Phare and Tacis programs, have since 1992 provided international assistance to develop appropriate mechanisms and planning tools for the implementation of the Danube River Protection Convention. In the particular context of the Pollution Reduction Programme, the causes and the effects of water pollution have been analysed and policy guidelines, strategies, and projects for pollution reduction and water management have been developed. The project considers root causes for “Inadequate Management of Water Resources”, referring primarily to the middle and lower Danube countries, taking into account problems related to socio-political transition, reforms and general economic recession; war and displacement of population; absence of national strategies for water management and inefficient environmental management, enforcement and compliance.

Concerning the direct causes, important sources of pollution or priority “hot spots” where identified for the municipal, industrial and agricultural sectors. 51 “Significant Impact Areas” have been identified in the Danube River Basin, which are in particular affected by industrial pollution, COD and toxic materials as well as by excessive nutrient loads. Special consideration was also given to the nutrient transports to the Black Sea, indicating a total of 551 kilotons of Nitrate and 48,9 kilotons of Phosphorus reaching annually the Black Sea.

Over 400 projects have been developed, responding generally to “hot spots” or point sources of emission, representing national priorities and taking equally into account the obligation to mitigate trans-boundary effects. Particular attention was given to the identification of sites for wetland restoration, which play an important role not only as natural habitats, but also as nutrient sinks.

The total investment required to respond to the priority projects is estimated to be about 5,66 billion US$, covering the following sectors:

- Municipal waste water collection and treatment plants: 3,57 billion US$
- Industrial waste water treatment: 0,81 billion US$
- Agricultural projects and land use: 0,16 billion US$
- Rehabilitation of wetlands: 1,12 billion US$

The expected results of the Pollution Reduction Programme show a considerable decrease of pollution in terms of COD/BOD, respectively in terms of N and P. The implementation of the proposed priority projects in the municipal, industrial and agricultural sectors will lead to a reduction of about 640,000 tons of COD/BOD and of about 100.000 tons of N and P. The latter has a direct influence on the Black Sea and will contribute to achieve common Danube and Black Sea goals to restore marine ecosystems in the north-western shelf.

The Danube Water Quality Model (DWQM) was developed in the frame of the Danube Pollution Reduction Programme to simulate the actual in-stream nutrient load. Simulations have been conducted to support the Trans-boundary Analysis as well as to support the definition of priority measures of the Pollution Reduction Programme demonstrating nutrient reduction through implementation of the projects and policy measures. Details about the work can be found in the related report (GEF, 1999).

2. Materials and Methods

2.1 System description

The Danube Water Quality Model (DWQM) describes the fate of the nutrients nitrogen (N) and phosphorus (P) in the Danube catchment. These nutrients are discharged in the aquatic environment due to human activities and natural processes. The model contains a schematisation of the Danube river and its main tributaries, derived from (Vituki, 1996) and the National Reviews (GEF, 1998), called "the network" from now on, see Fig. 1.

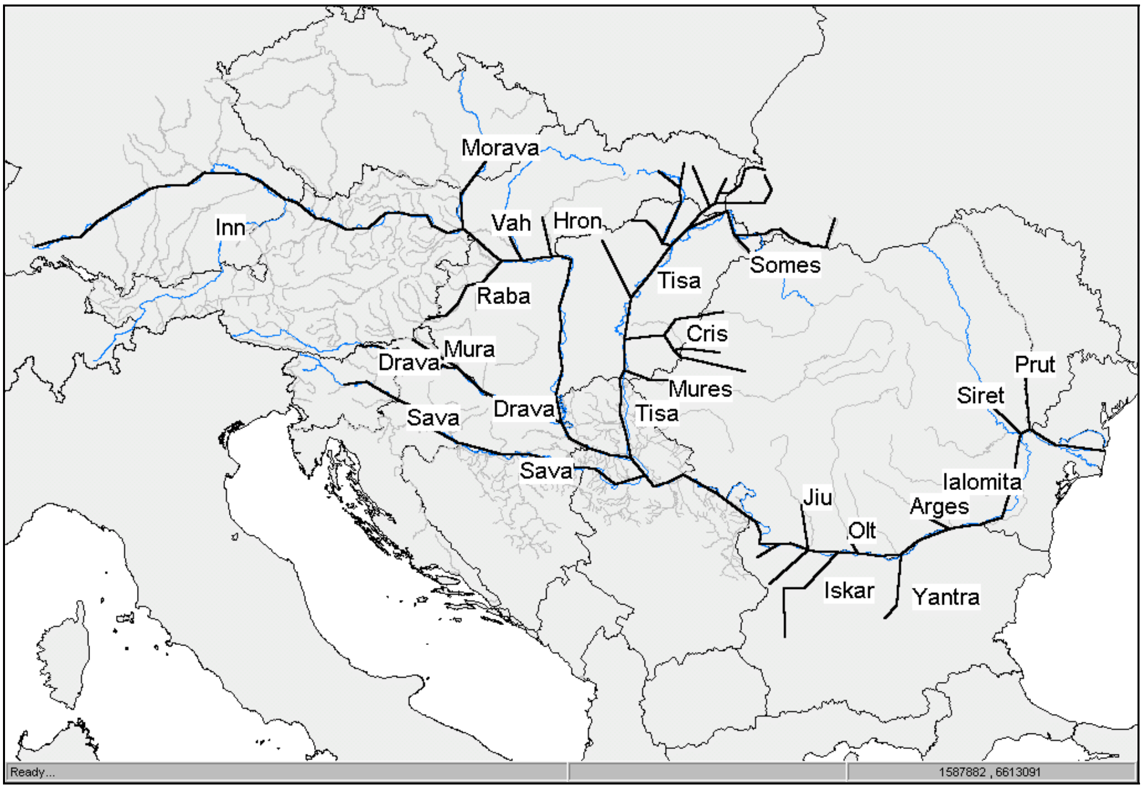

Fig. 1: The river network of the DWQM.

In the remainder of this paper, the word "catchment" will refer to everything outside the network: land area, small tributaries, ground water, etc. The catchment is simply schematised as its surface area, as a function of the distance along the river.

With the DWQM's objectives in mind, the catchment has been subdivided over the 13 principal Danube countries (see Fig. 2).

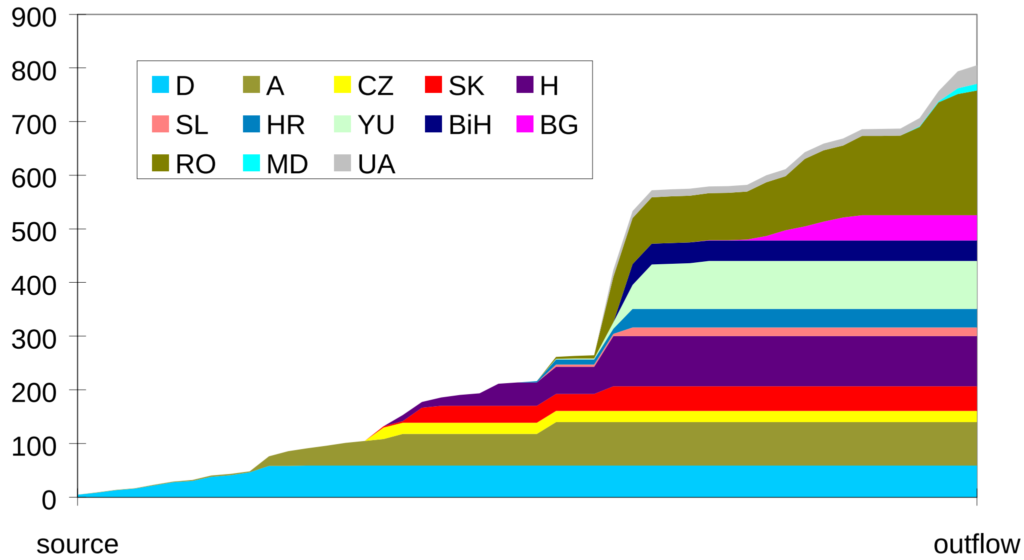

Fig. 2: The catchment profile along the Danube (in 1000 km^2), subdivided over the 13 principal Danube countries.

2.2 Conceptual model

The conceptual model of the DWQM is shown in Fig. 3. The emissions are split into two parts: the emissions directly to the river network and the remaining emissions. The remaining emissions are subject to retention in the catchment[1]. The word retention refers to any process which effectively removes nutrients from the catchment if we look at a period of several years, under the present conditions. Seasonal cycles of uptake and release are therefore not considered retention. Relevant retention processes of nitrogen are: (a) denitrification in the ground water and the surface water, (b) long term accumulation of nitrogen in the ground water. Retention processes of phosphorus include: (c) net storage in the sediments of lakes, flood plains and wetlands. The part of the remaining emissions not retained in the catchment reaches the network as effective emissions to the river.

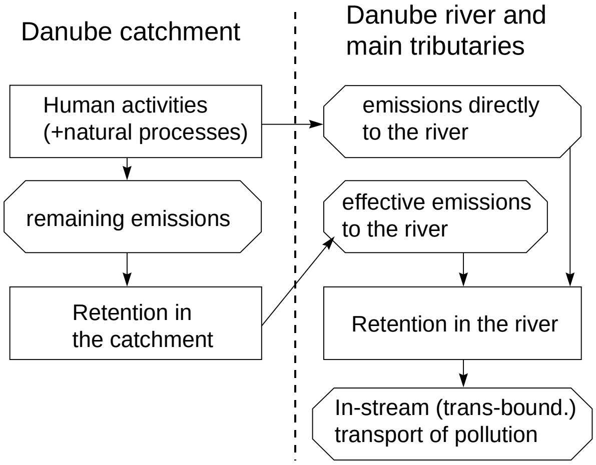

Fig. 3: Systems diagram

All emitted nutrients in the river are subject to retention in the river. The final result is the in-stream transport of nutrients which is equal to the trans-boundary nutrient loads at the borders between the Danube countries.

[1] The subject of retention of nutrients in the aquatic cycles of river catchments has been described in detail by many authors, e.g. Tonderski (1997), de Wit (1999).

2.3 Implementation

The total emissions have been computed for all the Danube countries based on the “materials accounting method” (University of Vienna ea., 1997). The emissions estimates were originally made for the years 1988/1989 and 1992, but were later updated (University of Vienna, 1999) to 1994-1997 based on data collected in the National Reviews (GEF, 1998), see Fig. 4 and Fig. 5. Large individual point sources of N and P discharging directly to the river network were identified based on the EMIS inventory (Mehlhorn, 1998) and the National Reviews (GEF, 1998). The remaining emissions (Fig. 3) were computed by subtracting these emissions directly to the river from the total emissions discussed above.

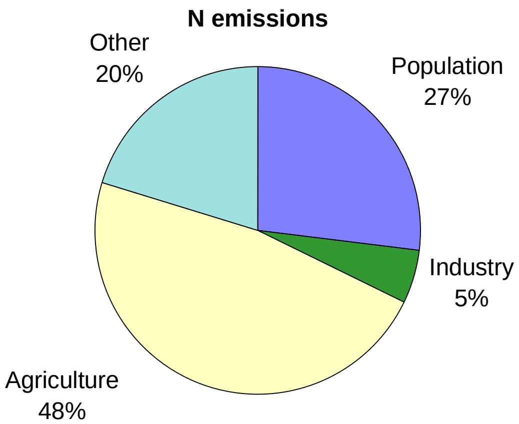

Fig. 4: Subdivision of N emissions.

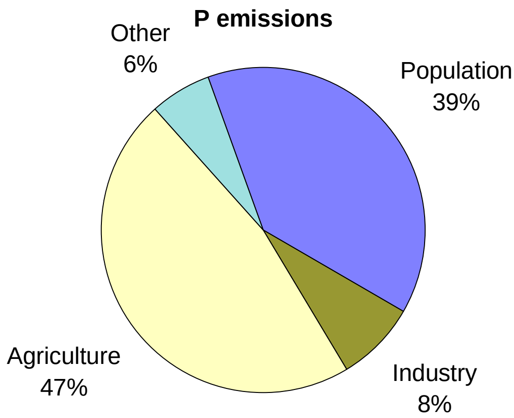

Fig. 5: Subdivision of P emissions.

The retention in the catchment is represented by an empirically derived "immission/emission-ratio". High (95% probability) and low (5% probability) estimates for this factors for N and P, as a function of the area specific run-off, were derived from Behrendt ea. (1999). The values for N range from 5-36% (low runoff) to 59-88% (high runoff), while the values for P range from 5-36% (low) to 72-100% (high).

Based on an analysis of the available data, two processes were identified which are expected to cause a non-negligible retention in the river: the denitrification (N) and the net sedimentation in the backwater area of the Iron Gates dams on the Yugoslavian-Romanian border (P), see Perišic ea. (1990).

The hydrology and the water balance are very relevant because water is the carrier of a large part of the emissions. The hydrology and water balance model was based on the observed river flow data for selected stations in the network. The diffuse inflows between two such stations were divided over the river stretch in between, proportional to the increase of the catchment area. Since the catchment increase along the river has been mapped per country (see Fig. 2), also the diffuse inflow can be divided over the different countries. The model is evaluated for subsequent steady states, with a time interval of 1 month for the period 1994-1997.

The effective emissions to the river (see Fig. 3) are discharged in close connection with the diffuse inflow. The emissions per country were divided in three categories: those with a constant discharge rate (typically point sources), those with a discharge rate proportional to the diffuse inflow (typically ground water inflows) and those with a discharge rate proportional to the square of the diffuse inflow (typically erosion related emissions), see (Jolankai, 1992). The diffuse inflow is known per country as a function of space and time. With the above considerations in mind, the concentration of N and P in the diffuse inflow is computed, again per country and as a function of space and time.

The final step in the computation procedure is the computation of the in-stream loads. This is done by solving the partial differential advection equation, including sources and sinks with the appropriate boundary conditions and initial conditions.

2.4 Model Calibration/Validation

The methodology for the calibration and validation was selected with the following main consideration in mind: there are so many uncertainties involved in the DWQM exercise, that it is not a sensible thing to tune certain model parameters to obtain a good fit between model predictions and field data. This would probably result in compensating one big error with another one, and would make the analysis of policy measures less reliable.

In stead, we tried to work with state-of-the-art knowledge and data, to quantify the largest uncertainties and to see if an agreement exists between model predictions and field data, taking into account these uncertainties. In particular, we used the following quantified uncertainties: (i) high and low estimates of the point sources part of emissions, (ii) 80% and 120% of best estimates of the diffuse part of the emissions, and (iii) 5% and 95% probability values of the immission/emission ratio representing the retention in the catchment.

Observed concentrations and in-stream loads were used to validate the DWQM. The in-stream loads are of course not really “observed” but they are computed from observed concentrations and river discharges. The method proposed by Buys ea. (1998) for use in the Danube basin was adopted. In relation to the observed concentrations we had to accept the fact that the basin-wide uniformity of sampling, analysis and quality control procedures can never be perfect. Apart from that, the observed concentrations needed to be corrected before the validation exercise could be carried out. Total nitrogen concentrations could on many occasions only be obtained by estimating the organic nitrogen concentration. Total phosphorus concentrations were found not to be representative for the river load. Two systematic errors were defined: an underestimation because of the low sampling frequency (Zessner ea., 1998) and an underestimation because of the use of surface samples only. Both problems have not yet been investigated thoroughly on a basin-wide scale. We used an approximate correction factor of 2 for both problems together.

2.5 Validation results

Typical validation results for the concentrations of N and P are shown in Fig. 6 and Fig. 7.

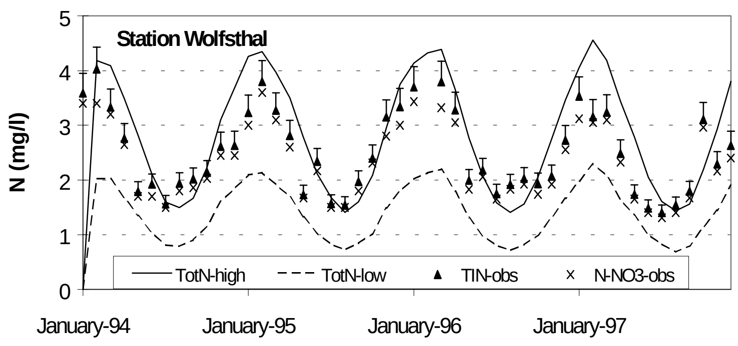

Fig. 6: Validation results: nitrogen at Wolfsthal (km 1874).

Fig. 6 shows the results for nitrogen at Wolfsthal (km. 1874). The solid and dotted lines represent the higher and lower computed concentrations. The triangles represent the measured concentrations of total inorganic nitrogen, with the error bars representing the estimated organic nitrogen concentration.

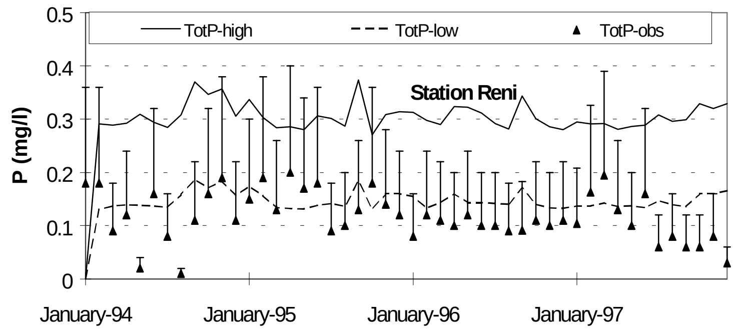

Fig. 7: Validation results: phosphorus at Reni (km 132).

Fig. 7 shows the results for phosphorus at Reni (km. 132). This time the error bars on the observed values represent the correction factor of 2 discussed above. Both graphs demonstrate the fact that the observed and the predicted values match well, taking into account the large uncertainties.

Typical validation results for the in-stream loads of N and P are shown in Fig. 8 and Fig. 9.

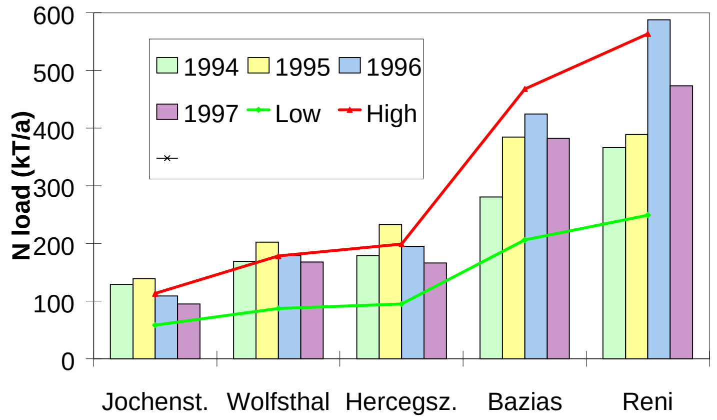

Fig. 8: Validation results for the in-stream loads of nitrogen.

Fig. 8 shows the results for nitrogen at various stations along the Danube. The solid lines represent the higher and lower computed values. The bars represent the values computed from measured concentrations and discharges for the years 1994-1997.

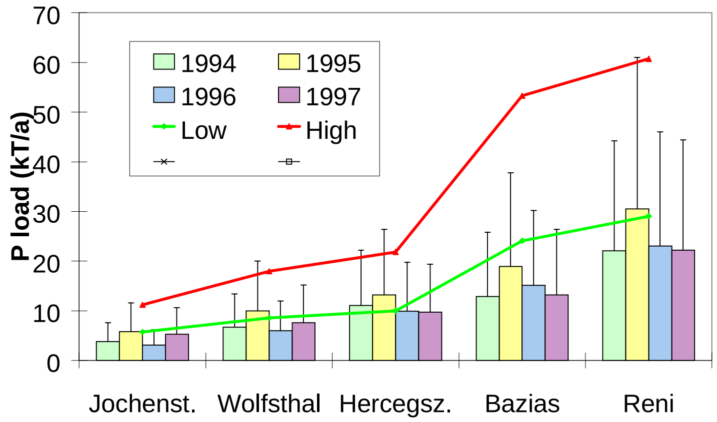

Fig. 9: Validation results for the in-stream loads of phosphorus.

Fig. 9 shows the results for phosphorus. This time the error bars on the observed values represent the correction factor of 2 discussed above.

Both graphs demonstrate the fact that the observed and the predicted values match well, taking into account the large uncertainties.

3. Results

3.1 The Trans-boundary Analysis

The Danube Water Quality model has been used to support the Trans-Boundary Analysis (TBA). To this end, a computation was carried out for a situation somewhere between the high and low estimates described in paragraph 2.4. The precise definition of the computation was made by matching the in-stream loads upstream of the Danube Delta with the best available load data derived from observed nutrient concentrations and water discharges.

The overall computation presented before was split into 13 different computations: each one of them with the emissions from one individual country. The results of the 13 computations per country were superimposed to obtain the overall result. Because all equations in the DWQM were strictly linear, this was a mathematically valid procedure.

The results are presented in Fig. 10 and Fig. 11. Both figures present the nutrient loads (vertical axis) as a function of the distance along the river (horizontal axis).

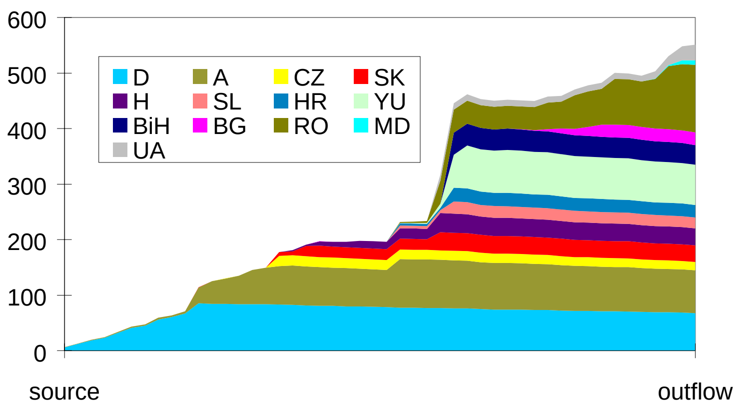

Fig. 10: In-stream loads of Nitrogen.

Fig. 10 shows the gradual increase of the in-stream nitrogen load from the source of the Danube up to the middle Danube area, where it increases very rapidly, due to the inflows of the Drava, Tisa and Sava tributaries. The gradual increase continues up to the outflow. The country contributions show a gradual or jump-wise build-up, similar to the build-up of their catchment contributions (see Fig. 2). Downstream, the country nitrogen load contributions decrease gradually. This is the result of the in-stream denitrification.

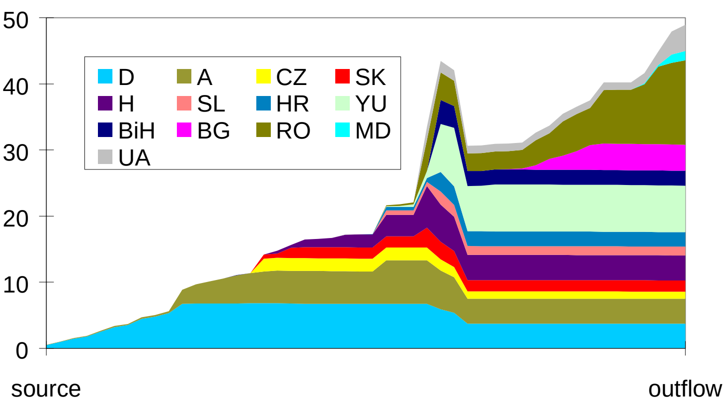

Fig. 11: In-stream loads of Phosphorus.

Fig. 11 shows a similar picture for phosphorus. In this case however, the in-stream removal is not distributed over the whole river as with nitrogen. Phosphorus is only removed from the river in the Iron Gates lakes area, downstream of the inflows of the Drava, Tisa and Sava tributaries. Therefore, the in-stream load sharply decreases just downstream of the strong increase at the locations of these tributaries.

3.2 The Pollution Reduction Programme

Taking into account the implementation of all projects and pollution reduction measures in the Danube River Basin countries, the expected pollution reduction in terms of N and P is presented per Country and Sector in Fig. 12 and summarised per Sector in Fig. 13.

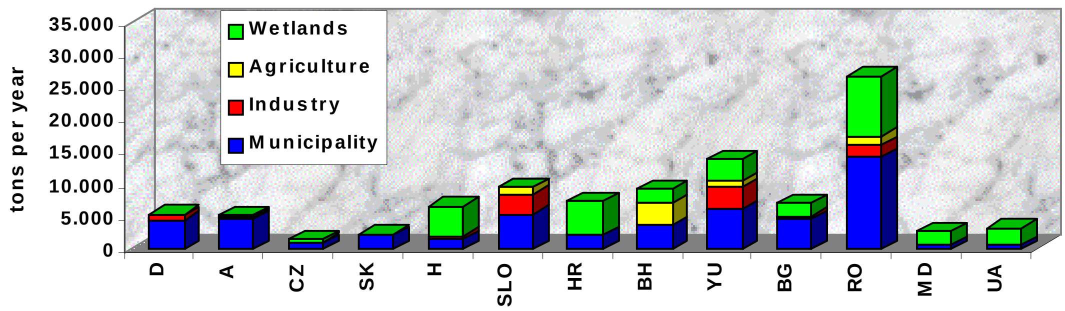

Fig. 12: Expected pollution reduction of N and P from proposed and ongoing national projects per country and per sector.

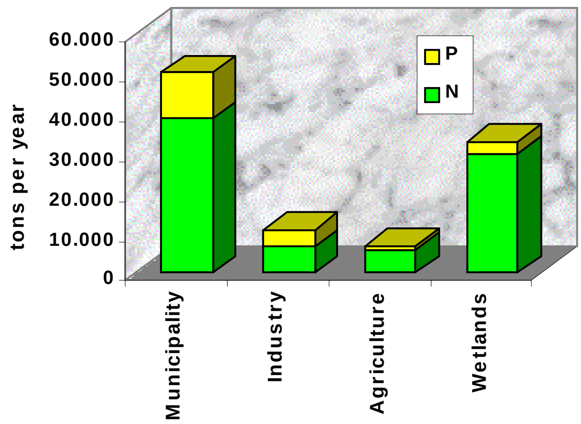

Fig. 13: Expected pollution reduction of N and P from proposed and ongoing national projects, summarised per sector.

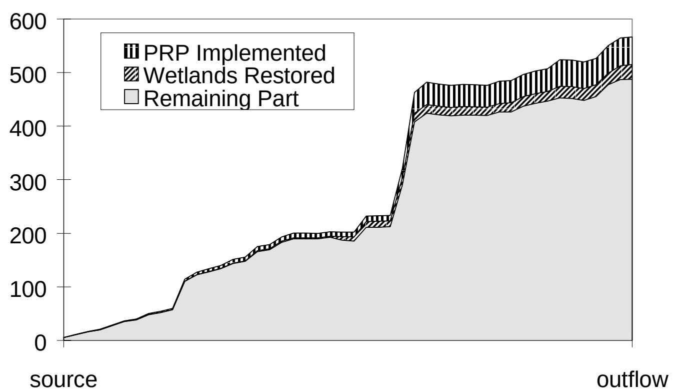

Fig. 14: In-stream nitrogen load profile for the Danube river, before and after implementation of the PRP, with the additional effect of the restoration of 17 wetlands.

The presentation shows the particular importance of N and P reduction through municipal waste water treatment facilities and through the restoration or rehabilitation of wetlands functioning as nutrient sinks. Concerning the relatively low reduction from the agricultural sector, it should be noted, that agricultural projects refer mainly to point sources of pollution (animal farms). The largest share of the nutrient pollution from agriculture however, are the diffuse emissions caused by fertiliser application, which have to be reduced through a change of agricultural practices and new policy instruments.

The positive impacts on the Black Sea are indicated in the results of the simulation within the Water Quality Model concerning the load reduction of phosphorus and nitrogen (see Fig. 14 and Fig. 15).

All together the load reduction of the nutrients to the Black sea is expected to reach the amount of 81,272 t/y for nitrogen and 20,371 t/y for phosphorus after the implementation of the proposed projects for municipal, industrial, agricultural waste water treatment plants and wetland restoration.

The highest concentration of hot spots is in the middle but also in the lower part of the Danube River Basin. As the DWQM results show, that P reduction in respect to the Black Sea might be more effective closer to the Black Sea, whereas N reduction does not appear to be so distance related, emphasis should be given to projects in the middle and lower Danube to reduce loads to the Black Sea. These considerations should be balanced with the responsibility of all countries who contribute nutrients to the Danube to take action (Polluter Pays Principle).

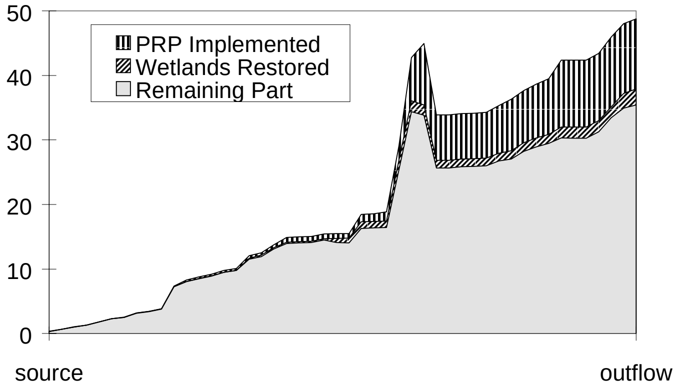

Fig. 15: In-stream phosphorus load profile for the Danube river, before and after implementation of the PRP, with the additional effect of the restoration of 17 wetlands.

Upstream countries have fewer hot spots, but they still remain significant suppliers of nutrient loads to the Black Sea. These countries should consider identifying and implementing wetlands rehabilitation projects as part of their own nutrient reduction strategies. Nutrient reduction for diffuse sources of pollution in the upstream countries Germany and Austria can merely by achieved through agricultural policy reforms and change of agricultural practices.

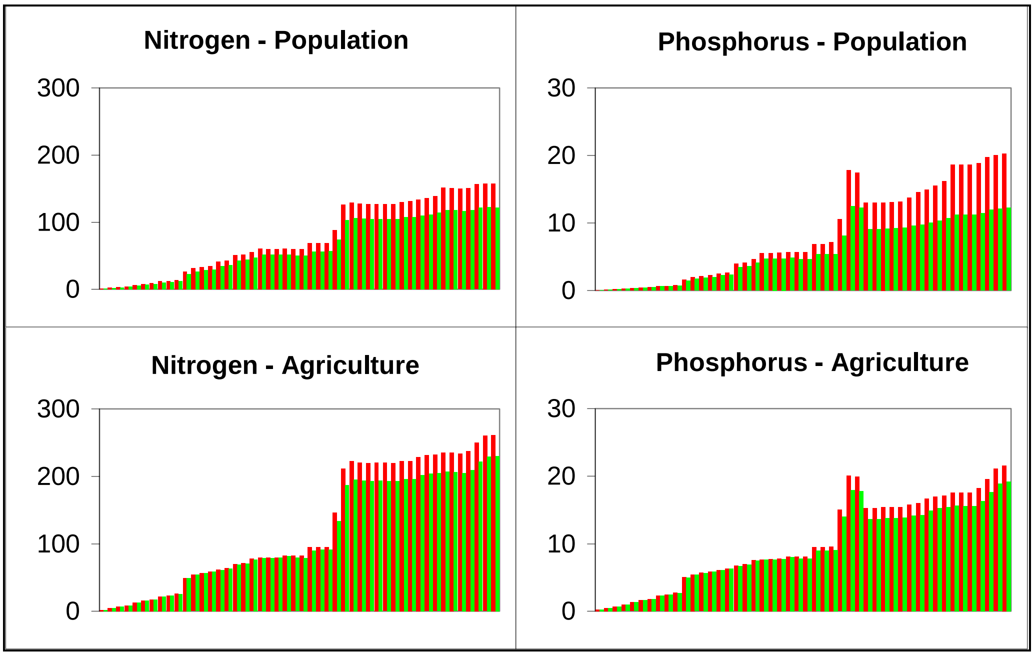

Fig. 16: Sectoral analysis of the effects of the PRP on the Danube in-stream nutrient loads: comparison of in-stream loads before (dark) and after implementation (light).

The analysis of the effects of emission reductions per sector (see Fig. 16) shows clearly the importance of actions to be undertaken in the central and downstream countries of the Danube River Basin. Projects developed for the urban sector (population) are leading to a considerable decrease of nutrient emissions in particular phosphorus, which reflects the result of important investments in this sector. The industrial sector seems, in terms of nutrient emissions insignificant, but could have a devastating effect if old industries with outdated technologies would be put back to operation. The agricultural sector accounts for the highest contribution of the nutrient load and proposed measures are in fact too insignificant to produce a real remarkable effects. In the downstream countries the reduction of nutrients is merely due to the rehabilitation of wetlands then to the reduction of use of fertilisers and pesticides. Highest attention has therefore to be given to agricultural policy reforms and changes of agricultural practices.

4. Conclusions and recommendations

The DWQM has provided a quantitative synthesis of all available knowledge regarding the fate of nutrients in the Danube basin. Even though many knowledge gaps exist, our understanding of the system has increased and a common basis was established for the evaluation of the current status of the basin and the assessment of the effects of the pollution reduction from point sources of emissions and of in-stream reduction of nutrient loads through the restoration of the wetlands. As such, the DWQM provided a vehicle to carry the discussion one step beyond just complaining about how much we do not know yet.

Important spin-off of the current exercise is a clear insight in the existing knowledge gaps, which can be summarised as follows:

- insufficient knowledge on a basin-wide scale of the in-stream transports of nutrients: in particular: (*) the organic part of nitrogen, and (*) the particulate part of phosphorus;
- insufficient knowledge on a basin-wide scale of the current emission levels, against the background of (*) the rapidly changing economical conditions in major parts of the basin, and (*) the residence time of the aquifers;
- insufficient knowledge on a basin-wide scale of the retention in the catchment: which physical and hydrological conditions affect this retention most?;
- insufficient knowledge on a basin-wide scale of the retention in the river: (*) the relevance of net sedimentation of phosphorus in other reaches than the Iron Gates, and (*) the relevance of denitrification in the river and the role of the organic carbon cycle in this respect.

Most of the identified gaps have been addressed in the DANUBS research proposal, which has been submitted to the EU for financial support. In this programme, 13 research institutes from different Danubian countries as well as from Greece and from the Netherlands participate. The programme is oriented towards the management of the nutrients balance in the biosphere. It not only deals with the Danube on itself, but also takes into account the effects of the Danube plume on the North-western Shelf of the Black Sea.

With its further development, the Danube Water Quality Model will become a valuable tool to monitor the effects of measures and actions applied by the various countries to reduce the nutrient loads to the Danube River and to control effectively the compliance with the EU Nitrate Directive. Thus, it can contribute to a controlled development which will allow the Black Sea ecosystems to recover and the economic conditions to improve through a sustainable management of resources.

5. Acknowledgements

The authors wish to express their gratitude towards the members of a Technical Working Group, which made an indispensable contribution to the results presented in the current paper. This group consisted of Helmut Fleckseder (ICPDR), Don Graybill (UNDP/GEF), Geza Jolankai, Helmut Kroiss, Bernd Mehlhorn (ICPDR, EMIS), Steffen Mueller, Ilya Natchkov (EU), Liviu Popescu (ICPDR, MLIM) and Matthias Zessner. Furthermore, the work presented would have been impossible without the data and expertise collected by the Danube countries under the guidance of the MLIM and EMIS Expert Groups of the ICPDR.

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