The Narew River Basin:
A model for the sustainable management of agriculture, nature and water supply

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The Narew River Basin: A model for the sustainable management of agriculture, nature and water supply

Marek Giełczewski

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Koninklijk Nederlands Aardrijkskundig Genootschap/
Faculteit Ruimtelijke Wetenschappen, Universiteit Utrecht

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Promotores:

Prof. Dr. P.A. Burrough	Utrecht University
Prof. Dr. S. Ignar	Warsaw Agricultural University
Prof. Dr. M.J. Wassen	Utrecht University

Co-promotores:

Dr. W. Bleuten	Utrecht University
Dr. T. Okruszko	Warsaw Agricultural University

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1 INTRODUCTION

1.1 Problem definition

Although the technological developments of previous centuries have increased the welfare and standards of living of many people, there have also been major alterations in the structure and functioning of their environment (Smith et al., 1999). People have dramatically changed the globe by land clearing, agriculture, forestry, animal husbandry and urbanization, and by altering major hydrological cycles (Vitousek et al., 1997). In turn these actions have led to all sorts of problems related to natural resources that in turn affect the well being of people and natural flora and fauna. For example, a major problem is the change of the quality and quantity of surface water, which is a direct consequence of human activities (Meybeck, 1998). In many cases these changes in water quality and quantity are the result of the addition of chemical substances from diffuse and point sources (Naiman & Decamps, 1990), which have led to deterioration and/or shortage of drinking water resources, especially in densely populated and highly industrialized areas (Bai & Imura, 2001). Examples of water quality deterioration are now known for all continents particularly through the compilation of the GEMS-Water programme that was launched by UNEP in 1978 (Fraser et al., 1995).

The Polish Vistula river is a prime example of a major catchment in which all the water quality issues caused by high population densities, intensive agriculture, major industries, and mining activities have been combined (Santiago et al., 1994); this results in difficulties with providing a sufficient and safe water supply for the capital city of Warsaw.

At present Warsaw gets its water from four sources, namely groundwater from the deep Oligocene aquifer in the Warsaw area, the Vistula river surface water, the Vistula river bed groundwater and water from the Zegrzynski Reservoir (see figure 1.2), which collects water from the catchments of the Bug and Narew rivers. The city has about 2 million inhabitants and needs up to 12 $m^{3}\cdot s^{-1}$ of water to satisfy domestic and industrial demands. At present, all possible surface water sources of drinking water in Warsaw are of poor quality, with none of them meeting international standards. Water exploited from those sources requires an intensive treatment process that is costly in chemicals and energy. However, even the treated water is of insufficient quality for customers requiring high quality water, and many persons find its taste unacceptable.

The Warsaw economy needs much more good quality water than can be supplied by groundwater from the Oligocene aquifer. Water from this source is distributed only to users that require high quality water e.g. the food processing industry, electronics and health care. There is also an open public tap programme for the people of Warsaw whereby they may collect small quantities of this groundwater for domestic use.

Surface water from the Vistula river is used only in emergencies. It is polluted by heavy industry up stream in the Upper Silesia region and by sulphur mines in the vicinity of Tarnobrzeg. Its quality is not expected to improve significantly even in the long term. In the coming years the Vistula river bed groundwater might also be too polluted for everyday use as drinking water.

The fourth source, the Zegrzynski Reservoir, is supplied mainly with water from the Bug and the Narew rivers, and it is intended to be the main source of drinking water for Warsaw. Water is already being pumped to a purification plant with a planned in-coming capacity sufficient to cover the city needs. Unfortunately, the Bug river is polluted by discharges from Ukrainian and Belarussian coal mines and industry, a situation that will not change until there are international agreements, which is unlikely in the short term.

The Narew river might present a unique opportunity to achieve a long lasting solution for the water quality problems of the Warsaw agglomeration. Moreover, its realisation may contribute to sustainable development of the region. The reasons why the Narew River Basin may form a suitable alternative to existing supply sources are:

(i) the basin supplies good quality water compared to other possible sources and to world quality standards,
(ii) there is an adequate supply – discharge at the mouth of the river is always sufficient, even during low flow periods,
(iii) the water from the basin may be relatively easily exploited - water abstraction infrastructure is already present close to the river mouth,
(iv) almost the entire basin, except for the very upper sub-catchment, is located in Poland, which provides favourable opportunities for operational management,
(v) the absence of significant point polluters (e.g. heavy industry, mines, big cities),
(vi) feasible identification and elimination of the existing point sources,
(vii) there is only extensive agriculture at present,
(viii) the basin is already covered in 32% by forest and almost 10% of its area is protected in the form of national and landscape parks, and other nature protection forms,
(ix) the existence of strong regional NGOs (e.g. Green Lungs of Poland Foundation) that formulate and promote policies of sustainable development of the region.

Of course, there are numerous environmental and economical problems in the Narew River Basin, too. Water quality is below standard in some river stretches, there is pressure on the natural environment due to the intensification of agriculture and development of tourism, there is insufficient wastewater treatment infrastructure and there is a lack of money for environmental investments, to mention the most important. These problems might constitute a serious threat to natural ecosystems of the basin, which are recognized internationally for their exceptionally high quality and rich biodiversity (Wassen, 1990, Banaszuk, 1996). The main additional factor that may have significant impact on the development of the Narew River Basin is the inevitable perspective of Poland joining the European Union. The current application for membership means the gradual adjustment of Polish regulations and standards in many areas. For example, foreseen changes in an implementation of new environmental and agricultural policies or in the introduction of agricultural subsidies must be taken into account. This raises a number of questions:

(i) To what extent do urban point sources contribute to the nutrient loads in the basin?
(ii) What is the effect of today's agriculture on river water quality and then in turn on aquatic ecosystems?

(iii) Which river stretches are the most effected by nonpoint pollution?

(iv) What will be the effect of different management scenarios on non-point emissions, river water quality and nature?

Linking the two general problems concerning the quality of drinking water in Warsaw and the conservation of high nature quality in the Narew River Basin creates mutual dependency. For the continuation of its high nature quality the Narew River Basin depends on demands for good quality water. On the other hand the good quality of drinking water in Warsaw depends on the success of the environmental management of the basin. The functions of a large city and unspoiled nature interact and could support each other in a sustainable way. In this case "sustainability" implies supporting social and economic development by using the high quality water from the Narew river outlet as drinking water for Warsaw without compromising the quality of nature in the Narew River Basin.

The successful implementation of sustainable development requires investigation in three fields: physical environment, society and economy. They are interconnected, with the economy being dependent on society and the environment while human existence and society are dependent on, and within the environment (Giddings et al., 2002). In this thesis the core, physical environmental, aspect of the possible sustainable development in the Narew River Basin is addressed. Complete elaboration of the concept of sustainable development will need research in the other two fields.

1.2 Research aims

The hypothesis appearing from the problem definition is that sustainable development of the Narew River Basin could be reached if the basin could provide Warsaw with good quality drinking water. So, it would then become a factor of great interest to the population and authorities of Warsaw to maintain the conditions for the desired quantity and quality of water leaving the basin. Therefore, the question is: is it possible to help decision makers to make a land and water management plan for the Narew River Basin, aimed at the sustainable use of the big discharge of Narew river water, which is, compared to most river basins in Europe, of exceptional good quality? At the same time this quantity and quality is the condition for the survival of the high biodiversity of land and water ecosystems in the basin.

The aim of this thesis is to attempt to answer this question by understanding the balance in the physical environment of the Narew River Basin between land use – surface water – aquatic vegetation in such a way that if Narew river water is used for Warsaw, then the ecological quality of the Narew River Basin will be maintained. More specifically, the thesis deals with a large scale analysis of how land use changes impact the nutrient emissions, water quality and natural ecosystems in the Narew River Basin. On the more general level the thesis contributes to the development of tools for analysing integrated management strategies at the river basin scale and to enhance understanding of their role for sustainable development at this scale.

To answer this question, the following objectives were formulated:

(i) construct a tool for integrated modelling of the nutrient emissions – water quality – aquatic ecosystems cause-and-effect chain. This topic is addressed in more detail in section 1.5,

(ii) design a set of scenarios describing foreseen future variation in land use and nutrient sources management,

(iii) predict nutrient emitted loads, nutrient concentrations in surface water and the presence of aquatic plant species for these scenarios,

(iv) evaluate the various scenarios in terms of their ability to fulfil sustainable development criteria. An overview of these criteria is given in section 1.4.

1.3 Tackling the physical environment (land use – surface water – aquatic ecosystem) cause-and-effect chain

To tackle the challenge of investigating the environmental aspects of sustainable development it is necessary to analyse the relations of the land use – surface water – aquatic ecosystem cause-and-effect chain. Mackey (1996) has argued that we need to be able to investigate how projected changes in land use and environmental conditions may affect biodiversity. Similarly, Hansen and Rotella (1998) argued that in order to improve landscape management we need to quantify the links between key abiotic factors, ecological processes, vegetation and land use. According to Burrough et al. (2001), in our search for models of sustainable human settlement and economic development the conservation of biodiversity remains one of the greatest challenges. These relations can only be understood if there are sufficient and appropriate data and the tools to analyse them properly (Burrough et al., 2001). Numerical environmental models are a possible solution as they provide a means to simulate physical landscape processes over time and space, and give decision makers an indication of the outcome for different options (Pullar & Springer, 2000).

In recent years there has been increasing interest in the integrated modelling of river basins, which has resulted in a number of studies addressing the simulation issue. These studies include theoretical framework studies (e.g. Pullar & Springer, 2000; Vos et al., 2000; Johnston et al., 2000; Soulsby et al., 2001) as well as implemented systems (e.g. Rousseau et al., 2000; Krysanova & Becker, 2000; Voinov et al., 1999). The range of studies includes river basins of different sizes (e.g. Krysanova & Becker 2000; Rousseau et al., 2000; Vinay & Sivapalan, 2001) and those addressing the national level (e.g. Alkemade et al., 1998; Soulsby et al., 2001). Some studies are restricted to land use – water quality integration (e.g. Rousseau et al., 2000; Tim & Jolly, 1994) and they have included elements of aquatic ecosystems (e.g. Olvera-Viascan et al., 1998; Refsgaard et al., 1998) and/or economical aspects (e.g. van den Bergh et al., 2001; Voinov et al., 1999; Pieterse et al., 2002). They are also often supported by and are embedded in Geographical Information Systems (e.g. Pullar & Springer, 2000; Krysanova & Becker, 2000; Rousseau et al., 2000).

The number of numerical models that have been used for integrated basin modelling is enormous and their diversity with regard to scale and approach is broad. For example Jorgensen (1999) estimates that more than 4000 ecological models have been used as tools in research or environmental management. Twenty years ago, Haith (1982) evaluated tens of non-point source pollution models.

In order to design and evaluate environmental policy scenarios and land use change scenarios, it is first necessary to have considerable amounts of relevant data and the means to carry out the necessary data management operations. Many of these technical data manipulation tasks can be carried out using Geographical Information Systems (GIS). Second, it is essential to be able to choose the most suitable models for the task in hand (in the case of this thesis this means existing models for nutrient emissions, water quality and nature development). Finally, these models need to be linked to the GIS to create an integrated Decision Support System (Alkemade et al., 1998; Pfeffer, 2003).

The elements (existing models or modelling concepts) selected for and incorporated in such an integrated tool must be relevant for the spatial and temporal scales of the environmental processes and relations the tool is designed to model. The selection is often influenced by limitations in data and their applicability for predictive modelling, which are more the rule than the exception, since collecting data on fine-grain patterns as well as large structures is generally costly and time consuming (Wassen & Verhoeven, 2003). The structure of an integrated tool must also enable for an effective integration of particular elements on the data exchange (output – input) level.

Clearly, with so many models to choose from, it is necessary to be careful to select only those models that meet one's needs. To effectively investigate the effects of different management strategies in land use – surface water – aquatic ecosystems, cause-and-effect chain models for every element of the chain need to be used.

Traditional approaches for assessing the impact of land use change on water quality have been based on the development of detailed physically based models that predict nutrient concentrations in real time (Johnes, 1996). They work well in the small catchments that they were originally constructed for (e.g. Lunn et al., 1996; Skop & Sorensen, 1998). They are, however, dependent on site-specific parameters, which require additional effort and expense to measure and impose a theory upon the data, a theory that may or may not be complete (Worrall & Burt, 1999). Thus, they are expensive to construct and difficult to calibrate in larger catchments, owing to their large data requirements (Johnes, 1996) An alternative to the physically-based approach is use of an empirical model, such as the export coefficient (Johnes, 1996) and USLE (Wischmeier & Smith, 1978), especially for management use (Worral & Burt, 1999), or the distributed parameter, simulation model, such as HSPF (Bicknell et al., 1984), AGNPS (Young et al., 1989) and SWAT (Arnold et al., 1993). Although, the research emphasis has shifted in recent years from empirical models to simulation ones, satisfactory results are still provided by these empirical models to describe nutrient losses from agricultural catchments (e.g. Johnes & Heathwaite, 1997; Sandner et al., 1993; Ripl, 1995; Mander et al., 2000). They are especially useful for studies in which a fully distributed analysis is not an objective and/or/when available data are limited.

For in-stream water quality determination, water quality models may be used to represent the physical, chemical and biological transformations, which occur within a river. The number and detail of processes represented varies according to the purpose of the model and the required determinants (Whitehead et al., 1997). The processes described by such models are based on the principles of mass balance along a river reach, thus they may be applied at all spatial and temporal scales (Wade et al., 2001). Several such models describing pollutant transport in the multi-reach river network have been applied at the river basin scale in Western Europe (e.g. QUASAR; Lewis et al., 1997; QUESTOR; Eatherall et al., 1998; INCA; Whitehead et al., 1998; RIVERSTRAHLER; Billen et al., 1994) as well as in Central and Eastern Europe (e.g. DESERT and STREAMPLAN; Somlyody, 1997; Kindler et al., 1998).

Ecological models generally link abiotic information (e.g. water quality and quantity) to fauna and flora that depend on these site conditions (Wassen & Verhoeven, 2003). Generally, three predictive modelling approaches: (i) mechanistic, (ii) statistical and (iii) expert systems can be distinguished when the impact of changes in environmental site conditions on plant communities response is to be described (Olff et al., 1995). Mechanistic ecological models, containing causal relationships in ecosystems derived from experimental studies, are available for relatively simple and well-studied ecosystems, for example shallow freshwater lakes (van Liere & Gulati, 1992; Janse et al., 1992). Mechanistic models are the most complex of the three approaches and as such to be preferred above the others (Ertsen, 1998). However, their development requires extensive experimental testing which costs time and money (Wassen & Verhoeven, 2003).

An example of an expert systems approach is the ecological indicator system, which is based on expert knowledge (Ertsen, 1998). Ranking lists containing indicator values for plant species have been used for the construction of expert-knowledge based models (Olde Venterink & Wassen, 1997). In these lists indicator values for several environmental factors, such as moisture and nutrient status, are assigned to plant species, grouped along gradients of these environmental factors. The ranking lists are predominantly based on a compilation of expert experience and not on the results of a direct gradient analysis (Olde Venterink & Wassen, 1997). Moreover, they are assembled for certain geographical conditions and thus their extrapolation to other regions is limited. Therefore, expert systems are especially useful for a descriptive study of vegetation where time is limited and field measurements are few (Mountfort & Chapman, 1993; Ter Braak & Wiertz, 1994; Ertsen, 1998).

In empirical statistical models the identification of independent variables explaining species response is based entirely on statistical analysis (Norton & Possingham, 1995). The statistical approach assumes that when an ecosystem is characterized by a given set of stable site conditions the vegetation present in this ecosystem is related to environmental factors. Generally, a regression model is used to specify the functional relationship between a response of a plant species and one or more explanatory variables, for instance water quality variables (Bio et al., 2002). Those models are often based on available data or on a limited data set especially collected for the purpose of the model development (De La Ville et al., 1997; Ertsen et al., 1998). Therefore, empirical models are suitable for studying regional landscapes like watersheds and river valleys, where generally applicable models for a range of ecosystems are needed (De Becker et al., 2001; Wassen & Verhoeven, 2003) and where available data are sufficient or feasible to collect.

For the purpose of studying load emissions and water quality in the Narew River Basin it was efficient to focus the analysis on two nutrients, nitrogen (N) and phosphorus (P) and their compounds. This was for two reasons:

(i) P is the most biologically active nutrient, with N coming second (Berner & Berner, 1996). This means that biological activity will often be limited by the availability of P and N. Increasing the availability of these two limiting nutrients may cause an increase in biological activity and in turn intensify the eutrophication process (De Wit, 2000). A growth in nutrient emissions may be foreseen if agriculture in the basin will intensify,

(ii) N and P (and their compounds) are two elements that at the moment caused quality problems to surface water in the basin (Gielczewski et al., 1998).

In this study natural ecosystems were taken to be aquatic vegetation because the structure and functioning of aquatic communities depends on surface water composition and reacts rapidly to changes in surface water quality (Soulsby et al., 2001). Furthermore, the aquatic ecosystems in the basin are well developed and highly valued for their biodiversity (Wassen, 1995).

1.4 The sustainability criteria

Suitable criteria must be established in order to be able to determine if a particular scenario fulfils the requirements of complying with the concept of sustainable development. For water quality, I chose as first criterion the first water quality class limit according to Polish law: this applies to the quality of water at the mouth of the river, because this is where water will be abstracted. First-class water quality conforms to Polish State standards set by the Ministry of Environmental Protection, Natural Resources and Forestry (Water Classification, 1991). It is the best class of three inland surface water classes and is defined as water suitable for: (i) providing the population with drinking water, (ii) providing plants with high quality water, and (iii) ensuring the survival of the Salmonidae family in its natural habitat. The same criterion but applied to all river stretches was chosen for the aquatic vegetation aspect of sustainable development. As an additional criterion the preservation of at least the present composition of aquatic vegetation was assumed.

1.5 An Integrated Management Tool

Recognition of the interplay between land use, water resources and the natural environment has given rise to integrated catchment area management studies (Newson, 1982). O'Riordan (1999) argued that although catchment management has traditionally relied on engineering solutions to manage or rectify perceived problems, a shift towards a more holistic approach to environmental management is needed. Some key scientific issues need to be addressed which are prerequisites to the holistic understanding of the basin, if the management of river basins is to contribute to an achievement of sustainable development (Soulsby et al., 2001). Such a holistic approach will make it possible to describe major relations within the land use – surface water – aquatic ecosystem cause-and-effect chain, such as the influence of land use changes on nutrient emissions, river water and aquatic ecosystem quality. Thus this approach will enable an assessment of the environmental status of the basin and provide a basis for sustainable management. To elucidate the critical linkages that determine the ecological response of the land use changes requires an integrated interdisciplinary approach in studies at the river basin level.

This thesis contributes to the development of a holistic approach to environmental management and presents an integrated management tool (IMT) for the Narew River Basin. The proposed tool integrates the models for assessing changes in three major aspects of the land use – surface water – aquatic ecosystem cause-and-effect chain: (i) nutrient emissions in the catchment, (ii) in-stream water quality in the river network and (iii) presence of aquatic plant species. The selection of modelling approaches used here attempts to find models that support the achievement of study objectives and to match their complexity both with current understanding of the driving processes and an ability to parameterise those processes with available data.

For modelling nutrient emissions from the catchment to surface water an export coefficients based approach was adopted and a module named NULAM (NUtrient Load Assessment Module) was developed. This is a lumped model, which calculates nutrient losses for each land use type and each type of livestock (including people) found in the catchment (Johnes, 1996). Despite its simplicity, the models based on this approach have proved to be very successful in modelling nutrient losses from catchments (e.g. Johnes, 1996; Johnes & Burt, 1993).

The output results from the nutrient emission modelling were supplied into an in-stream water quality model. The in-stream water quality modelling was based on the existing water quality model STREAMPLAN (Spreadsheet Tool for River Environmental Assessment, Management and PLANning), this model is best described in De Marchi et al. (1996) and has been successfully used in a number of modelling studies in Central and Eastern Europe (e.g. Somlyody, 1997; De Marchi et al., 1998). The model is a one-dimensional, linear and steady state approach and the physical processes are described based on the principles of mass balance along a river reach. It models changes in concentration of water quality constituents at nodal points of individual river reaches as a result of inputs, reactions and mixing along reach length.

The nutrient concentrations, being the result of in-stream water quality modelling, were used as input for the empirical statistical model INCORS (Influence of Nutrient Concentrations On the Response of Species). This approach was applied to a number of studies focused on the response of plant species to changes in site factors (e.g. Barendregt & Nieuwenhuis, 1993; Ertsen, 1998; Bio et al., 2002). The functional relationship between plant species (response variables) and nutrient concentrations (explanatory variables) was specified by a logistic regression model. Multiple logistic regression modelling was performed within the framework of Generalized Linear Models (Nelder & Wedderburn, 1972; McCullagh & Nelder, 1989), which has been successfully applied in numerous ecological studies (e.g. Austin et al., 1984; Margules et al., 1987; Zimmermann & Kienast, 1999).

The IMT was designed to address policy issues by investigating alternative scenarios for basin management (land use change and effluent discharges). For the entire Narew River Basin the IMT is characterized by a semi-distributed approach, so that the spatial variations within the basin and the ways different sub-basins are managed can be taken into account, even though individual sub-catchments have been modelled in a lumped manner. The term semi-distributed is used here after Whitehead et al. (1998), as it is not intended to model the basin area in a detailed manner. Rather, different land use types and sub-catchments are modelled simultaneously and the information is fed sequentially into a multi-reach river model. Over the whole basin the IMT carries out computation at selected locations, which are common for all three component models. These locations are based on the hydrological characteristic of the basin and represent the most downstream points of sub-catchments in case of nutrient emission modelling, the nodal points of individual reaches in in-stream water quality modelling and the vegetation recording points in plant species response modelling. As GIS is a suitable tool for the management, query, and visualisation of the necessary information in environmental modelling (Pullar & Springer, 2000), the IMT implementation is GIS-aided. The GIS system (MapInfo) was used to prepare the input data for both models (e.g. delineation of sub-catchments, calculation area of sub-catchments and the percentage of each land use type) and scenarios (e.g. calculation of changes in land use type areas for different scenarios) development. The input data as well as the scenario study results were visualised in the GIS. This gives an excellent opportunity for people within the participatory planning process to be able to understand the possible ecological effects of the measures proposed in their plans (Hermann & Osinski, 1999).

The place of the IMT in the process of searching for sustainable development of the basin and its structure with regard to the input databases, the component models and the hierarchical linkage between the individual models is schematised in figure 1.1.

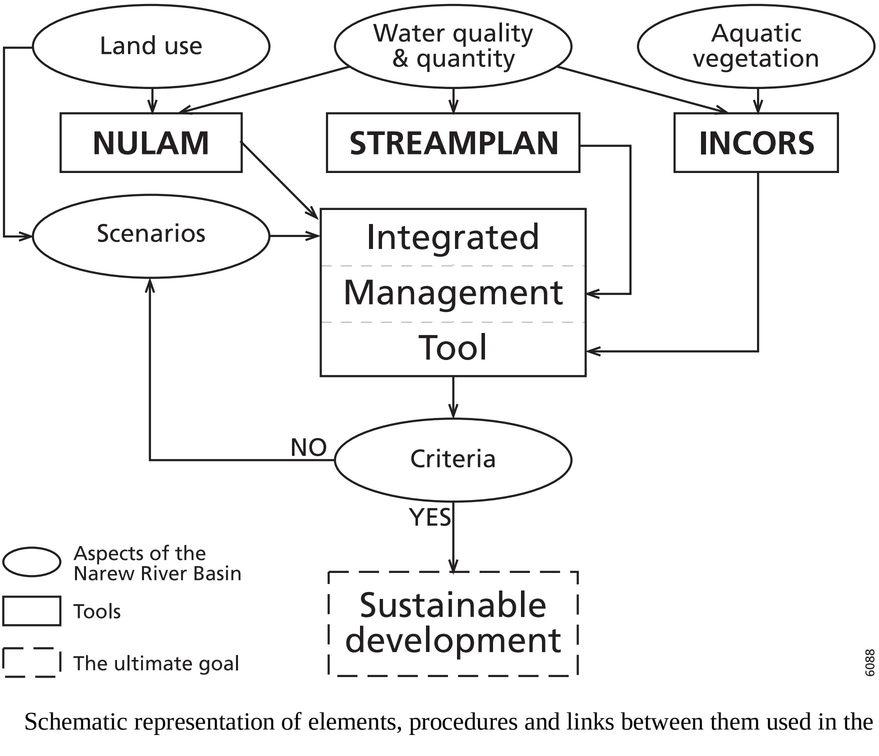


Figure 1.1 Schematic representation of elements, procedures and links between them used in the thesis

The hierarchical order of sub-models in the IMT with first NULAM, then STREAMPLAN and last INCORS is important because this is a natural order of changes in the investigated cause-and-effect chain. Thus, the output results of the first model are input data to the next one when the effects of scenarios are calculated.

1.6 The Narew River Basin

1.6.1 Geomorphology, climate and hydrology

The Narew River Basin is situated in the north-eastern part of Poland (figure 1.2). The Narew River is the fifth largest in the country with regard to river length (484 km) and the size of the basin (ca. 28000 km^2 before confluence with the Bug river). The entire basin, except for the most upper part of the catchment (ca. 1200 km^2), is located in Poland, but the head catchment is located in Belarus.

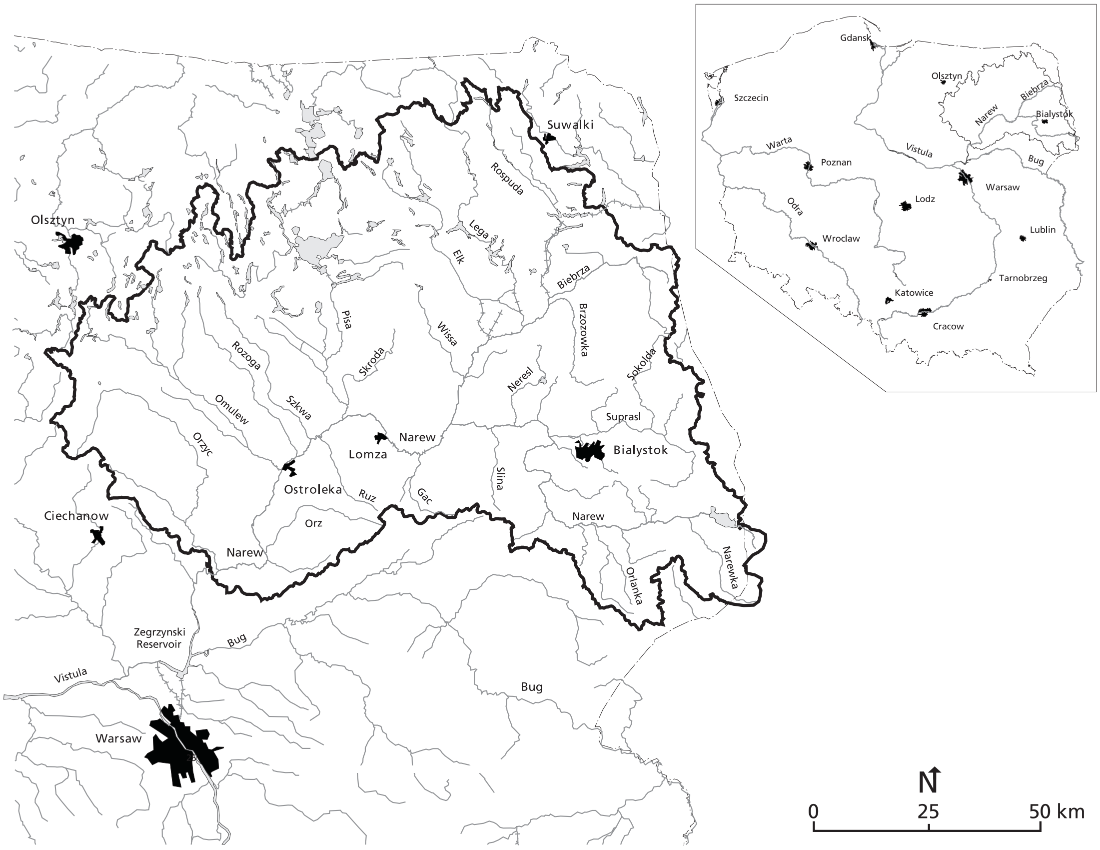


Figure 1.2 Location of the Narew River Basin

The basin is developed in areas covered by land-ice during the last two glaciation periods: Riss and Würm. From north to south the basin includes the following sequence of glacial landscape types: moraine lake district, outwash plains, ice-marginal river valleys and moraine hills. Sandy soils of various types predominate. During the Holocene the main valleys were filled up with mesotrophical-eutrophic peat layers, which still are partly undrained at present.

Poland is located in a temperate climatic zone in which marine and continental air masses collide. This climate type features characterize also the Narew River Basin. However, due to its location in northeastern Poland the impact of continental air is more visible in the basin compared to the rest of the country. The yearly average temperature is 7.2 ^{o}C and precipitation equals 617 mm.

The river network of the basin is fully developed and rich in tributaries, which mostly originate in the postglacial lakes located in the northern part of the area. In the lake district region there are more then 500 lakes larger than 1 hectare. A few irrigation and transportation channels create interconnections between lakes and the river network. The flow regime is typical for the lowland rivers in this part of Europe with peak flows after snow melting and regularly appearing low flow periods in the fall of the summer. The yearly average flow recorded at the Zambski Koscielne gauging station is 55 $m^{3}\cdot s^{-1}$, with average yearly maximum of 147 $m^{3}\cdot s^{-1}$. This location is regarded in this study as the point closing the Narew River Basin. It is the most downstream gauging station before confluence of the Bug and Narew rivers into the Zegrzynski Reservoir and the last where discharge data exclusively refer to the Narew river characteristics.

1.6.2 Population and economy

The Narew River Basin is one of the least populated in the country. The estimated number of inhabitants of the region is about 1.5 million. On average there are 55 inhabitants per square kilometre of the basin area, while in the rest of the country the average population density is more than twice as large, being up to 123 inhabitants per square kilometre. More than half of the population (60%) lives in the cities and towns. The biggest city of the basin is Bialystok, the capital city of Podlaskie voivodeship, with 285.000 inhabitants. The other cities are decidedly smaller and none of them exceeds 70.000 inhabitants. All cities have sanitary sewerage systems, transporting effluents to wastewater treatment plants, and storm drainage systems that drain off precipitation to the nearest receiving water. In most cities the sewerage network is distributive.

The Narew River Basin is an agricultural region, with a small degree of industrialization and no heavy industry. Existing production is connected with agriculture and is based on local raw materials, which are mainly: milk, meat, cereals, vegetables, fruits and wood. Industries that are developing are mainly agriculture, food and timber processing and recently tourism. Wastewater from most enterprises located in the cities discharge through the municipal main sewerage system and thence to wastewater treatment plants. Enterprises that are dispersed throughout the basin area have their own effluent treatment systems and systems of sewerage effluents.

1.6.3 Land use and nature areas

Agricultural land dominates the basin, covering almost 55% of its area (figure 1.3). The upland of the basin area is mainly used for arable land, the river valleys are used as pastures and grasslands. The forestation ratio of the Narew River Basin is slightly over 32%, which is somewhat higher than the average for the entire country, which equals 28% (GUS, 1997). The biggest and compact forest complexes are located in the east, north and west parts of the area.

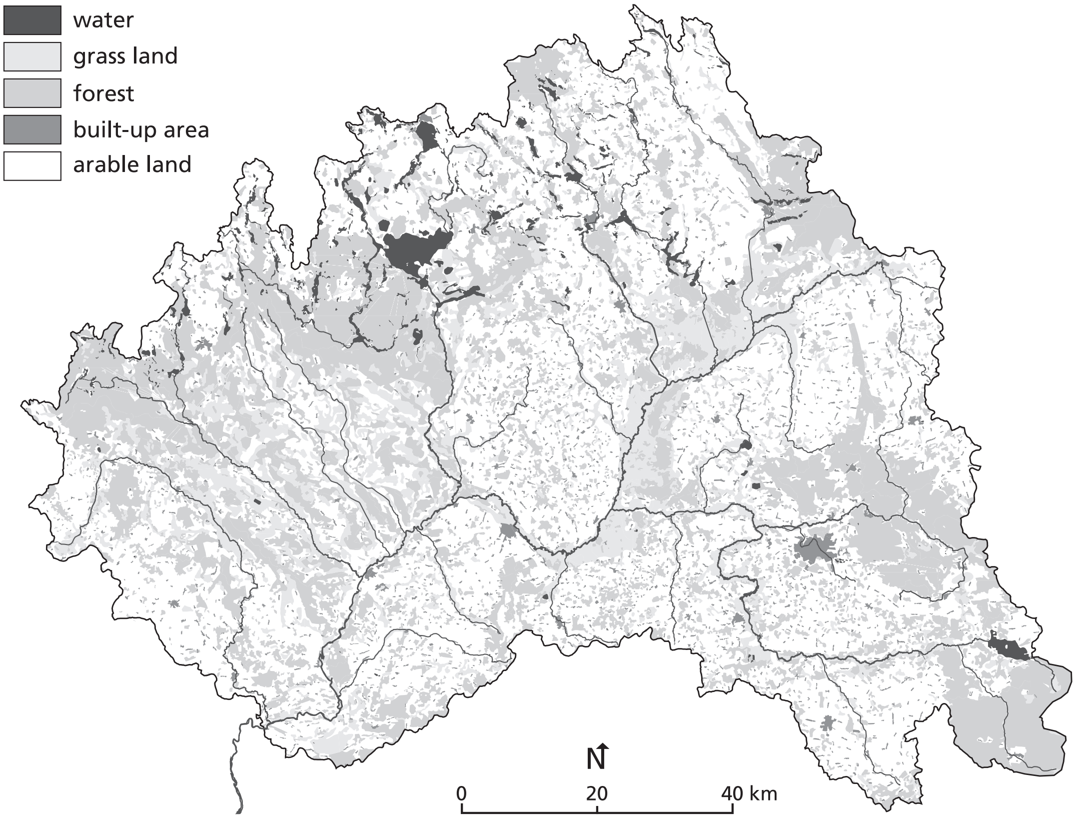


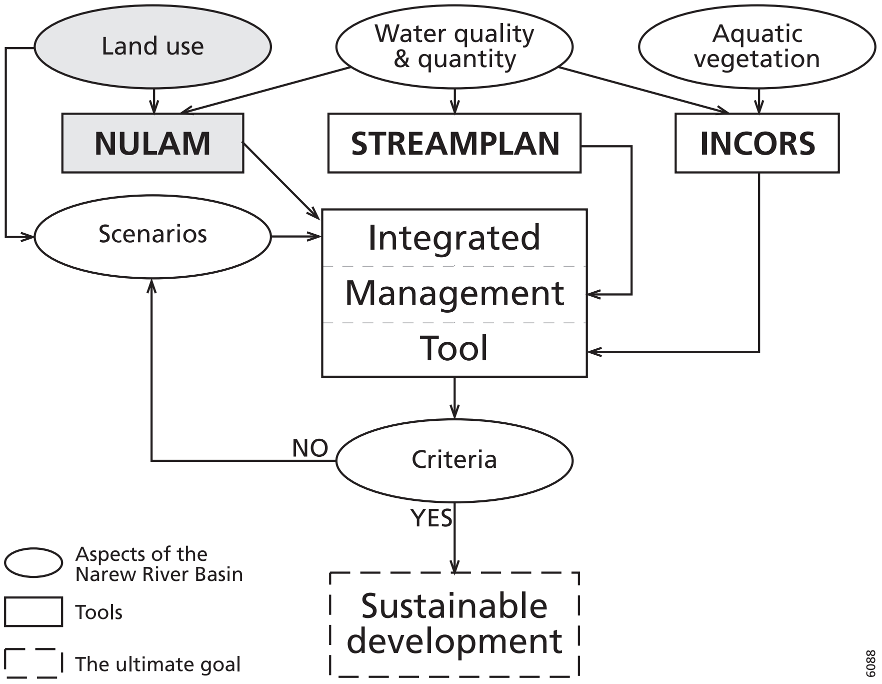
Figure 1.3 Land use in the Narew River Basin

The basin is rich in nature areas. It is the core of the region known as “the Green Lungs of Poland”. The Narew and the Biebrza river valleys among Europe’s last active, regularly flooded riverine valleys. Until now, a considerable part of the valleys has been utilized for extensive (environmentally sound) agricultural practices, thanks to which it still boasts wet meadows of a significant biodiversity value. Additionally, in the south-eastern part of the basin, there are a number of alder carrs which are groundwater fed. All those habitats are protected in the form of national parks. The existence of three large national parks (ca. 750 km^2) and a number of other protected areas (landscape parks ca. 1300 km^2, strict reserves ca. 170 km^2) emphasises the basin's natural value and importance.

1.7 Framework of the thesis

So far, this chapter has given a general overview of the research aims and topics that will be addressed. The main structure of this thesis reflects the building procedure and structure of the Integrated Management Tool (IMT) described in section 1.5. For each of the IMT component models the input database is presented, the current situation and relations are investigated, and the modelling approach is elucidated. Finally, the component models are integrated, the IMT is implemented for the scenario study, and the results are evaluated and discussed.

Chapter 2 describes the present land use and livestock characteristics in the basin, defines them as sources of nutrient loads, and quantifies them. Subsequently, a simple, lumped model is presented that can predict nutrient emissions from the sub-catchment to surface water as a function of land use and livestock characteristics in the upstream sub-catchment. Chapters 3 and 4 deal with aspects of water quality in the basin. The first one gives an insight into the present status of the water quality with the main focus paid to nutrients. The questions regarding the impact of different land use types and sources on nutrient concentrations in the river network are addressed. In the following chapter an in-stream water quality model is presented that can predict the surface water nutrient concentrations at nodal points along river stretches as a function of sub-catchment inputs and in-stream processes. Chapters 5 and 6 deal with ecohydrological issues in the Narew River Basin. The first of these two chapters describes the present condition of the aquatic ecosystems, elaborates interrelations between aquatic vegetation and surface water, and proposes classification of aquatic vegetation as a function of water quality and river dimension. The following chapter presents an empirical statistical model that allows for prediction of the response of aquatic plant species to changes in nutrient concentrations in surface water. Chapter 7 integrates the findings of the previous chapters and brings all the component models of the IMT to a common platform. Few scenarios of possible management in the basin are proposed, designed and finally quantified. Further, in this chapter I use the IMT for scenario studies in order to answer two of the main research topics defined in sections 1.1 and 1.2 regarding (i) predicting changes in land use – surface water - aquatic ecosystem cause-and-effect chain after implementation of the different management policies in the Narew River Basin and (ii) pointing the way towards sustainable development of the basin. Chapter 8 discusses the applicability of the IMT in the decision making process and reflects on the possibilities and constraints of the developed tool.


Land use
Water quality & quantity
Aquatic vegetation
NULAM
STREAMPLAN
INCORS
Scenarios
Integrated Management Tool
Criteria
NO
YES
Sustainable development
Aspects of the Narew River Basin
Tools
The ultimate goal
6088

2 THE NUTRIENT LOAD ASSESSMENT MODULE (NULAM) FOR THE NAREW RIVER BASIN

2.1 Introduction

Diffuse sources of nutrients are especially important in the Narew River Basin due to the domination of agricultural land use in the area, the relative scarcity of industrial and urban areas and therefore, the limited size of existing point sources.

This chapter describes a method for estimating the loads of nitrogen and phosphorus exported from the land to surface water. Subsequently, it presents the spatial distribution and volume of the nutrient export among different sub-catchments of the basin. The method is based on the assessment of the nutrients' diffuse load emitted from the sub-catchment and of the load transported in surface waters. This also gives a picture of the spatial distribution and volume of both nitrogen and phosphorus emitted from a sub-catchment and transported by surface waters.

In this study all emissions from sources that enter surface water in a diffuse manner and at intermittent intervals that are mainly related to meteorological events (Novotny & Chester, 1981) are defined as diffuse loads. The volume of the diffuse nutrient load is regarded as the difference between total export from a sub-catchment and the identifiable point source loads (Novotny & Olem, 1994). This implies that two main emission sources are considered: from land use and through excretion from humans and livestock. In recent years, diffuse sources have been of great concern because they are more difficult to estimate and to control than point sources (De Wit, 1999). They also add considerably to total nitrogen and phosphorus input loads (e.g. Iserman, 1990; Dojlido et al., 1994; Meinardi et at., 1995; Tonderski, 1997) and this share is gradually increasing in importance (De Wit et al., 2000) due to the strong reduction of point source emissions through the development of 'cleaner' production technologies, construction of more and better waste water treatment plants and upgrading of existing ones (e.g. Stanners & Bourdeau, 1995).

Several other studies have investigated the impact of nutrient diffuse sources on surface water pollution. The issue has been examined for large river basins, such as the Mississippi River (Meade, 1995), the Rhine and Elbe rivers (De Wit, 1999), the Baltic Sea drainage area (Stalnacke, 1996; Arheimer & Brandt, 2000) as well as for smaller catchments (< 2000 km^2) (e.g. Ferrier et al., 1995; Johnes & Heathwaite, 1997; Dorioz et al., 1998; Brigault & Ruban, 2000). There have also been studies of diffuse nutrient emission and the export rate for North-east Poland. However, these either included the Narew River Basin as part of the much bigger basin of the Vistula river (Tonderski, 1997) or they concentrated on small, experimental catchments (Hillbricht-Ilkowska et al., 2000; Pinay & Burt, 2001) located within the Narew basin. Therefore, previous studies addressed the problem of nutrient emission at too coarse or too detailed scales to find the answer for the question of this study, which is the estimation of nutrient emissions to surface water in sub-catchments of the Narew River Basin. Thus, one of the challenges of the present study was to develop a method appropriate for a study area size of ca. 28000 km^2, taking into account characteristic features such as hydrological divisions, land use and agricultural patterns.

Some other preconditions which had to be met by the approach were that the method had to allow for a scenario study, that the module had to be compatible with two other modules in order to be able to build an integrated management tool (see chapter 4 for the water quality model and chapter 6 for the ecohydrological vegetation model) and yet being relatively simple and ready to implement at local decision making level. The method chosen fulfilled all the above-mentioned requirements. It is based on the concept of export coefficients (e.g. Vollenweider, 1968; Beaulac & Reckhow, 1982; Johnes, 1996) and is called the NULAM model (NUtrient Load Assessment Module).

First, this chapter briefly presents the collected hydrological and statistical databases necessary for the analysis and the development of the module. Second, land use and agricultural characteristics of the basin are described against the background of its hydrological division. Then, the procedure for calculating nutrient loads is elaborated and explained, which is the core of NULAM. Subsequently, the observed loads in rivers, nutrient load export rates and the loads generated in the sub-catchments are presented with emphasis paid to their area-specific volume and spatial distribution. Finally, the results are discussed and conclusions are drawn.

2.2 Data

In order to use the NULAM module, the appropriate data had to be collected. The analyses were performed for the hydrological units based on three types of data; hydrological, chemical and statistical. The hydrological units (sub-catchments) reflect the hydrological division of the basin and are distinguished mainly on the basis of the existing gauge station network, which is the required scale for this study. The hydrological and chemical data were obtained from field campaigns carried out directly at the required scale; their characteristics and methods of collecting are presented in chapter 3. Statistical data, however, were available only for administrative units, communities and voivodeships (the highest level administrative unit in the country). Thus, it was first necessary to combine and transform these data to the required hydrological units.

2.2.1 Hydrological division

The part of the Narew River Basin which is the subject of analysis, (down to the gauge station of Zambski Koscielne, ca. 28000 km^2) was divided into 52 different sub-catchments. These sub-catchments are the core elements on which all the calculations and analysis of nitrogen and phosphorus were performed. The division aimed to reflect the hydrological characteristics of the basin by including the major and the most important tributaries and by selecting important stretches along the main course. Additionally, the division was based on the network of gauge stations operated by the State Weather Service (IMGW) which enabled the use of available hydrological data (discharge, river profiles and river slopes). Thus, the selected set included two types of sub-catchments, namely differential and head ones. The first are sub-catchments between the gauge stations which, delimit stretches of the Narew river and its main tributaries which are modelled for water quality (see chapter 4). The headwater sub-catchments include the tributaries, which are not modelled for water quality and headwaters of the modelled rivers. Both differential and head sub-catchments of the modelled rivers were named after the gauge station that closed a certain river stretch, while head sub-catchments of tributaries were named after the name of the tributary.

The hydrological division data (sub-catchments borders) were acquired in digital form from 1:200000 maps available in the Hydrological Atlas of Poland (IMGW, 1980). The paper maps were digitised using MapInfo software (MapInfo Inc., 2001). Next this program was used to create a digital map of hydrological divisions (figure 2.1) and to calculate the surface area of particular sub-catchments (table 2.1).

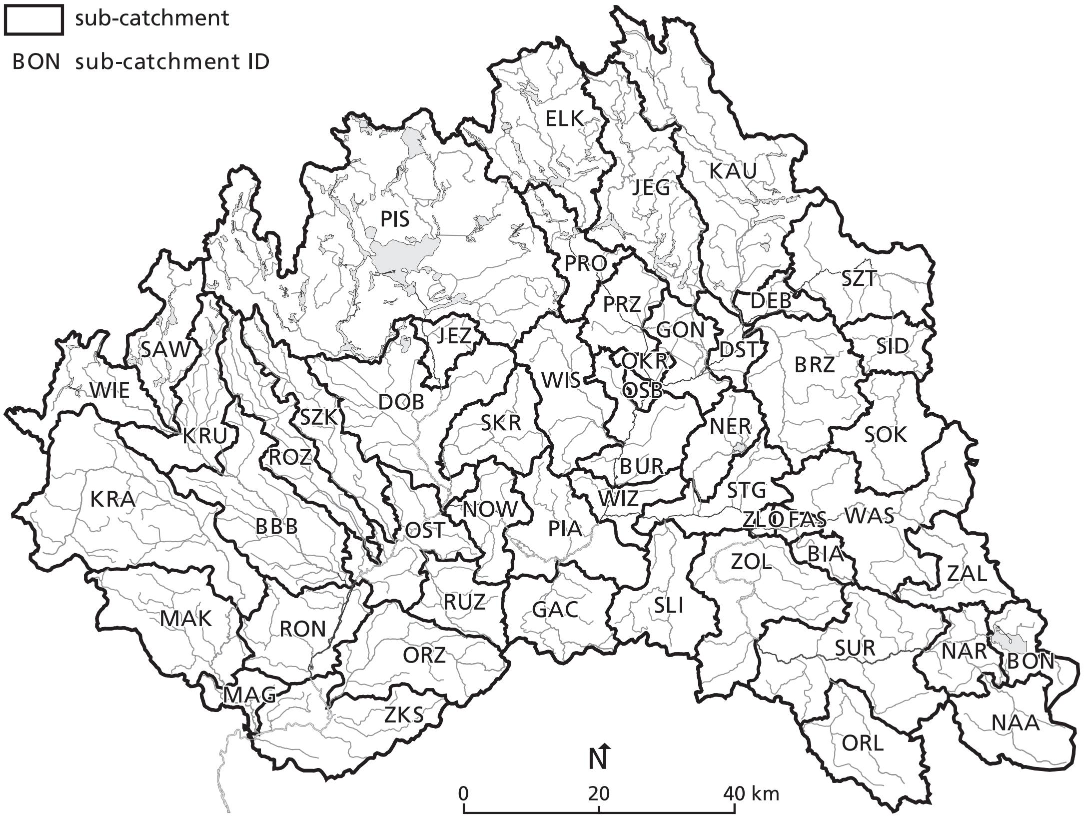


Figure 2.1 Hydrological division of the Narew River Basin

The sizes of the sub-catchments range from 30.05 km^2 (Zlotoria ZLO) to 2998.01 km^2 (Pisz PIS), whereas the average sub-catchment size is 511.31 km^2 and median value is 460.79 km^2.

Table 2.1 Sub-catchments in the Narew River Basin

No	Code[a]	Name[b]	River[c]	Area in km²	No	Code[a]	Name[b]	River[c]	Area in km²
1	BON	BONDARY	Narew	1095.00	27	OKR	OSOWIEC KANAL	Kanal Rudzki	67.52
2	NAA	Narewka		590.00	28	OSB	OSOWIEC BIEBRZA	Biebrza	46.76
3	NAR	NAREW	Narew	287.95	29	WIS	Wissa		516.66
4	ORL	Orlanka		477.48	30	BUR	BURZYN	Biebrza	443.80
5	SUR	SURAZ	Narew	949.12	31	WIZ	WIZNA	Narew	226.93
6	ZOL	ZOLTKI	Narew	781.28	32	GAC	Gac		442.75
7	ZAL	ZALUKI	Suprasl	351.89	33	PIA	PIATNICA	Narew	544.69
8	SOK	Sokolda		463.19	34	PIS	PISZ	Pisa	2998.01
9	WAS	WASILKOW	Suprasl	825.80	35	JEZ	JEZE	Pisa	158.83
10	BIA	Biala		108.02	36	SKR	Skroda		380.77
11	FAS	FASTY	Suprasl	64.12	37	DOB	DOBRYLAS	Pisa	918.39
12	ZLO	ZLOTORIA	Narew	30.05	38	NOW	NOWOGROD	Narew	294.64
13	NER	Neresl		278.67	39	RUZ	Ruz		305.74
14	SLI	Slina		467.78	40	SZK	Szkwa		487.06
15	STG	STREKOWA GORA	Narew	382.33	41	ROZ	Rozoga		491.48
16	SID	Sidra		226.17	42	OST	OSTROLEKA	Narew	484.40
17	SZT	SZTABIN	Biebrza	609.53	43	WIE	WIELBARK	Omulew	408.16
18	KAU	Kanal Augustowski		1347.74	44	SAW	Sawica		403.94
19	DEB	DEBOWO	Biebrza	140.16	45	KRU	KRUKOWO	Omulew	458.39
20	BRZ	Brzozowka		694.45	46	BBB	BIALOBRZEG BLIZSZY	Omulew	801.93
21	DST	DOLISTOWO STARE	Biebrza	178.51	47	RON	ROZAN	Narew	509.03
22	JEG	Jegrznia		857.63	48	KRA	KRASNOSIELC	Orzyc	1266.07
23	GON	GONIADZ	Biebrza	299.59	49	MAK	MAKOW MAZOWIECKI	Orzyc	670.38
24	ELK	ELK	Lega[d]	851.70	50	MAG	MAGNUSZEW MALY	Orzyc	143.51
25	PRO	PROSTKI	Lega[d]	309.12	51	ORZ	Orz		616.81
26	PRZ	PRZECHODY	Kanal Rudzki	300.78	52	ZKS	ZAMBSKI KOSCIELNE	Narew	661.91

[a] The sub-catchment unique code used to mark them in tables and on maps in this chapter

[b] The sub-catchments denoted with capital letters are modelled by the quality model (see chapter 4), the other are non modelled tributaries.

[c] If blank the river's name is the same as the name of the sub-catchment

[d] The upper course of the Rudzki Canal waterway

2.2.2 Statistical data

Statistical data, available for administrative units, consisted of land use, livestock and population data, published in the Local Data Bank by the Polish Central Statistical Office (GUS, 1997). The smallest unit for which the data were published was the community level; these were also the most detailed data available. The analysed area of the Narew River Basin is comprised of 146 communities in total of which 107 are located entirely within the basin whereas 39 are cut by the basin borders. A digital map of North-eastern Poland's administrative division (1:200000) was obtained in MapInfo format (IMAGIS, 1997). The map contains the former division of the country, established in 1975. It consisted of two levels, communities and voivodeships. The current division into three levels (communities, counties and voivodeships) was established in 1999 and changed significantly the number of voivodeships and their borders. Communities remained the same. Since the analyses were carried out for the years 1996-1997 and some data (fertiliser usage) were available only for the former voivodeships the former division is regarded as more suitable and was used in this study. Figure 2.2 shows the Narew River Basin and the administrative units, communities and former voivodeships of North-eastern Poland. The Narew River Basin covers, entirely or partially, six voivodeships.

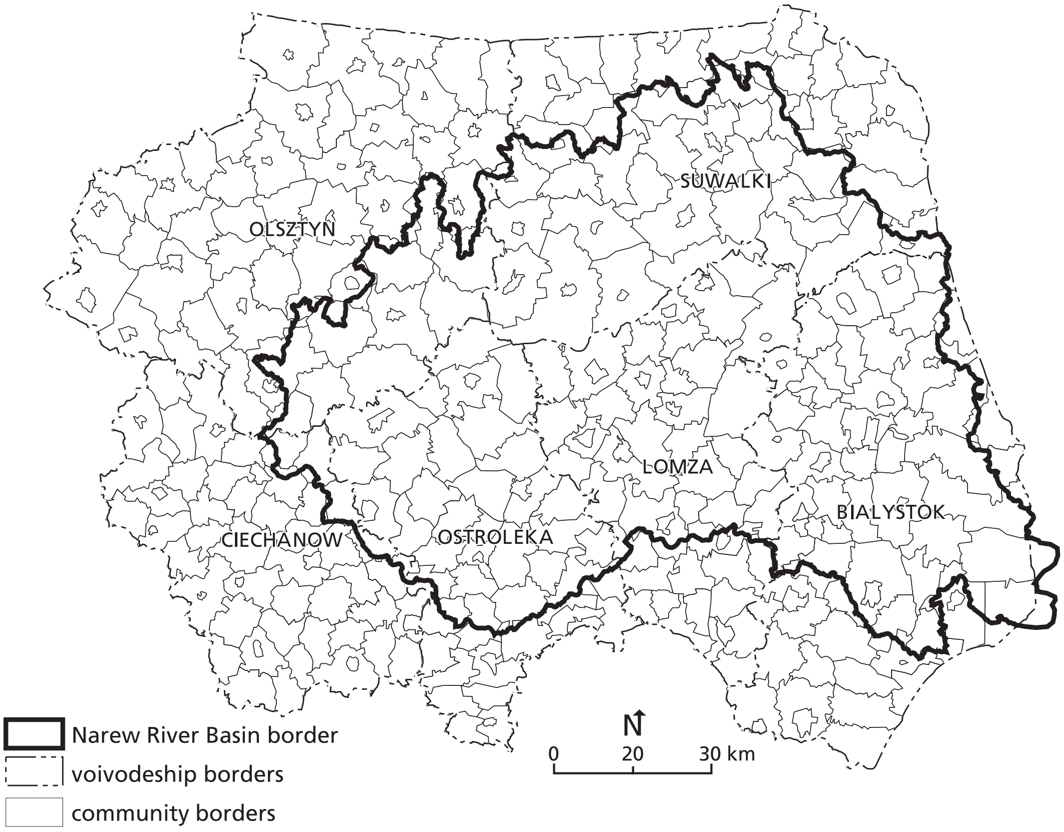


Figure 2.2 Narew River Basin and the administrative division of the region

Subsequently, the statistical data were attached to the map. The entire set of the statistical data for every community (polygon) consists of:
- 8 land use characteristics (given in km^2):
  - forest,
  - meadow,
  - pasture,
  - arable land,
  - orchard,
  - waste land,
  - water (lakes),
  - built-up area;
- 5 livestock characteristics (given in head):
  - cattle,
  - pigs,
  - horses,
  - sheep,
  - poultry;
- 2 population characteristics (given in person number):
  - total population,
  - population connected to sewerage system.

The statistical data for one necessary characteristic, namely the amount of applied fertilisers, were not available at the community level: the most detailed level for which the data of fertiliser usage in kilograms per hectare were available (GUS, 1997b) was at the voivodeships level.

2.2.3 The recombination of the data

The collection of data resulted in two maps of the basin differentiated by the way the area was divided into units. One map (figure 2.1) carries hydrological units data, the second (figure 2.2) has the statistical data linked to the administrative units (communities and voivodeships). Due to this discrepancy it was necessary to transform the statistical data from the administrative units to hydrological ones. This was done in MapInfo by overlaying the two maps and summarising the community based statistical data over the sub-catchment areas, which contained particular communities. In two cases: i) when the area of one community lies within more then one sub-catchment and ii) when a community is cut by a basin border (a part of the community is situated outside the basin) the data attributed to such a community were divided proportionally over respectively i) the sub-catchments that contain this community or ii) the part of the community located within the basin. The fertiliser data, available only for voivodeships, were transformed into hydrological units analogous to the data from communities.

2.2.4 Nutrient sources data

The three main sources of nutrients in the sub-catchments are (Johnes, 1996): i) land use, ii) livestock production and iii) human waste deposition. The nutrient input of each source depends respectively: i) on land use for the inputs of nitrogen and phosphorus to each land use type through fertiliser applications and atmospheric deposition, ii) on livestock production for the nutrients excreted per animal for each livestock type and iii) on human waste for the nutrients deposited per head.

According to one of the earlier North American studies of diffuse pollution (Rast & Lee, 1983) the validity of distinguishing more than four main land use type: agriculture, forest, urban area and wetlands in a catchment may be questionable. However, several recent studies (e.g. Jones & Heathwait, 1997; Twarog & Jarzabek, 1998; Brigault & Ruban, 2000) showed that when more detailed data are available the land use classification might be broader which enhances the precision of the results. In the Narew River Basin the combination of available statistical data and an extensive literature search on the livestock types and human excretion coefficients allowed the inclusion of population and six different land use types:

- forest,
- arable land (including orchards),
- grass land (meadows and pastures),
- waste land,
- water (lakes),
- built-up area;

and five types of livestock:

- cattle,
- pigs,
- horses,
- sheep,
- poultry

in the calculation of nutrient inputs in the sub-catchments.

Land use

The maps of figures 2.3-2.6 show the land use pattern over the basin divided into sub-catchments. Agricultural use of land dominates, with over 55% of the basin occupied by arable land (34.5%) and grass land (meadows and pastures, 20.6%). Arable land occupies more than 50% of all areas in the middle and south-western parts of the basin, reaching a maximum of 60.9% in the Makow Mazowiecki (MAK) sub-catchment (figure 2.3). It is also a major type (over 40%) in the south of the basin and in some sub-catchments in the east. In the north-western and south-eastern parts arable land occupies less and its share is below 30%, with a minimum of even less than 10% in the sub-catchment of the Narewka river (NAA).

Grass land occupies relatively large parts of the sub-catchments of the west-east oriented strip going throughout the middle of almost the entire basin (figure 2.4), where its share is above 20% of total land, with a maximum of over 33% in the

Bialobrzeg Blizszy (BBB) sub-catchment. Less grass land is found in the outside sub-catchments in the north, south and east parts of the basin and in two middle sub-catchments dominated by arable land (Skroda river SKR and Nowogrod NOW). Its share drops below 10% in the sub-catchments of the Narewka river (NAA) and Wielbark (WIE), which are dominated by forests.

Sub-catchments with more than 50% of forest cover (figure 2.5) are concentrated in three vast forest complexes: Knyszynska and Bialowieska Forests in the east and south-east, and Kurpiowska Forest in the north-west. Sub-catchments covering the cores of these complexes have the largest forest cover with almost 75% of area covered by forest in the Narewka river (NAA) sub-catchment. The other highly forested sub-catchments, over 30%, are located on the edges of those complexes and in the areas covered by smaller but compact forests in the north (Augustowska Forest) and south (Biala Forest) of the basin. The least forested sub-catchments dominated by arable land and/or green land are located in the south, middle and north-eastern parts of the basin along the Narew, Biebrza and Elk rivers. In the south and north-west forest cover is less than 30%, whereas in the middle it drops below 20%, reaching a minimum of just 6% in the Neresl river (NER), Piatnica (PIA) and Nowogrod (NOW) sub-catchments.

The other three land use types distinguished cover less than 13% of the basin (figure 2.6) with waste land occupying over 7.5%, waters embracing 2.8% and built-up areas covering almost 2.5% of total land. The largest surface (over 20%) these three types occupy in i) the urban sub-catchment of the Biala river (BIA) containing the city of Bialystok, ii) sub-catchments of the Biebrza middle and lower courses having a large share of waste land and iii) sub-catchments in the north covering the Mazurian lake district. Except for the Biala river (BIA), Orlanka river (ORL) and Nowogrod (NOW) sub-catchments the built-up areas do not exceed 5% of total land and in 18 sub-catchments this figure is even below 2%. Lakes are almost restricted to the sub-catchments up north located in the Great Mazurian Lake District (7 sub-catchments) and the Bondary sub-catchment (BON) containing the Siemianowka reservoir. In the rest of the sub-catchments water covers less than 1.5% and in 17 of them lakes are not present at all.

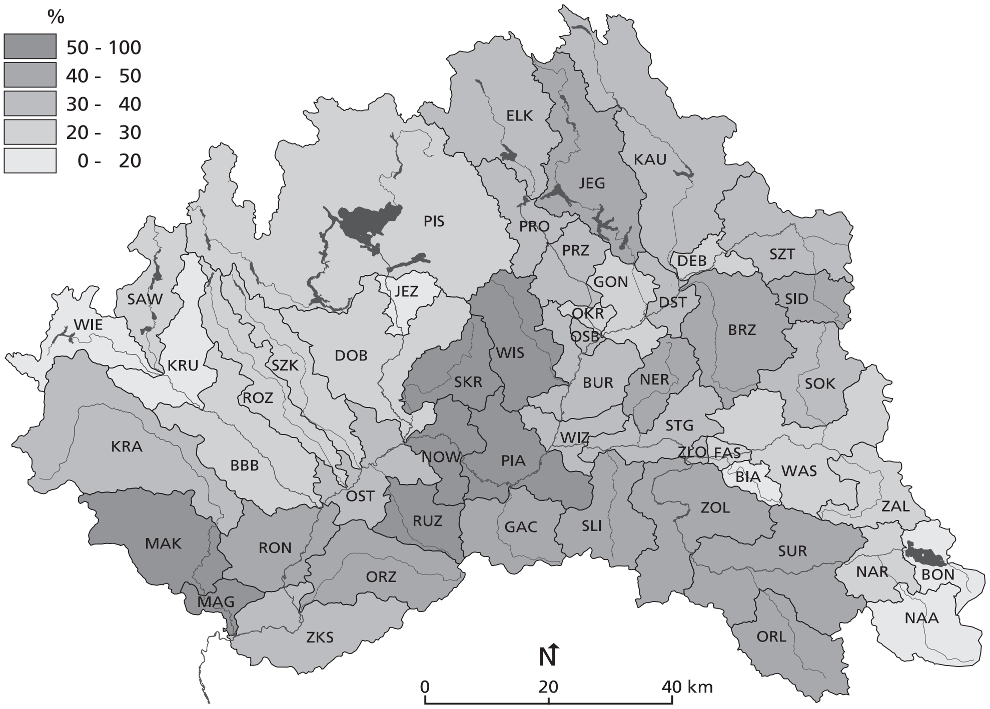


Figure 2.3 Arable land (%) in sub-catchments of the Narew River Basin

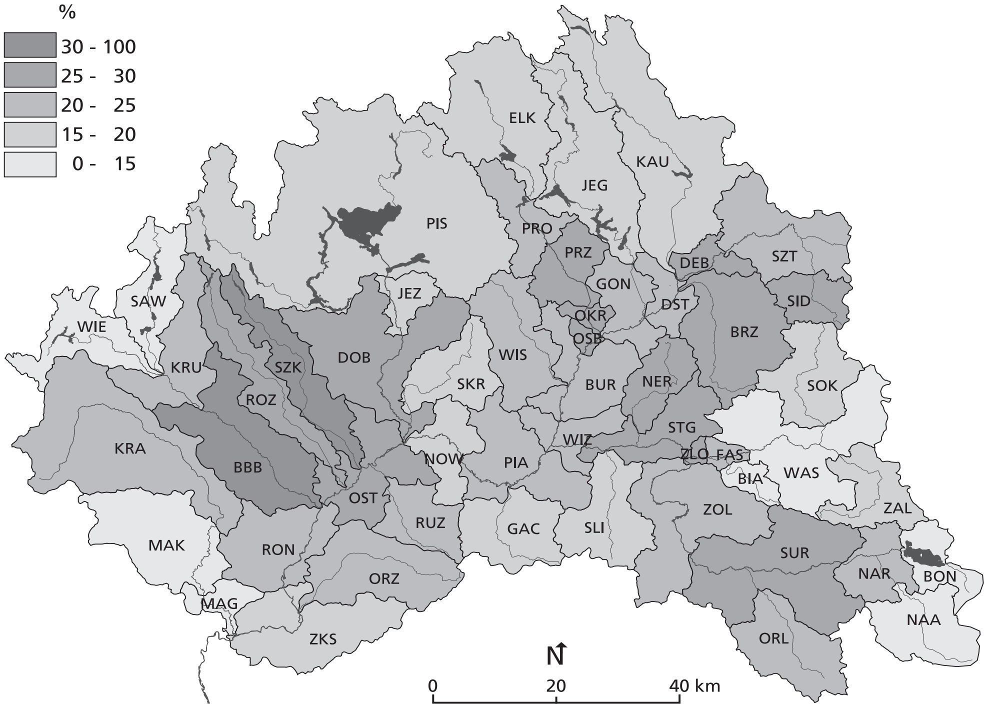


Figure 2.4 Grass land (%) in sub-catchments of the Narew River Basin

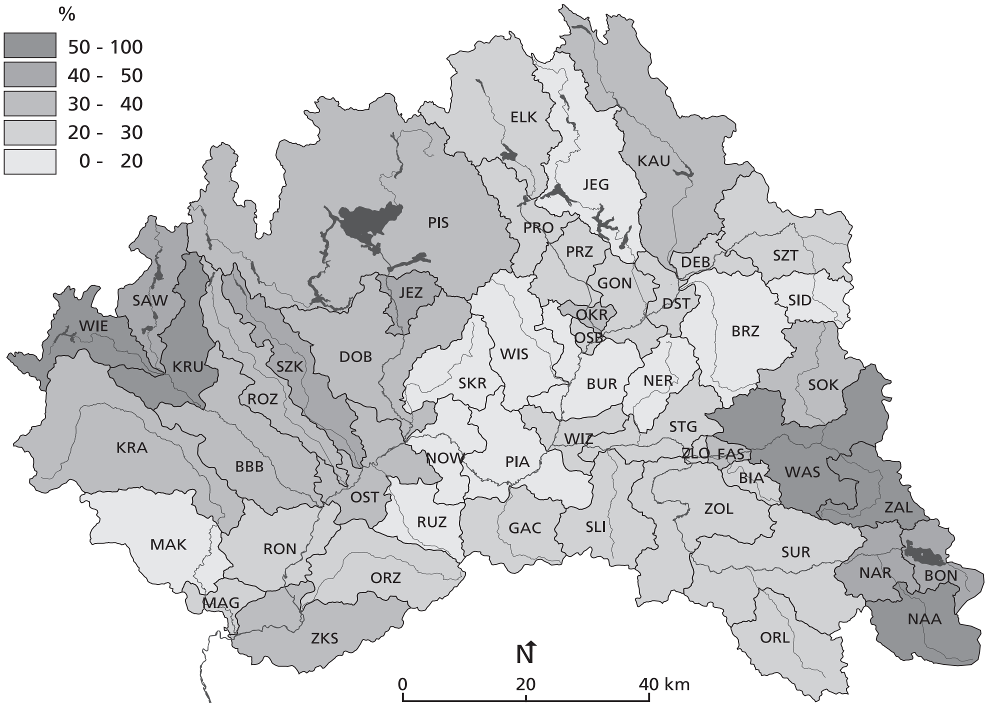


Figure 2.5 Forest (%) in sub-catchments of the Narew River Basin

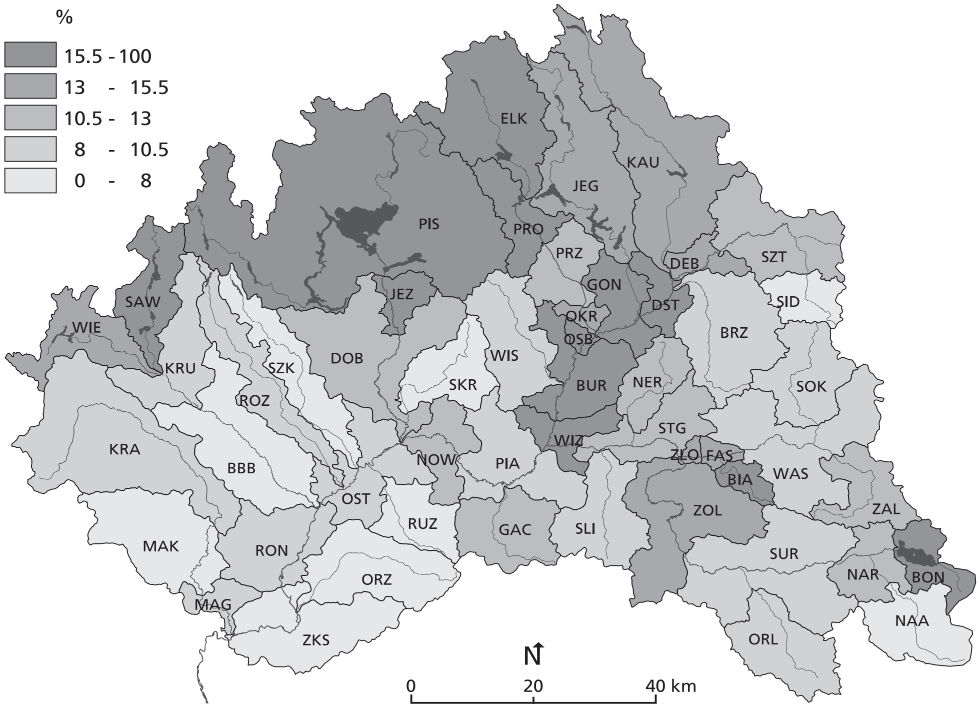


Figure 2.6 Water, waste land and built-up area (%) in sub-catchments of the Narew River Basin

Fertiliser usage

Because data on fertilisers were only available per voivodeships as the mean number of kilograms applied per hectare of agricultural land, the spatial pattern of fertiliser usage in the basin resembled the pattern of the voivodeships. The nitrogen fertiliser application in the voivodeships covering the basin ranged from 25.2 kg ha$^{-1}\cdot$yr^{-1} in Suwalki voivodeship to 59.1 kg ha$^{-1}\cdot$yr^{-1} in Ciechanow voivodeship and for phosphorus fertilization from 6.9 kg ha$^{-1}\cdot$yr^{-1} to 22.5 kg ha$^{-1}\cdot$yr^{-1} in the same voivodeships (table 2.2).
The average application of fertilisers over the entire basin was 40.8 kg N ha$^{-1}\cdot$yr^{-1} and 14.6 kg P ha^{-1} yr^{-1}.

Table 2.2 Fertiliser usage (kg ha$^{-1}\cdot$ yr^{-1}) in the voivodeships of the Narew River Basin

	NRB area	Nitrogen	Phosphorus
	%	kg ha$^{-1}\cdot$ yr^{-1}	kg ha$^{-1}\cdot$ yr^{-1}
Bialystok	28.73	45.9	17.9
Ciechanow	1.65	59.1	22.5
Lomza	19.35	50.8	20.4
Olsztyn	9.41	37.3	8.8
Ostroleka	17.80	41.9	15.1
Suwalki	23.06	25.2	6.9
Narew River Basin	100.00	40.8	14.6

When translated into hydrological units the highest doses of fertilisers (over 50 kg N ha$^{-1}\cdot$yr^{-1} and over 20 kg P ha$^{-1}\cdot$yr^{-1}) were applied in the middle part of the basin in the sub-catchments located entirely within Lomza voivodeship (figures 2.7 and 2.8). The smallest doses of fertiliser (below 30 kg N ha$^{-1}\cdot$yr^{-1} and below 10 kg P ha$^{-1}\cdot$yr^{-1}) were applied in sub-catchments in the north of the basin, located in the Suwalki and Olsztyn voivodeships.

The intermediate doses ranging from 40 to 47 kg N ha$^{-1}\cdot$yr^{-1} and from 12 to 19 kg P ha$^{-1}\cdot$yr^{-1} were received by the rest of the basin covered mainly by Bialystok voivodeship in the east and Ostroleka voivodeship in the west. The Ciechanow voivodeship, characterised by the highest fertiliser usage, had only a minor impact on overall sub-catchments dosage due to its very limited contribution to the total basin area.

Figure 2.7 Nitrogen fertiliser usage (kg$\cdot$ha$^{-1\cdot}$ yr^{-1}) in sub-catchments of the Narew River Basin

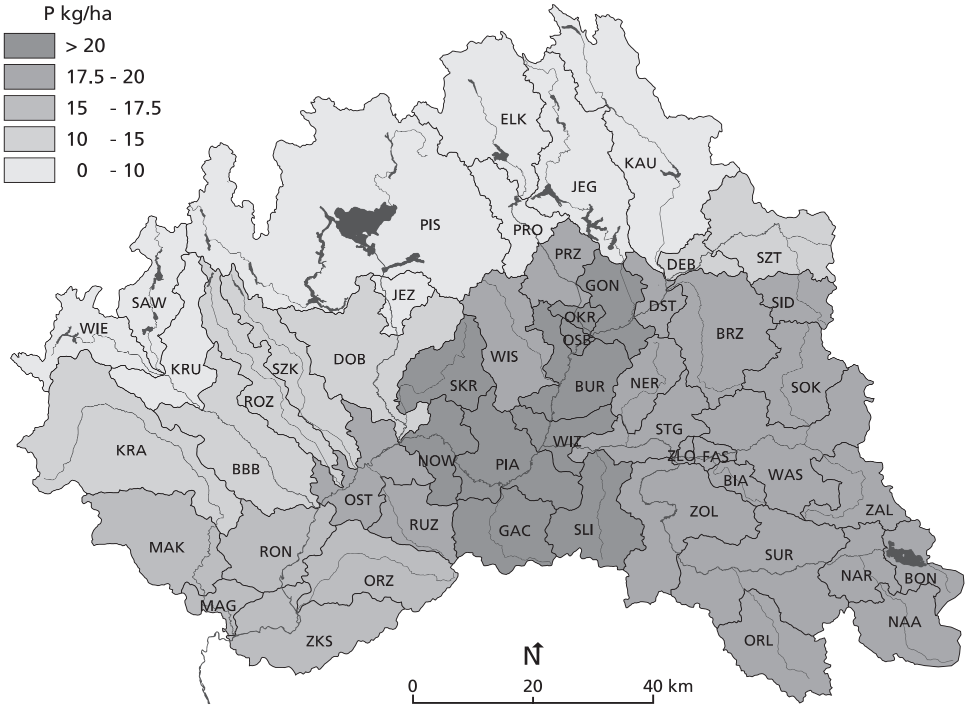


Figure 2.8 Phosphorus fertiliser usage (kg$\cdot$ha$^{-1\cdot}$ yr^{-1}) in sub-catchments of the Narew River Basin

Livestock

In general the spatial distribution of livestock density followed the land use patterns of the basin. Two main characteristics could be distinguished i) all animal types were less dense in forest and lake dominated sub-catchments in the south-eastern and north-western parts of the basin and ii) non grazing animals (pigs and poultry) were also less frequent in sub-catchments having a large share of green land in west of the basin (figures from 2.9 to 2.12). In these sub-catchments densities were respectively below 20 head·km^{-2} for cattle and pigs (below 50 head·km^{-2} for pigs in green land dominated sub-catchments), 30 head·km^{-2} for poultry and 1.5 head·km^{-2} for horses and sheep, whereas average densities were respectively 28 head·km^{-2} for cattle, 40 head·km^{-2} for pigs, 71 head·km^{-2} for poultry and 3 head·km^{-2} for horses and sheep. All animal types except for horses and sheep were the most frequent in the south and middle sub-catchments where arable land dominated. Here figures exceeded respectively 40 head·km^{-2} for cattle, 80 head·km^{-2} for pigs, 110 head·km^{-2} for poultry. Additionally, such high poultry density occurred in the non-forested sub-catchments in the surroundings of the city of Bialystok. In the same sub-catchments and some other sub-catchments in the east the highest density of horses and sheep occurred, exceeding 4.5 head·km^{-2}. The above average densities for all animal types were also recorded in the sub-catchments in the north-eastern part of the basin.

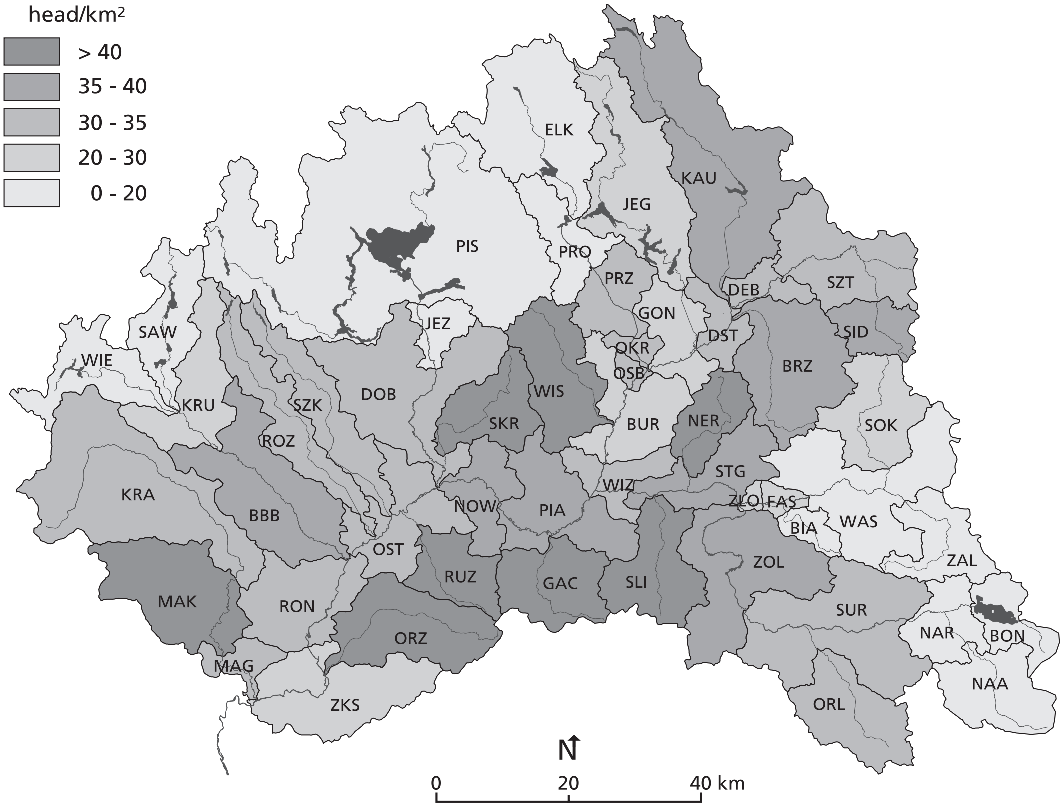


Figure 2.9 Cattle density (head·km^{-2}) in sub-catchments of the Narew River Basin

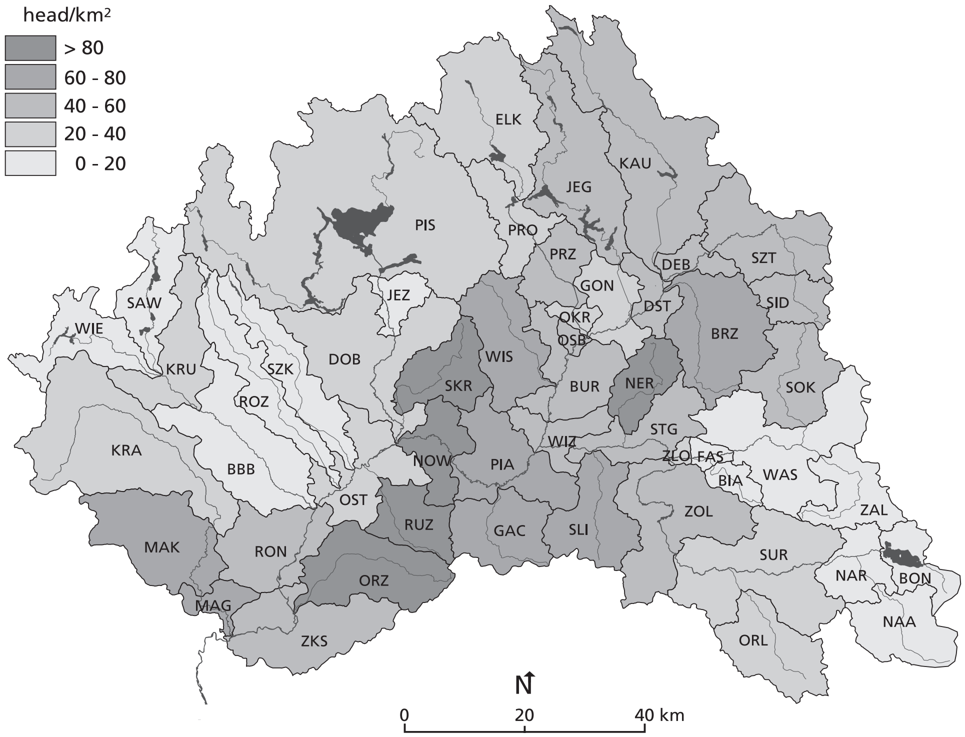


Figure 2.10 Pigs density (head·km^{-2}) in sub-catchments of the Narew River Basin

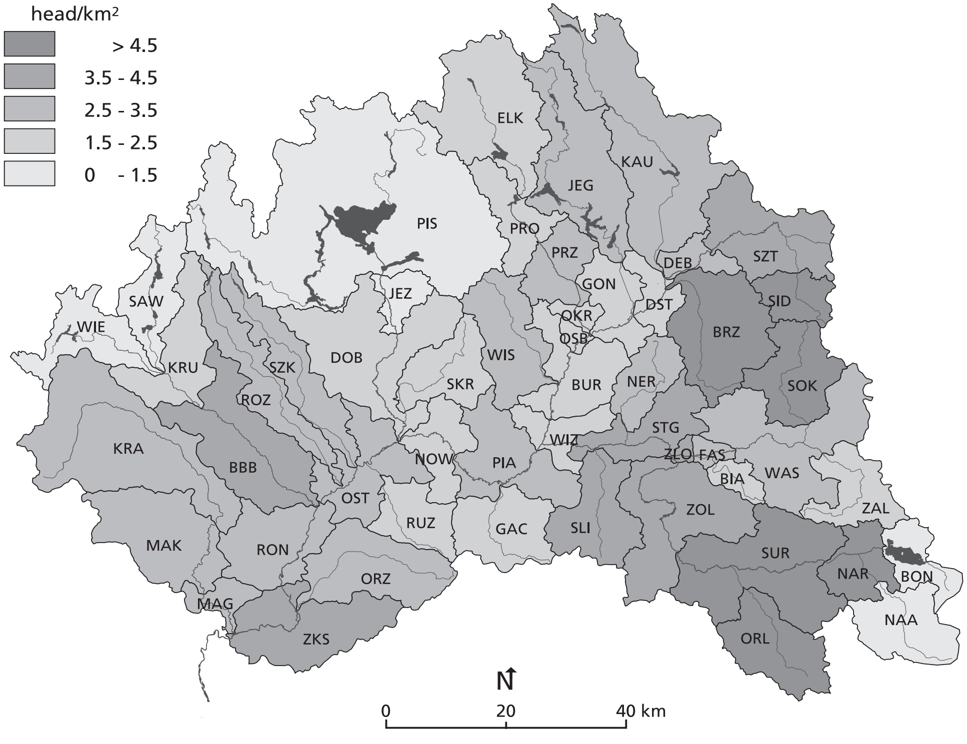


Figure 2.11 Horses and sheep density (head·km^{-2}) in sub-catchments of the Narew River Basin

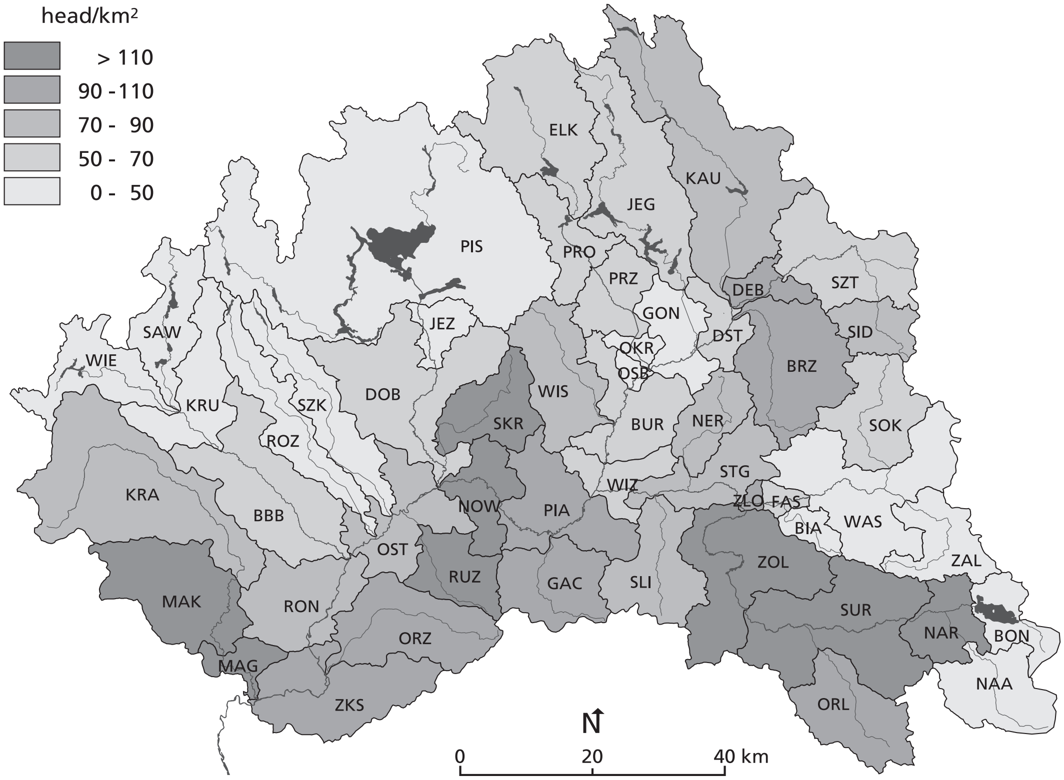


Figure 2.12 Poultry density (head·km^{-2}) in sub-catchments of the Narew River Basin

Population

In 1997 the total population of the basin was just above 1.5 million inhabitants. This gives an average density just over 55 inhabitants·km^{-2}, which is approximately half the country average of 118 inhabitants·km^{-2} (GUS, 1997b). So, the region is relatively sparsely populated with higher densities related only to a limited number of bigger towns. The highest density (figure 2.13), over 2000 inhabitants·km^{-2}, was in the Biala river sub-catchment (BIA) covering a major part of the biggest city of the basin, Bialystok (ca. 285000 inhabitants). The other sub-catchments with density exceeding 80 inhabitants·km^{-2} cover; the part of the Bialystok located outside of the Biala river (BIA) sub-catchment (Fasty sub-catchment, FAS) or other major towns Lapy (Zoltki ZOL sub-catchment), Elk and Grajewo (Prostki PRO and Przechody PRZ sub-catchments), Zambrow (Gac river GAC sub-catchment), Lomza (Piatnica PIA and Nowogrod NOW sub-catchments), Ostroleka (Ostroleka OST and Rozan RON sub-catchments) and Makow Mazowiecki (Magnuszew Maly MAG sub-catchment).

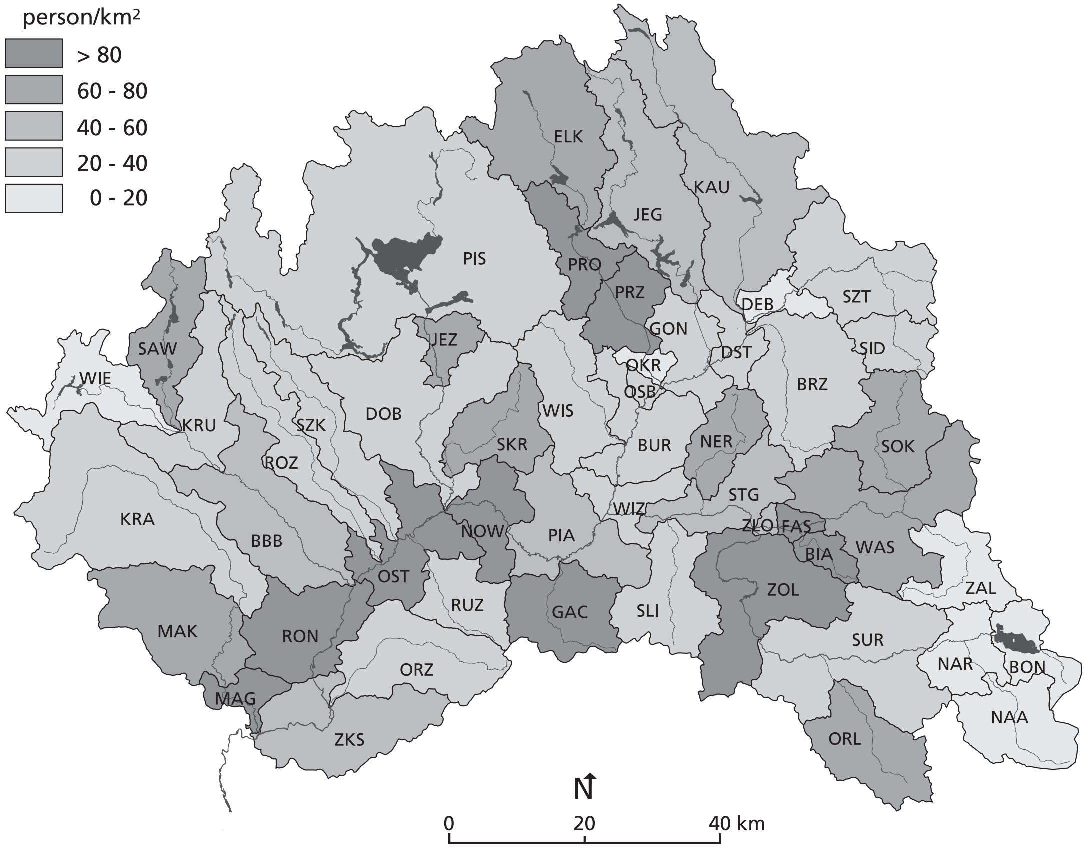


Figure 2.13 Population density (person$\cdot$km^{-2}) in sub-catchments of the Narew River Basin

The most sparsely populated sub-catchments are forest dominated areas in the south-western part of the basin and the Wielbark (WIE) sub-catchment with a population density below 18 inhabitants$\cdot$km^{-2}, reaching a minimum of less than 3 inhabitants$\cdot$km^{-2} in the Bondary (BON) sub-catchment. For this study nine major towns (Bialystok, Lapy, Elk, Grajewo, Lomza, Piatnica, Pisz, Ostroleka and Makow Mazowiecki), which are located along the river stretches modelled in the water quality model (see chapter 4), are treated as point sources. All the other towns are treated as diffuse sources because they are too small to be included as point sources at this study scale. These nine selected town are located within 14 sub-catchments. For these sub-catchments inhabitants living in these town were assumed to be connected to sewerage. So, the population treated as diffuse source, for these sub-catchments, was reduced by number of inhabitants having their wastewater treated. The highest part of total population (88%) was connected to sewerage in the Biala river (BIA) sub-catchment. The total population of the rest 38 sub-catchments was regarded as not being connected, even though sewerage systems may be present there.

Detailed data on land use, agriculture and population characteristics for all the sub-catchments are presented in Appendix A.1.

2.3 Method of computing nitrogen and phosphorus loads

This section explains how NULAM calculates the nitrogen and phosphorus loads. The applied method is based on the export coefficient model (e.g. USEPA, 1980; Reckhow & Simpson, 1980; Beaulac & Reckhow, 1982; Rast & Lee, 1983; Delwich & Haith, 1983), originally developed in North America, which has also been frequently used in Western Europe (e.g. Vollenweider, 1968; Jorgensen, 1980; Johnes & O'Sullivan, 1989; Brigault & Ruban, 2000) as well as in Poland (Twarog & Jarzabek, 1998). It assumes that the relation between a) the total nutrient load generated in a sub-catchment (from different nutrient sources) and b) the observed nutrient load in the surface waters (draining this sub-catchment) at the point closing the area may be expressed by the export coefficient (equation 2.1).

$$L_{iobs} = e_i * L_{igen} \tag{2.1}$$

where:
L_{iobs} – is observed load originating from sub-catchment i (kg·time^{-1}),
e_i – is export coefficient for sub-catchment i,
L_{igen} – is total load generated from the sum of all sources in sub-catchment i (kg·time^{-1}).

The export coefficients (e_i) calculated for each of the sub-catchment by means of equation 2.1 describe the fate of total generated nutrients load reaching the surface water. Each of the export coefficients was assumed to be constant for the particular sub-catchment and was thus also used for the scenario study (see chapter 7).

2.3.1 Observed riverine load

The combination of water quality data collected during the basin's surface water monitoring campaigns and discharge data provided by the State Weather Service was used for assessing the nitrogen and phosphorus loads in the rivers of the basin. For every sub-catchment the mass balance equations (equations 2.2 and 2.3) at the closing point were constructed. Based on these equations the fraction of the loads originating from the particular sub-catchment was calculated.

$$L_{cp} = L_{up} - (L_{iobs} + L_{tr}) \tag{2.2}$$

$$L_x = Q_x * C_x * k \tag{2.3}$$

where:
L_{cp} – is the load at the closing point of the sub-catchment i (kg·time^{-1}),
L_{up} – is the load at the closing point of the sub-catchment upstream of sub-catchment i (kg·time^{-1}),
L_{tr} – is the load of the tributary which confluences to the river stretch of sub-catchment i (kg·time^{-1}),
L_x – is the load of water constituents x at certain location (kg·time^{-1}),
Q_x – is the discharge measured at selected locations in September 1997 (m^3·time^{-1}),

C_x – is the concentration of water constituent x at certain location measured in September 1997 ($mg^{\cdot}l^{-1}$),
k – is units conversion factor.

For the head sub-catchments the observed load originating from sub-catchment i (L_{iobs}) is the load measured at the closing point of this area (L_{cp}). In the water quality monitoring program the two nitrogen compounds nitrate (NO_3-N) and ammonium (NH_4-N) were separately measured. Also the loads of these two compounds were separately calculated. Since the data for calculating generated load (L_{igen}) are available either only (fertiliser consumption) or predominantly (the excretion coefficients) for nitrogen the total N-load was found as the sum of the two compounds.

2.3.2 Sub-catchment generated load

The nutrient load emitted in a sub-catchment originates from the three main nutrient sources: land use, livestock production and human waste deposition (see section 2.2.4). The total generated nutrient load is the sum of the loads coming from these sources and for sub-catchment i was calculated by the following equation:

$$L_{\mathrm{igen}} = \Sigma(A_{\mathrm{ij}}*I_{\mathrm{ij}}) + \Sigma(N_{\mathrm{ij}}*E_{\mathrm{ej}}) + P_{\mathrm{i}}*E_{\mathrm{p}}*R \qquad (2.4)$$

where:
A_{ij} – is the area of sub-catchment i occupied by land use type j (ha),
I_{ij} – is the nutrient input coefficient for land use type j of sub-catchment i ($kg^{\cdot}ha^{-1}$);
N_{ij} – is the number of livestock type j for sub-catchment i (animals),
E_{ej} – is the excretion coefficient for livestock type j ($kg^{\cdot}animal^{-1}$),
P_i – is the number of people for sub-catchment i (person),
E_p – is the yearly emission coefficient of nutrients per person ($kg^{\cdot}day^{-1}$),
R – is the coefficient for removal of nutrients during wastewater treatment.

The nutrient input coefficient (I_{ij}) comprises of two characteristics: fertiliser application (F) and atmospheric deposition (D) and for sub-catchment i it is calculated as follows:

$$I_{\mathrm{ij}} = F_{\mathrm{ij}} + D \qquad (2.5)$$

where:
F_{ij} – is the fertiliser dose for land use type j of sub-catchment i ($kg^{\cdot}ha^{-1}$),
D – is the atmospheric deposition over the Narew River Basin ($kg^{\cdot}ha^{-1}$).

For sub-catchment i the area of each land use type, the number of each livestock type, the number of people and the fertiliser consumption characteristics were calculated based on statistical data and administrative and hydrological maps following the procedure described in section 2.2. The excretion coefficients and the human daily emission coefficient were derived from a literature survey (see below for sources). The variation of their values is enormous and depends very much on several reasons like the calculation method, the area they were derived from and applied to, the aim of the study, and the level of detail of the study. Therefore, the coefficients are strongly related to the area of investigation, characterised predominantly by climate (Brigault & Ruban, 2000) and to calculation scheme (Beaulac & Reckhow, 1982). For this study a necessary compilation was performed in order to select a consistent set of coefficients as best estimators reflecting conditions in the Narew River Basin and suitable to be used in the chosen calculation method. Three characteristic values for each coefficient were selected. These are the so-called 'regional', minimum and maximum values (table 2.3).

Table 2.3 Excretion coefficients and human yearly emission coefficient ($kg \cdot head^{-1} \cdot y^{-1}$)

	Nitrogen			Phosphorus		
	Regional	Minimum	Maximum	Regional	Minimum	Maximum
Humans	3.94	1.42	7.15	0.73	0.584	3.285
Cattle	70.2	12.41	151.8	9	1	39.9
Pigs	18.7	2.37	48.36	5	1.5	15.51
Horses	36.8	8.10	76.8	2	0.438	4.2
Sheep	8.9	1.02	25.4	1	0.3	5.5
Poultry	0.3	0.09	3.04	0.1	0.03	0.79

The regional characteristics and climate are two factors supposed to be predominant for the selection of the coefficients. Therefore, the regional values were based on a number of Polish publications addressing this subject (e.g. Kajak, 1979; Dojlido, 1987; Szpindor, 1992; Sapek et al., 1997; Twarog & Jarzabek, 1998). The two other characteristics (minimum and maximum) were selected based on the extended literature survey (e.g. Loehr, 1974; Beaulac & Reckhow, 1982; Frink, 1991; Klepper et al., 1995; Johnes, 1996; CBS, 1998; Worrall & Burt, 1999) and indicate minimum and maximum values of coefficients for conditions similar to those of the Narew River Basin. The regional values were regarded as the most appropriate for the region and applied in the module calculation procedure when the minimum and maximum characteristics were used in a sensitivity analysis procedure. The excretion coefficients and the human yearly emission coefficient were not differentiated over the basin and uniformly applied to all the sub-catchments. The same approach was used for the atmospheric deposition value, which was based on data from the national study presented by Taylor et al. (1997) (6.7 kg N $ha^{-1} \cdot y^{-1}$ and 0.14 kg P $ha^{-1} \cdot y^{-1}$).

2.3.3 Sensitivity analysis

Total generated nutrient load in the sub-catchments is the sum of inputs from several sources like agricultural and livestock production, population number and atmospheric deposition. A source's share in an overall input depends on the source type. An input from a particular source is defined by two factors i) the size of the source and ii) the parameter specifying the nutrient input per unit of the source. The first factor is described by area in case of land use or by the number of heads in case of population and livestock. The parameters of the second factor are fertiliser consumption for land use and the excretion coefficients for humans and livestock. A source’s size is in general a relatively stable feature of a certain sub-catchment and significant changes of size in general need quite some time. Consequently, the parameters specifying nutrient input may only indicate the source’s share in the overall input load. The method proposed in equations 2.4 and 2.5 contains 8 such parameters for each of the analysed nutrients nitrogen and phosphorus: fertiliser consumption, 5 excretion coefficients for different animal types, the human yearly emission coefficient and atmospheric deposition rate.

The following procedure was employed to assess the impact of each parameter on changes in generated nutrient load and thus for analysing the sensitivity of the generated nutrient load for these parameters:

- each of the parameters was subjected to one at a time change when the others were kept at the original regional values (see table 2.3);
- each parameter was changed 7 times, one at a time, by +10%, +20%, +50%, +100%, -10%, -20% and –50% of the original values;
- then after every change:
    - for each sub-catchment the newly generated nutrient load was calculated;
    - for each sub-catchment a relative difference (in %) between the newly calculated load and the one calculated for the original values was calculated;
    - for the entire basin the relative difference (in %) between loads in all sub-catchments were averaged;
- after all changes were computed, the mean relative differences for all parameters were compared.

2.4 Results

2.4.1 Observed load

The calculated riverine observed loads, based on measured discharges and concentrations, for every sub-catchment area were converted into area specific load in kg km^{-2}·y^{-1}. These loads ranged respectively from 12 kg N km^{-2}·y^{-1} (Slina river SLI sub-catchment) to $4.1\cdot10^3$ kg N km^{-2}·y^{-1}in Fasty (FAS) sub-catchment and from 2.2 kg P km^{-2}·y^{-1} (Jegrznia river JEG sub-catchment) to 170 kg P km^{-2}·y^{-1} in Zlotoria (ZLO) sub-catchment. The average over the entire basin, calculated as the load measured at Zambski Koscielne, the most downstream observation point, divided over the total area closed by this gauge station, is 151 kg N km^{-2}·y^{-1} and 12 kg P km^{-2}·y^{-1}.

The spatial distribution of area specific loads for both nutrients did not show any obvious pattern (figures 2.14 and 2.15). However, some characteristic relations might be pointed out. In case of nitrogen (figure 2.14) the highest area specific load, over 600 kg N km^{-2}·y^{-1}, was estimated for sub-catchments of the middle and lower courses of the Narew river (Piatnica PIA, Nowogrod NOW. Ostroleka OST, Rozan RON and Zambski Koscielne ZKS) and/or some sub-catchments downstream from point sources (Fasty FAS, Zlotoria ZLO, Nowogrod NOW, Jeze JEZ, Rozan RON and Magnuszew Maly MAG sub-catchments). In contrast, the sub-catchments with the lowest area specific load, below 50 kg N km^{-2}·y^{-1}, were mainly to be found in the upper Biebrza river

river SID, Sztabin SZT, Brzozowka river BRZ, Dolistowo DST, Jegrznia river JEG, Prostki PRO sub-catchments) or some head sub-catchments (Neresl NER, Slina SLI, Rozoga ROZ, Omulew WIE rivers).

For phosphorus the picture is even more scattered than for nitrogen (figure 2.15). Nevertheless, areas with the lowest area specific load (below 4 kg P $km^{-2} \cdot y^{-1}$) seem to occur together in the sub-catchments located in the upper part of the basin (Suraz SUR, Slina river SLI, Sidra river SID, Sztabin SZT, Jegrznia river JEG sub-catchments). The largest area specific loads, over 70 kg P $km^{-2} \cdot y^{-1}$, were estimated for some of the sub-catchments containing bigger towns or located downstream of them (Fasty FAS, Zlotoria ZLO, Strekowa Gora STG, Piatnica PIA, Sawica river SAW sub-catchments).

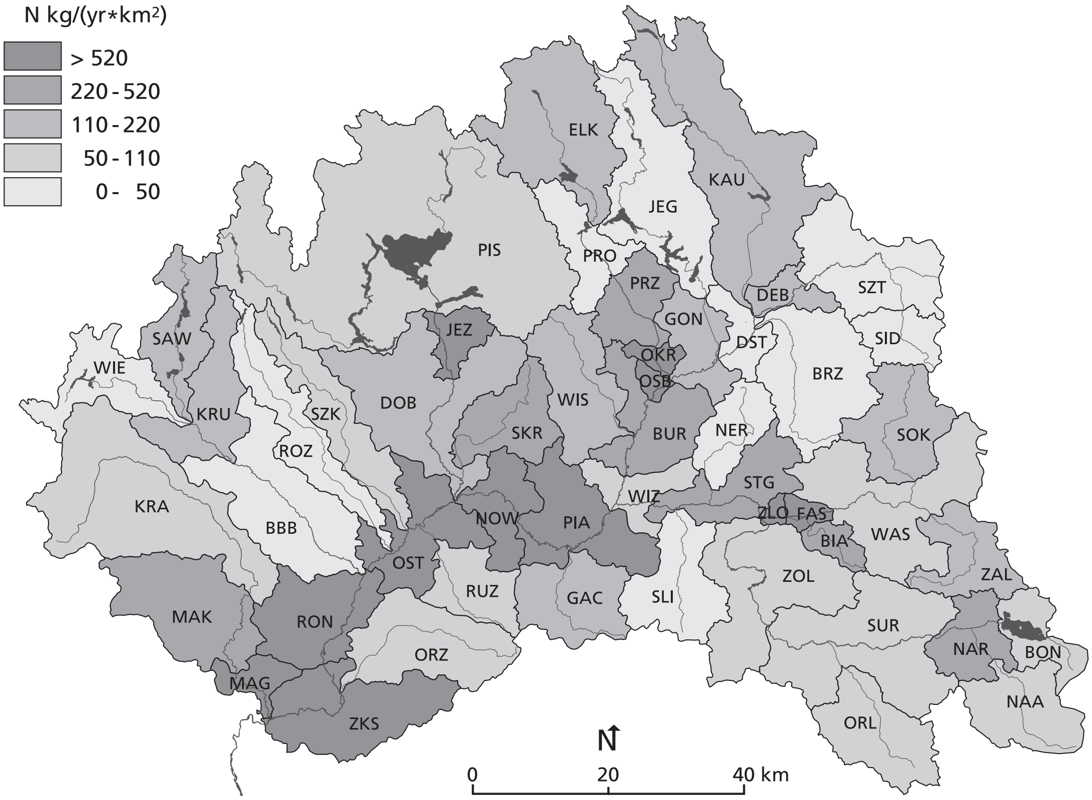


Figure 2.14 Observed N load (kg·$km^{-2} \cdot y^{-1}$) in sub-catchments of the Narew River Basin

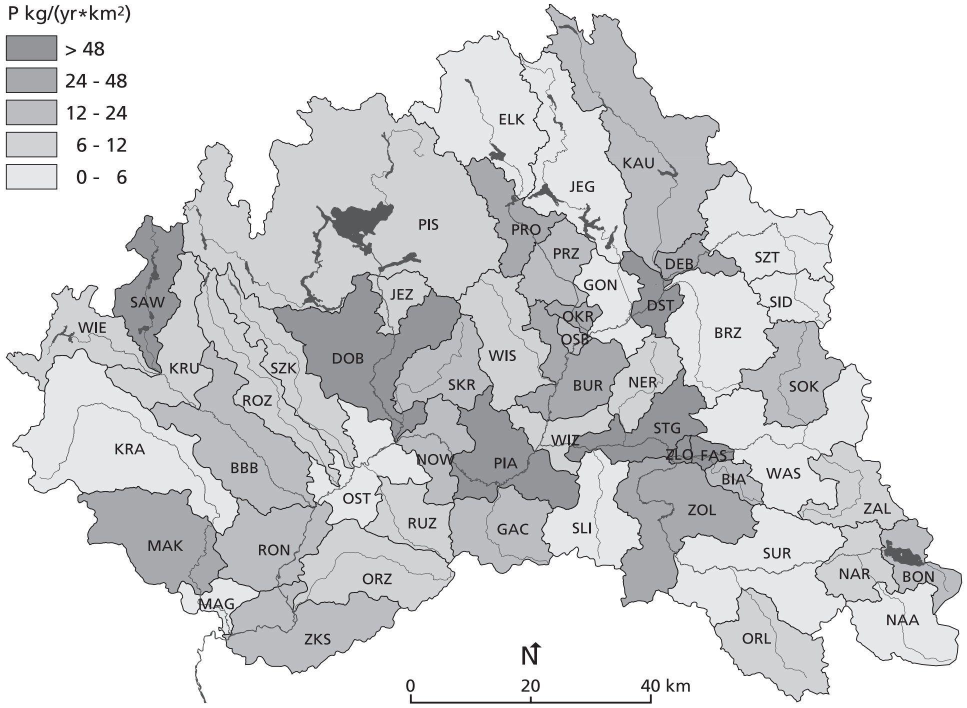


Figure 2.15 Observed P load (kg$\cdot$km$^{-2}\cdot$y^{-1}) in sub-catchments of the Narew River Basin

2.4.2 Generated load

The estimations of the generated nutrient load over the entire basin resulted in $149\cdot10^6$ kg$\cdot$y^{-1} of emitted nitrogen and $31.2\cdot10^6$ kg$\cdot$y^{-1} of emitted phosphorus (table 2.4). Thus, the basin average area specific nutrient loads were estimated for $5.4\cdot10^3$ kg N km$^{-2}\cdot$y^{-1} and $1.1\cdot10^3$ kg P km$^{-2}\cdot$y^{-1}. Two general sources contribute to total nutrient loads, namely land use (including atmospheric deposition) and livestock (with non-sewage connected part of population included). The shares of these two sources were estimated at 43.7% coming from land use and 56.3% coming from livestock for nitrogen and respectively 55.3% and 44.7% for phosphorus.

Table 2.4 Estimations of generated nutrient load for the Narew River Basin

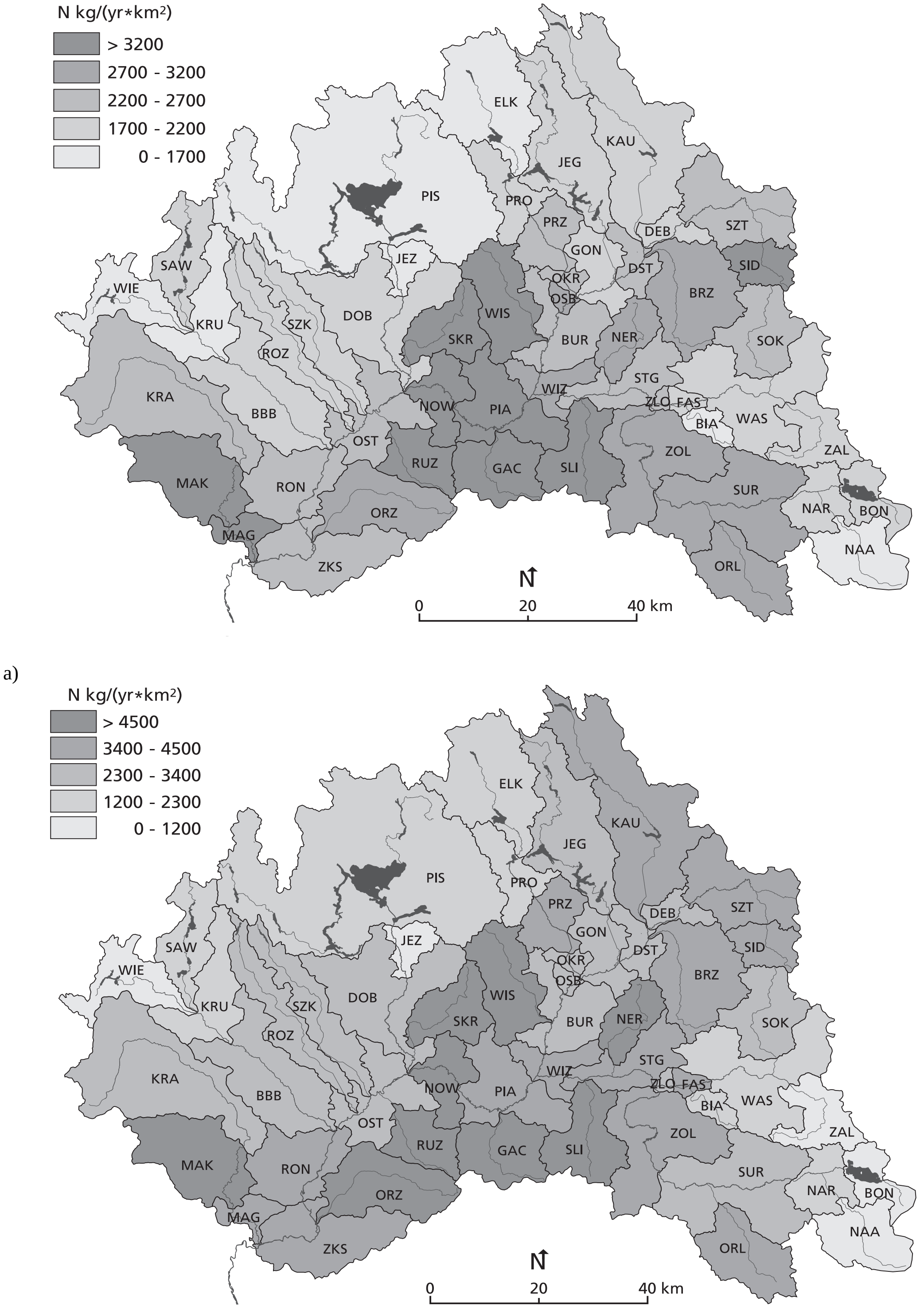
	Nitrogen			Phosphorus		
	Total load	Area specific load		Total load	Area specific load	
	10^6 kg$\cdot$y^{-1}	10^3 kg km$^{-2}\cdot$y^{-1}	%	10^6 kg$\cdot$y^{-1}	10^3 kg km$^{-2}\cdot$y^{-1}	%
Land use	65.1	2.4	43.7	17.3	0.6	55.3
Livestock	83.7	3.0	56.3	13.9	0.5	44.7
Narew River Basin	148.8	5.4	100	31.2	1.1	100

The spatial distributions over the entire basin of sub-catchments' area-specific loads coming from either land use or livestock were very similar for nitrogen and phosphorus (figures 2.16 and 2.17). The largest area specific loads coming from land use, with respectively over $3.2 \cdot 10^3$ kg N km$^{-2} \cdot$y^{-1} and $1 \cdot 10^3$ kg P km$^{-2} \cdot$y^{-1}, were estimated for the sub-catchments in the middle, middle-south and west of the basin. Also, in the south and east parts of the basin the area specific load was relatively high, above average for the basin. The lowest emitted loads were found in the sub-catchments in the north, middle-western and south-eastern parts of the basin, with values below $2 \cdot 10^3$ kg N km$^{-2} \cdot$y^{-1} and $0.45 \cdot 10^3$ kg P km$^{-2} \cdot$y^{-1}.

The estimation of the components of area-specific load, coming from livestock, resembled the spatial distribution of load coming from land use. The highest values, over $4.5 \cdot 10^3$ kg N km$^{-2} \cdot$y^{-1} and $0.75 \cdot 10^3$ kg P km$^{-2} \cdot$y^{-1}, were estimated for sub-catchments in the middle, middle-southern and west parts of the basin and the lowest amounts, below $2.3 \cdot 10^3$ kg N km$^{-2} \cdot$y^{-1} and $0.36 \cdot 10^3$ kg P km$^{-2} \cdot$y^{-1}, were emitted in the north-western and south-eastern parts of the basin. However, there were some shifts compared to land use originating load in the middle-western and north-eastern parts of the basin, where load coming from livestock had values above basin's averages.

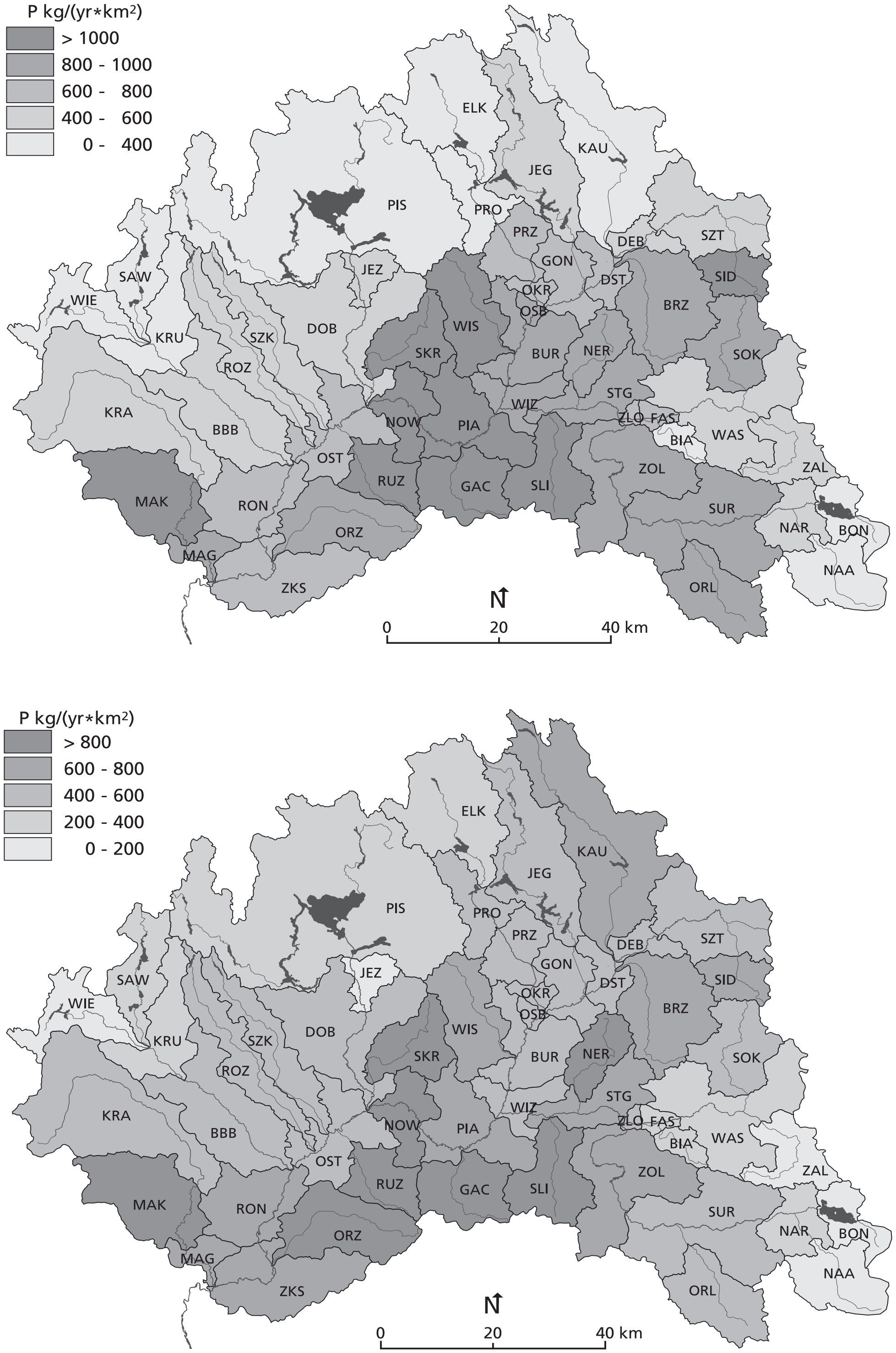
The spatial distribution of total generated nitrogen load was very much the same as the distribution of load originating from livestock since the latter contributed the major part of total load (figure 2.18). Therefore, (i) the highest total loads, over $8 \cdot 10^3$ kg N km$^{-2} \cdot$y^{-1}, were estimated for sub-catchments in the middle (Neresl NER, Wissa WIS and Skroda SKR rivers and Nowogrod NOW and Piatnica PIA), middle-southern (Slina SLI, Gac GAC, Ruz RUZ and Orz ORZ rivers) and west (Makow Mazowiecki MAZ) parts of the basin, (ii) the lowest loads, below $3.5 \cdot 10^3$ kg N km$^{-2} \cdot$y^{-1}, were calculated in sub-catchments in the south-eastern (Bondary BON, Narewka river NAA, Narew NAR, Zaluki ZAL, Wasilkow WAS and Biala river BIA) and north-western (Pisz PIS, Jeze JEZ, Wielbark WIE, Krukowo KRU and Sawica river SAW) parts of the basin and (iii) sub-catchments in the middle-western and north-eastern parts of the basin had load values above average. Land use contributed dominantly to the total generated nitrogen load in only 8 sub-catchments, which are these characterised by the lowest total load. At most land use contributed to over 90% of total load in Bondary (BON) sub-catchment. In the rest of the sub-catchments livestock originating load contributed more than 50% to the total generated load, with a maximum over 68% in Kanal Augustowski (KAU) sub-catchment.

The spatial distribution of total generated phosphorus load more resembled the distribution of land use originating load, which contributed on average more than half to total load (figure 2.19). Thus, the sub-catchments in the middle-western and north-eastern parts of the basin had estimated total generated loads below average, contrary to the nitrogen pattern. The same sub-catchments as for nitrogen were characterised by both the highest area-specific load with values of over $1.75 \cdot 10^3$ kg P km$^{-2} \cdot$y^{-1} and the lowest one with values below $0.79 \cdot 10^3$ kg P km$^{-2} \cdot$y^{-1}. Additionally, the total load for two other sub-catchments up north (Elk ELK and Prostki PRO) was estimated in the range of the lowest values. Livestock was a major source of total phosphorus load in only 7 sub-catchments, predominantly those characterised by the lowest total load, when in three others both sources contributed equally to total load. Livestock originating load contributed at most almost 67% in the Kanal Augustowski (KAU) sub-catchment. For the remaining 42 sub-catchments land use added more than 50% to total load, in five of them exceeding 70%.



b)

Figure 2.16 Generated N load (kg·km^{-2}·y^{-1}) in sub-catchments of the Narew River Basin per source: a) land use; b) livestock



a)

b)

Figure 2.17 Generated P load (kg·km^{-2}·y^{-1}) in the sub-catchments of Narew River Basin per source: a) land use; b) livestock

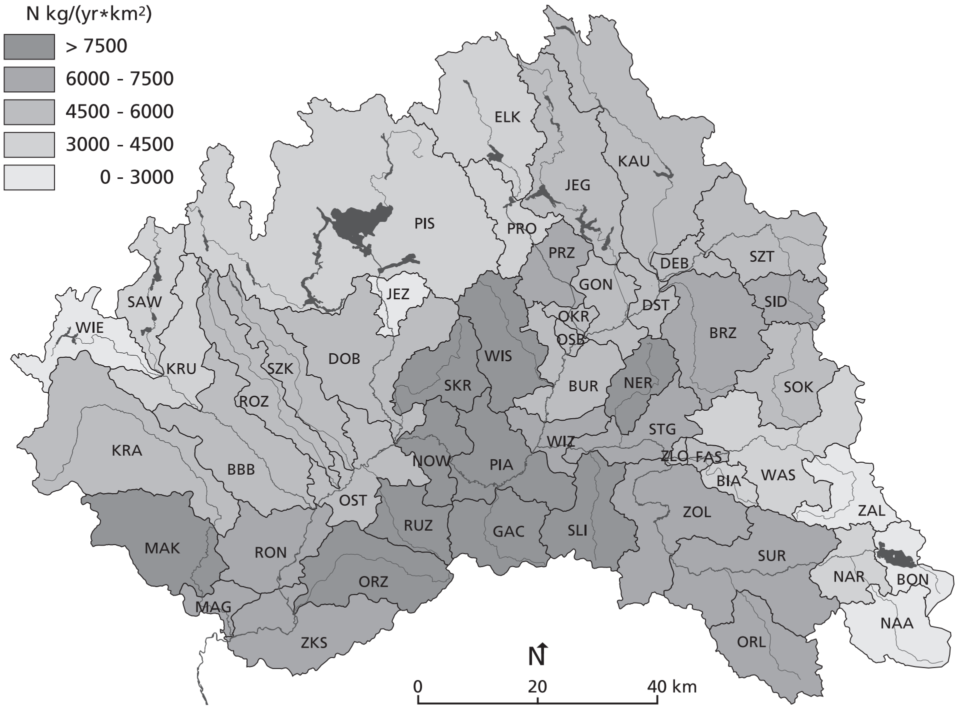


Figure 2.18 Total generated N load (kg$\cdot$km$^{-2}\cdot$y^{-1}) in sub-catchments of the Narew River Basin

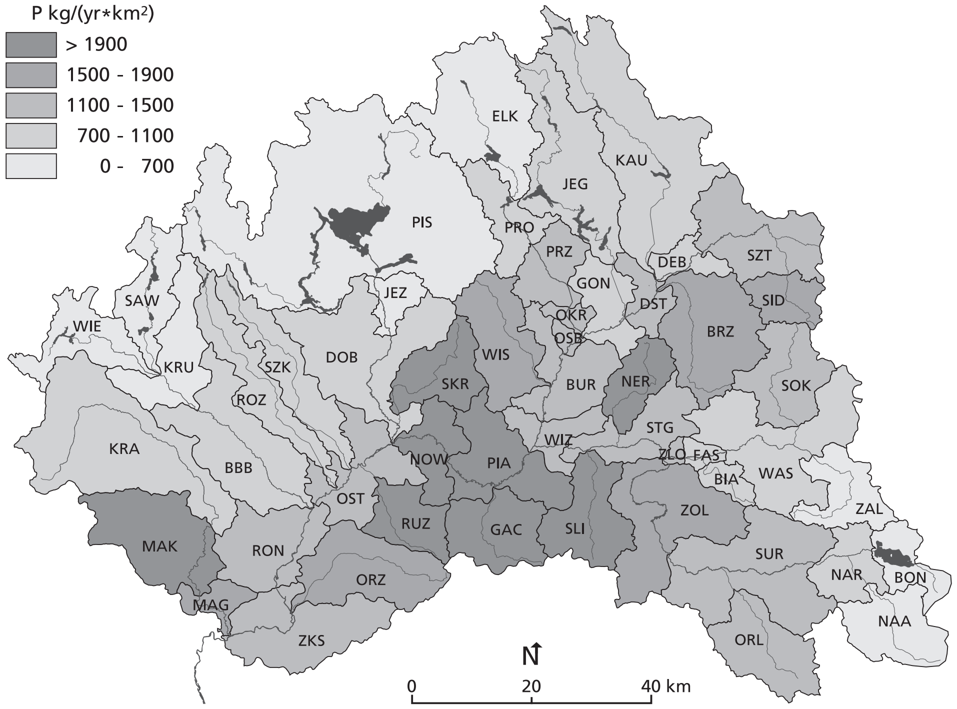


Figure 2.19 Total generated P load (kg$\cdot$km$^{-2}\cdot$y^{-1}) in sub-catchments of the Narew River Basin

2.4.3 Sensitivity analysis (the relative impact of sources to overall loads)

The sensitivity analysis was carried out following the procedure described in section 2.3.3, with livestock and human excretion and atmospheric deposition coefficients selected for succeeding module runs according to values given in table 2.5. In every run considering fertiliser usage, the dosages were changed by the appropriate fate of the start values, which were assigned separately for every sub-catchment area based on statistical data.

Table 2.5 Coefficient values (kg$\cdot$head$^{-1}\cdot$y^{-1}) used for succeeding runs in the sensitivity analysis

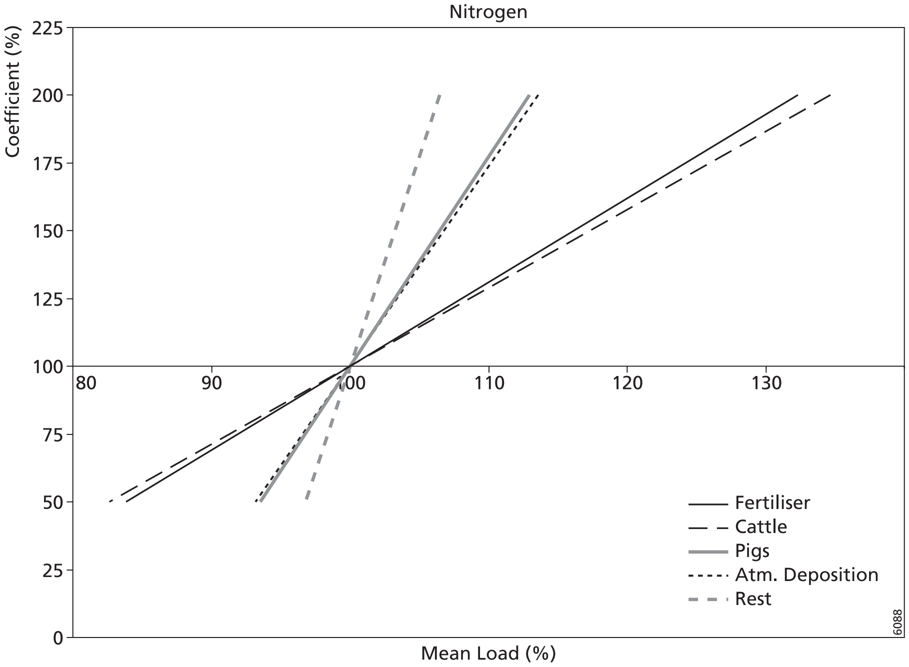
	Nitrogen							Phosphorus						
	-50	-20	-10	+10	+20	+50	+100	-50	-20	-10	+10	+20	+50	+100
Cattle	35.1	56.2	63.2	77.2	84.2	05.3	40.4	4.5	7.2	8.1	9.9	10.8	13.5	18.0
Pigs	9.4	15	16.8	20.6	22.4	28.0	37.4	2.5	4.0	4.5	5.5	6.0	7.5	10.0
Horses	18.4	29.4	33.1	40.5	44.2	55.2	73.6	1.0	1.6	1.8	2.2	2.4	3.0	4.0
Sheep	4.4	7.1	8.0	9.8	10.7	13.4	17.8	0.5	0.8	0.9	1.1	1.2	1.5	2.0
Poultry	0.15	0.24	0.27	0.33	0.36	0.45	0.60	0.05	.08	0.09	0.11	0.12	0.15	0.20
Atm. Dep.[a]	3.4	5.4	6.0	7.4	8.0	10.0	13.4	0.07	.11	0.12	0.15	0.16	0.20	0.27

[a] in kg$\cdot$km$^{-2}\cdot$y^{-1}

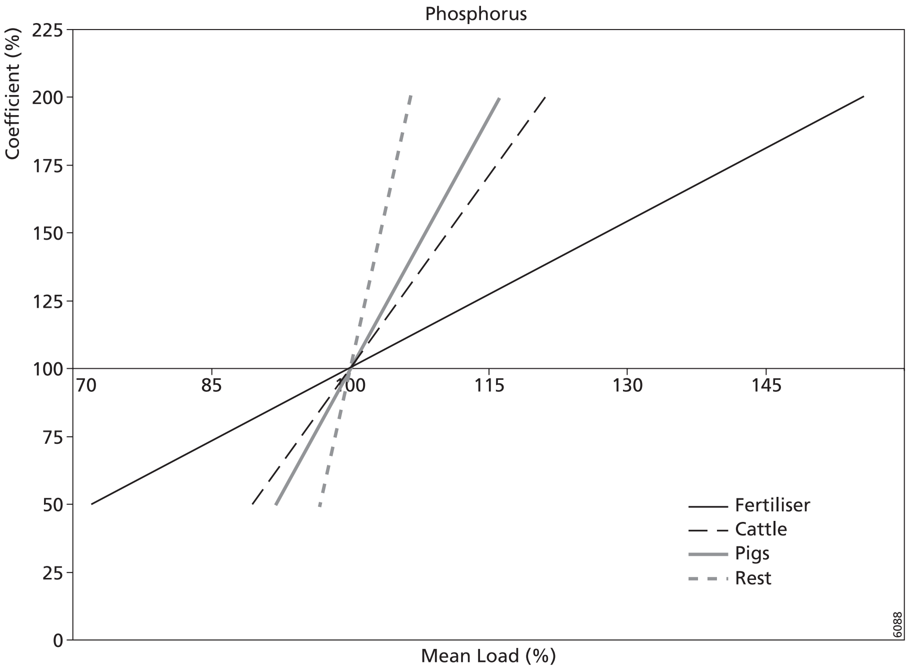
The mean relative change of load over the basin, when changing one of the coefficient types at a time, was calculated for each 8 sources of nutrients (fertilisation, population, cattle, pigs, horses, sheep, poultry and atmospheric deposition) using 7 different coefficient values. Those mean load changes were plotted against relative changes of coefficients (figure 2.10). Since, the mean changes of load, when coefficients were changed by +/- 50%, were estimated to be below +/- 2% for 4 sources (population, horses, sheep, poultry) for nitrogen the mean changes for these sources were summarised and plotted as one source. For phosphorus the mean changes of load, when coefficients were changed by +/- 50%, were estimated to be below +/- 2% for the same four sources as for nitrogen and additionally for the fifth source, namely atmospheric deposition. Thus, for phosphorus the mean changes for these five sources were summarised and plotted as one source.

The two dominant sources contributing to nitrogen load, are fertilisation and cattle. A change of coefficient values by +/- 10% resulted for both of them in over +/- 3% mean change of the load over the basin. They accounted for two-thirds (67%) of total mean load change if all coefficients had been changed by the same relative value at the time. For the same assumptions pigs and atmospheric deposition are the two next sources and contributed 27% to total mean load change with changes of +/- 1.3% for pigs and +/- 1.4% for atmospheric deposition when coefficients changed by +/- 10%. The other four sources played a minor role contributing together just for 6% to total mean change.

Fertilisation was the dominant source of phosphorus load and was accounted for 56% of total mean load change when all coefficients had been changed by the same relative value at the time. So, a change of fertilisation dosages by +/- 10% resulted in +/- 5.6% mean change of phosphorus load in the basin. The other two substantial sources, cattle and pigs, contributed for 37% to total mean phosphorus load change and respectively a +/- 10% change of their excretion coefficients resulted in +/- 2.1% change of the mean basin's load in case of cattle and +/- 1.6% change of this load for pigs. The remaining five sources had only a minor contribution of 7% of total mean change to phosphorus load.



a)



b)

Figure 2.20 Changes in mean load (%) vs. changes of the coefficients (%): a) nitrogen, rest is the sum of changes in population, horses, sheep and poultry; b) phosphorus, rest is the sum of changes in population, horses, sheep, poultry and atmospheric deposition

2.4.4 Export coefficients

The export of the total nutrient load emitted from different sources into surface water for the sub-catchment areas was estimated and described by two characteristics: an area-specific load export (in $kg^{\cdot}km^{-2\cdot}y^{-1}$) and an exact export coefficient (in %), specifying the part of the emitted load reaching the surface water. For both nitrogen and phosphorus area-specific load exports over the entire basin resembled the spatial distribution of their area-specific generated loads (figures 2.21 and 2.22). This means that, the middle, middle-southern and west parts of the basin are the regions where values of area specific export were estimated to be the highest with respectively over $7.8^{\cdot}10^3$ kg N $km^{-2\cdot}y^{-1}$ and $1.8^{\cdot}10^3$ kg P $km^{-2\cdot}y^{-1}$.

The lowest values were similar for both nutrients estimated for sub-catchment areas in the south-eastern and north-western parts of the basin, with export rates below $3.5^{\cdot}10^3$ kg N $km^{-2\cdot}y^{-1}$ and $0.6^{\cdot}10^3$ kg P $km^{-2\cdot}y^{-1}$. For the rest of the basin the values of area-specific export were for either nitrogen or phosphorus estimated around to basin's averages that respectively equalled to $5.1^{\cdot}10^3$ kg N $km^{-2\cdot}y^{-1}$ and $1.1^{\cdot}10^3$ kg P $km^{-2\cdot}y^{-1}$. Moreover, for both nutrients the spatial distributions of area-specific export followed the same pattern as for area-specific generated load. The north-eastern and middle-eastern parts of the basin are characterised by above average values for nitrogen and below average values for phosphorus.

The fate of the generated nutrient load reaching the surface water was very varied between different sub-catchments of the Narew river basin. Thus, the estimated export coefficient for nitrogen ranged from 0.14 % in the sub-catchment of Slina river (SLI) to almost 73% in Fasty sub-catchment (FAS) and for phosphorus varied from 0.13 % also in the sub-catchment of Slina river (SLI) to 14 % in Zlotoria sub-catchment (ZLO). The average export coefficients for the entire basin were estimated for 8 % emitted nitrogen load and 1.9 % of emitted phosphorus load. The spatial distribution of export coefficients showed a very scattered picture over the basin, especially in case of phosphorus, where it was difficult to pick out any clear pattern (figures 2.23 and 2.24).

For nitrogen the highest export coefficient values, over 8.5% of emitted load, were estimated for differential sub-catchments along the middle and lower courses of the Narew river and for all except one sub-catchments smaller than 160 km^2 (Biala river BIA, Fasty FAS, Zlotoria ZLO, Osowiec Kanal OKR, Osowiec Biebrza OSB, Jeze JEZ and Magnuszew Maly MAG). In general the spatial distribution of export coefficients over the entire basin stayed close to the spatial distribution of the calculated observed load, especially for nitrogen.

The detailed results of the estimated observed and generated loads, sensitivity analysis and export coefficients for all the sub-catchments are presented in tables in the Appendix A.1.

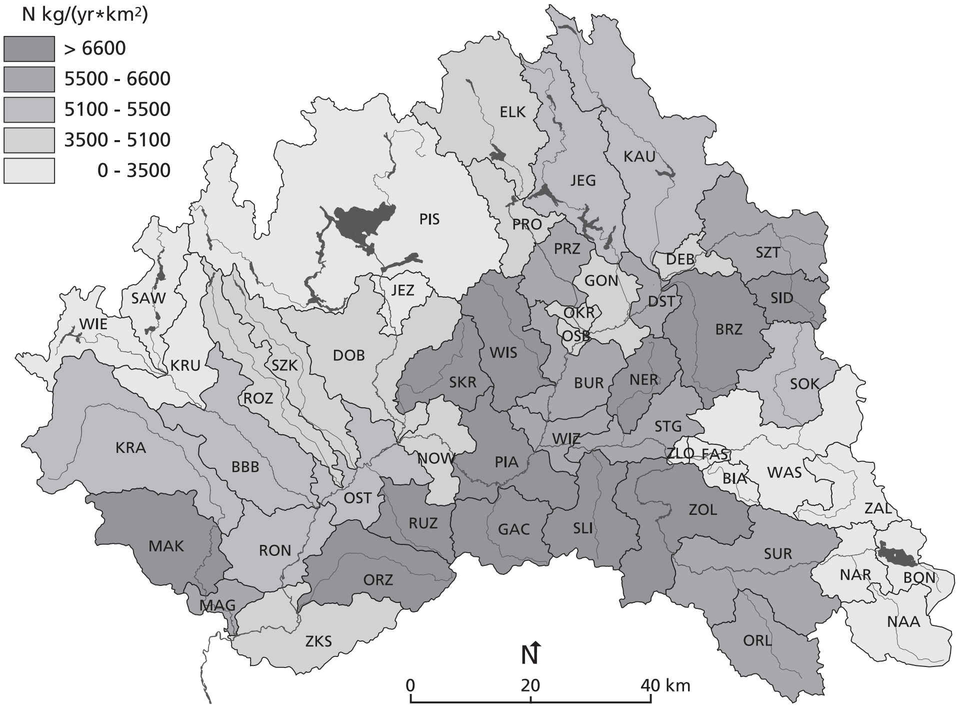


Figure 2.21 Nitrogen load export (kg·km^{-2}·y^{-1}) in sub-catchments of the Narew River Basin

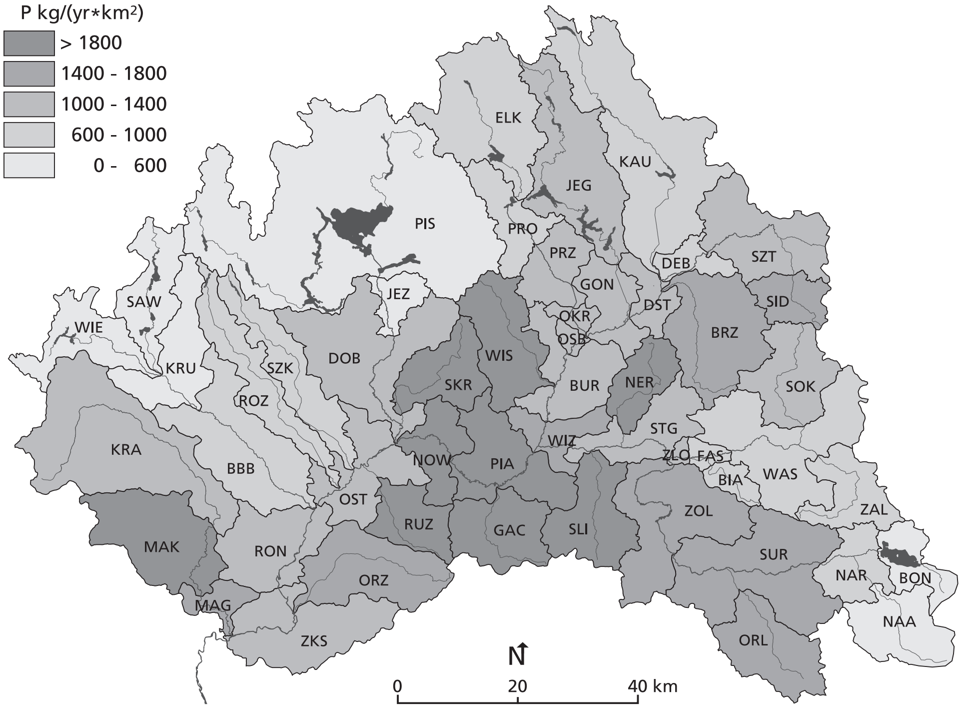


Figure 2.22 Phosphorus load export (kg·km^{-2}·y^{-1}) in sub-catchments of the Narew River Basin

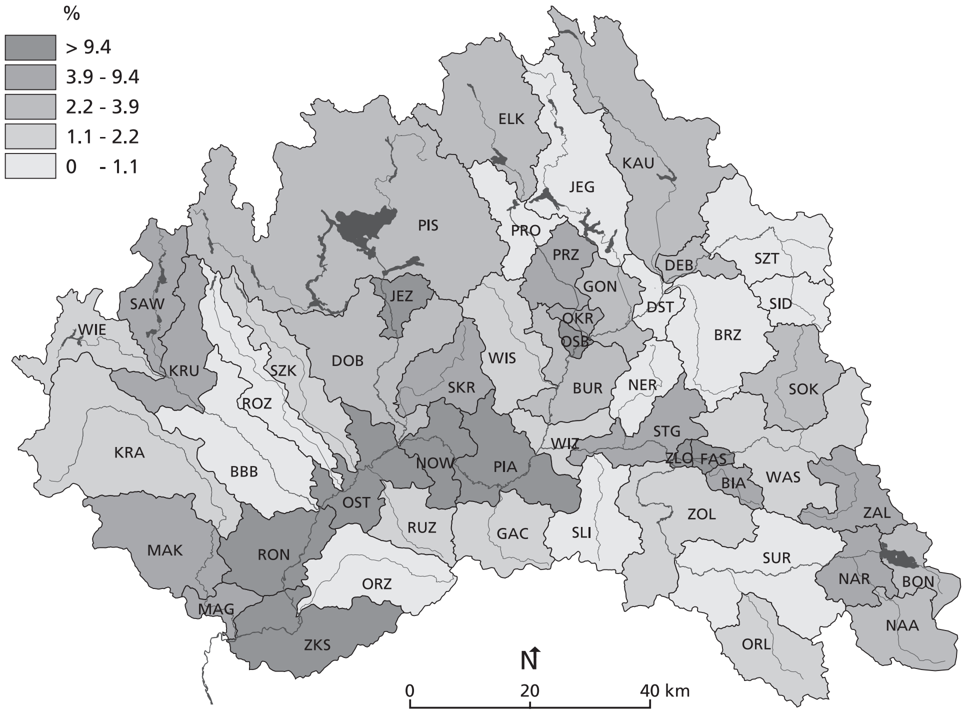


Figure 2.23 Nitrogen load export (%) in sub-catchments of the Narew River Basin

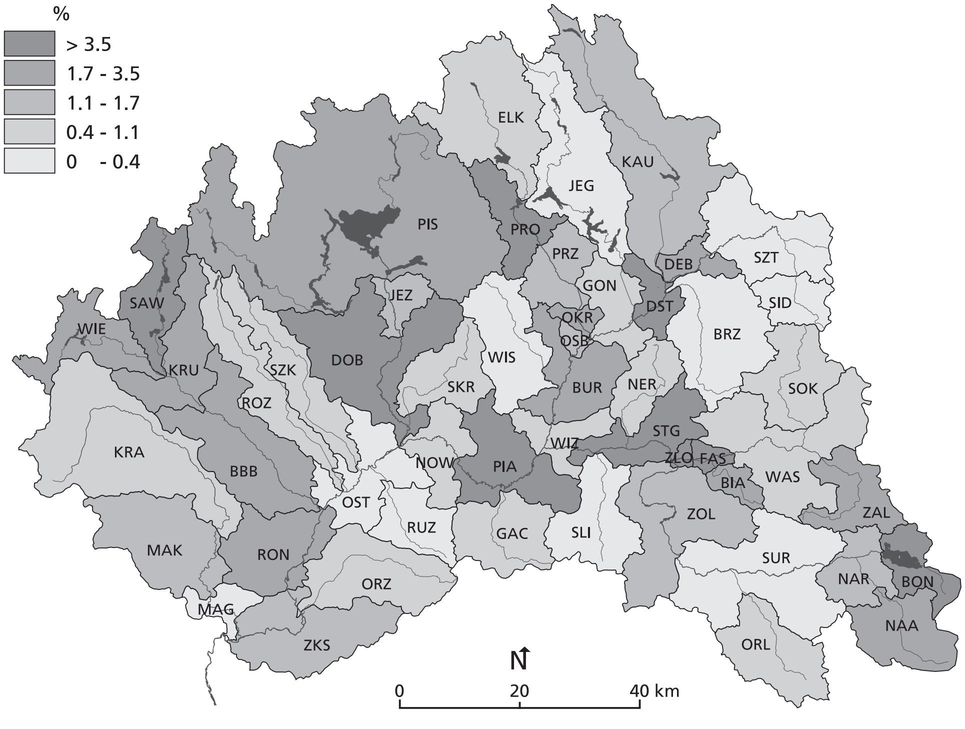


Figure 2.24 Phosphorus load export (%) in sub-catchments of the Narew River Basin

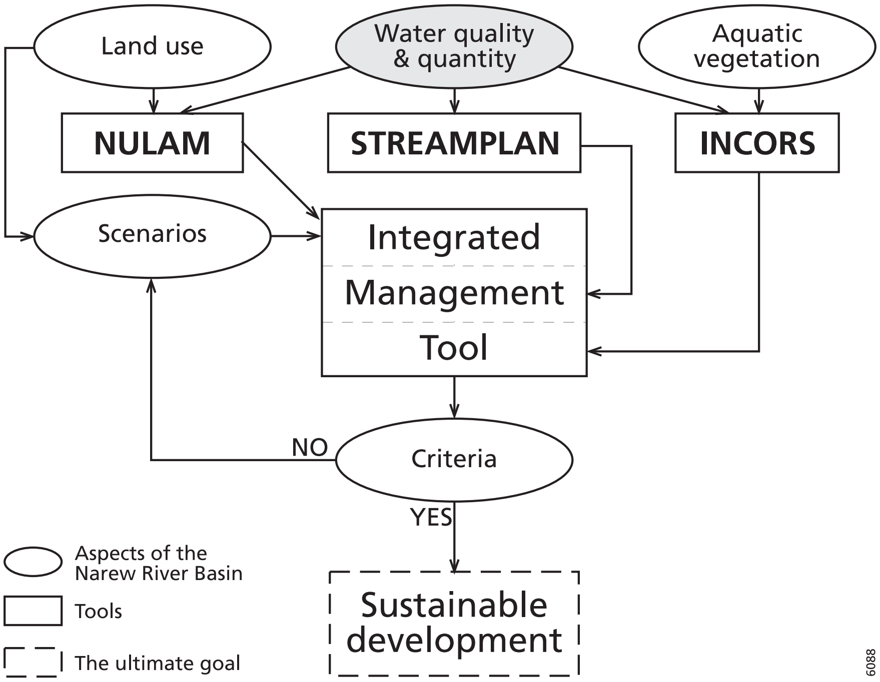
2.5 Discussion and conclusions

As an element of an integrated management tool (IMT) NULAM has a number of advantages: the simplicity of the procedure format, operation by commonly used simple spreadsheet environment, relatively modest data requirements fulfilled by readily available databases. It allows for a relatively simple and not laborious, thus inexpensive, evaluation of the impact of land use and land management policies on water quality of surface waters. From a process point of view one might argue that the module proposed in this chapter lacks a process-based description and it is therefore questionable whether it will correctly react to changing conditions. De Wit (1999) examined the performance of several nutrient fluxes models with increasing complexity (from lumped to semi-process based) and concluded that the use of more detailed process descriptions only brings improvements if the process descriptions are valid at the scale of the analysis. Therefore, improved large scale studies of nutrient fluxes in river basins first of all require much detailed data, especially on nutrient sources. With the data available for this study I conclude that NULAM is a sufficient module to be included in the IMT, which construction and application is one of the aims of this work.

From the results obtained I conclude that:

- estimates of area specific generated loads for both nitrogen and phosphorus are in acceptable agreement with values reported by other workers. For instance De Wit (1999) estimated area specific emissions from diffuse sources for Rhine and Elbe basin respectively for $4.2 \cdot 10^{3}$ kg N $km^{-2} \cdot y^{-1}$; $2.2 \cdot 10^{3}$ kg N $km^{-2} \cdot y^{-1}$ and $0.6 \cdot 10^{3}$ kg P $km^{-2} \cdot y^{-1}$; $0.2 \cdot 10^{3}$ kg P $km^{-2} \cdot y^{-1}$. The differences in methodology (e.g. including small point sources as diffuse sources in this study) and, size and location of study area limit somewhat such comparison although more comparable data were not available;
- emission from land use contributes for a major part to total phosphorus emission and accounts for as much as 55% of total generated P load at the entire basin scale;
- emission from livestock (including population) contributes for a major part to total nitrogen emission and accounts for as much as 56% of total generated N load at entire basin scale;
- the arable land dominated sub-catchment areas, in the middle and south parts of the basin, are characterised by the highest area-specific nutrient emissions;
- estimation of emitted load for nitrogen is most sensitive to changes in parameters that describe the fertiliser usage and cattle excretion; pigs excretion and atmospheric deposition parameters are less important, and other parameters are of minor influence;
- estimation of load emission of phosphorus is dominantly sensitive to changes in parameters that describe the fertiliser usage; cattle and pigs excretion parameters are of lesser importance and others are of minor influence;
- estimated export coefficients, similarly to area specific generated load, are in acceptable agreement with results reported in other studies when taking into account differences in methodology and in the size of the study area and the location. For instance Johnes (1996) estimated the export of emitted load as 15% total-N load and 3% of total-P load for two catchments in England. From

the estimates calculated by De Wit (1999) for the Rhine and Elbe basins it appeared that from 3 to 40% of N-load and from 1 to 9% of P-load, depending on the sub-basins, were exported. The Rhine and Elbe study and one by Skop and Sorensen (1998) for Danish catchment estimated the ranges of area specific export from 2000 – 11500 kg N km$^{-2\cdot}$y^{-1} and 400 – 2200 kg P km$^{-2\cdot}$y^{-1}.


Land use
Water quality & quantity
Aquatic vegetation
NULAM
STREAMPLAN
INCORS
Scenarios
Integrated Management Tool
Criteria
NO
YES
Sustainable development
Aspects of the Narew River Basin
Tools
The ultimate goal
6088

3 SURFACE WATER QUALITY PATTERNS IN THE NAREW RIVER BASIN

3.1 Introduction

Whereas chapter 2 concentrated on the influences of land use, this chapter studies water quality and quantity in the Narew River Basin. An assessment of the present status of surface water, an indication of unsatisfactory values for water quality parameters and a definition of the major factors determining water quality and its spatial distribution are essential elements in investigating the surface water link of the land use – surface water – aquatic ecosystem cause-and-effect chain. Analysing the relations between elements and constructing a tool for modelling the elements in this chain are some of the aims of this study (see section 1.2 and 1.3). An achievement of these aims requires the answers to questions concerning contribution and impact of different sources on the water quality in the basin, which were raised when defining the objectives of the thesis (see section 1.2). This chapter attempts to give such answers and describes the most important elements of surface water quality in the Narew River Basin. The collected database is described and overall water quality conditions are presented, with the main attention being paid to the relative concentrations of water quality components with reference to the water quality standards. By connecting the spatial pattern in water quality to the pattern of land use, the effects of different types of land use can be assessed by means of information on the quality of surface water. The spatial distribution of nutrient concentrations and their relation to land use types is also elaborated.

Abrahamsen & Nielsen A/S (1994) and Gromiec (1992) investigated water quality patterns and status in the Narew River Basin. According to their findings nitrogen and phosphorus are key components limiting quality of the surface water of the study area. These two studies differ from the present study by discrepanding temporal variation. Moreover, they were both carried out at a coarse spatial resolution compared to that used in this thesis. The analysis described in the present chapter is partly based on the above mentioned studies, but is more spatially oriented and has the following objectives: (i) to assess water quality components against water quality class limits, (ii) to identify water quality key components, (iii) to map the spatial distribution of nutrient concentrations, (iv) to distinguished sub-catchments, in which specific types of water quality correspond with specific types of land, (v) to map differences in the water quality with regard to the location of either urban and industrial point sources or agricultural non-point sources.

3.2 Methods

3.2.1 Database

In total ninety four locations (figure 3.1), located both on the mainstream and tributaries, were sampled monthly during a two year monitoring program (hydrological years 1996-1997). In total the database consists of twenty sampling rounds.
The chemicals analysed included heavy metals (cadmium Cd^{2+}, chromium Cr^{6+}, lead Pb^{2+}, zinc Zn^{2+}, manganese Mn^{2+}), nutrients (NO_3^-, NH_4^+, PO_4^{3-}), sulphate (SO_4^{2-}), calcium (Ca^+), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), chloride (Cl^-), iron (Fe^{2+}), copper (Cu^{2+}), silicium oxide (SiO_2) and aluminium (Al^+).

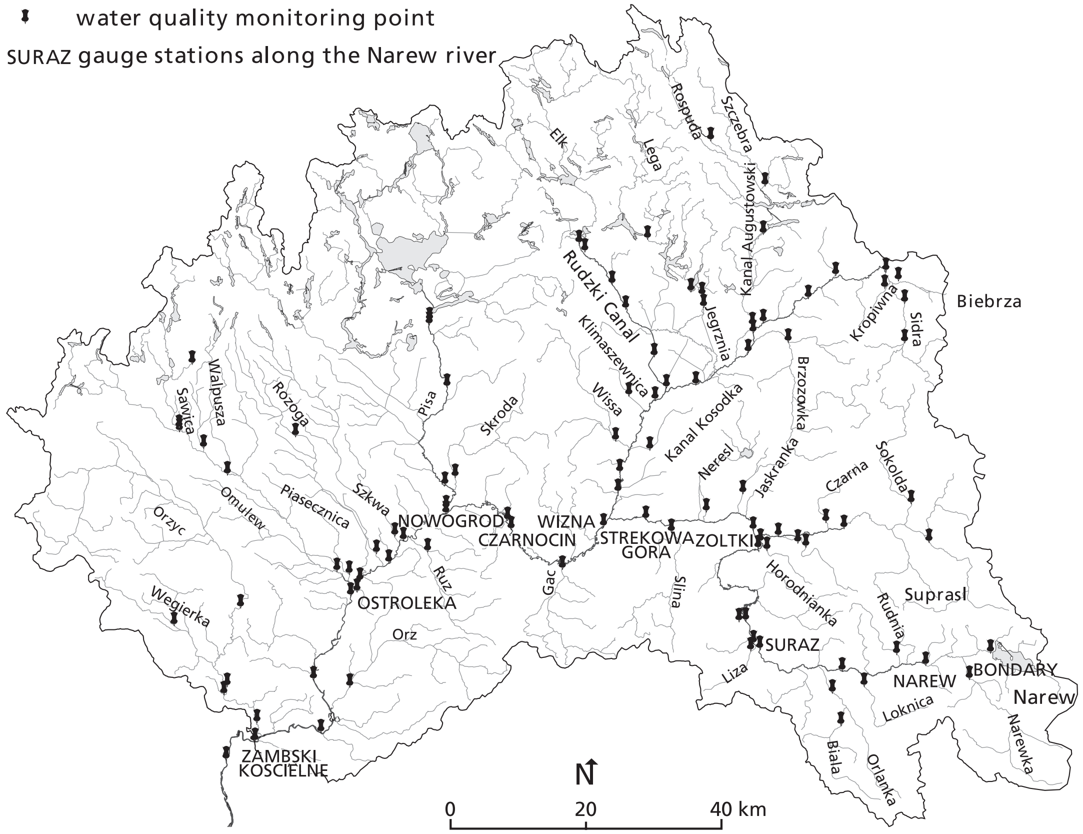


Figure 3.1 Water quality monitoring network in the Narew River Basin

Water samples taken in the field, were analysed directly for pH (WTW pH96), electroconductivity (WTW LF96) and alkalinity (MERCK 11109 Alkalinity Test), then they were filtered and divided into two sub-samples of 12 ml volume each and acidified to pH = 1 respectively with 0.5 ml 25 % nitric acid (HNO_3) and with 0.5 ml 5 %

sulphuric acid (H_2SO_4). The sub-samples acidified with H_2SO_4 were analysed for ammonium-N, nitrate-N and chloride by colorimetry on a continuous flow auto-analyser, the sub-samples acidified with HNO_3 were analysed for the remaining constituents by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). All samples were analysed by the Laboratory of Physical Geography, Utrecht University.

3.2.2 Methods for presenting spatial distribution patterns

More detailed analyses were carried out for nutrients since they have a specific impact on overall surface water quality in the Narew River Basin. For all three variables (NO_3^-, NH_4^+, PO_4^{3-}) the median value of all samples was calculated. According to Spahr and Wynn (1997) median values are the most suitable for such analyses because a median is not significantly influenced by outliers and is not affected by data below the detection limit when less than half of the data used for calculation is below such a limit. This is important when one deals with nutrient data, which are often reported as having values below laboratory detection limits. Also Johnes and Burt (1993) used the median to analyse nitrogen data. In this study the spatial distribution analyses were based on all selected sites because they all had ten or more concentration values above detection limits. Based on geographical co-ordinates (longitude and latitude) sites were incorporated into GIS files (MapInfo format) and corresponding median values were linked for graphic presentation. Concentrations of analysis variables were classified into the following class ranges: less than 30th, 30th to 60th, 60th to 90th, and greater than 90th percentiles of the median site concentrations.

At the same time as the acquisition of water quality data (see section 3.2.1), data on the hydrological division of the whole basin into sub-catchments and spatial differentiation of land use types were collected and stored in a geographic information system (GIS) database. These data were digitised from a thematic-topographical map (land cover, Kistowski (eds.), 1991) and the Hydrological Atlas of Poland (hydrological division, IMGW, 1980), both at 1:200000 scale. Data on land use types acquired from the topographical paper map were used to distinguish sub-catchments according to predominant land use type. They were of different origin than the statistical land use data assigned to communities, which were used for the purpose of load emission assessment for land use type performed in chapter 2.

The Narew River Basin was divided into 34 sub-catchments based on the collected numerical information and the total set of water quality monitoring locations (figure 3.3). The sites located at the downstream end of these sub-catchments were selected for further analyses. The criterion was to reflect the main characteristics of hydrological patterns in the basin, therefore to include into this division the mainstream and all major tributaries. Tributary sub-catchments were primarily selected on their size (tributaries with sub-catchment area of ca. 1% of the total basin area) and for the relative role they play in a certain part of the basin (e.g. Biala river sub-catchment draining the city of Bialystok, the largest in the basin). Three sub-catchments (Biebrza, Suprasl and Pisa) were subdivided into smaller parts because of their important role in overall water quality and/or their relative large size (Biebrza).

Five land use types were distinguished: arable land, grass land (meadows and pastures), forest, built-up area and water (lakes and ponds). Percentiles of each land use type in every sub-catchment were calculated. Based on this calculation all sites were grouped. Three groups of sites were distinguished due to the predominant land use types and the study aim. These groups are: (i) forest with prevailing and/or significant forestry land use, (ii) urbanisation with significant impact of built-up areas, and (iii) agriculture with prevailing agricultural land use. The classification criteria were: (i) forest - at least 35 % of the sub-catchment is covered by forest and population density is below 40 person$\cdot$km^{-2}, (ii) urbanisation - at least 5 % of the sub-catchment consists of built-up area and population density is above 80 person$\cdot$km^{-2}, and (iii) agriculture - all sites not included in the remaining two groups. Most sites (18) were classified as agriculture, 13 sites as forests and the remaining 3 sites as urbanisation. The analysed variables: ammonium, nitrate and orthophosphate, were combined within each group. The median values were used for further analysis.

3.3 Results

3.3.1 Overall water quality

Mean concentrations over the two years period were calculated for all measured water quality constituents (tables 3.2 and 3.3). Initial analyses of calculated values allowed for the general statement that surface water quality in the Narew river was fairly good. However in this thesis, the water quality issue is related to standards set by Polish Water Law (Water Classification, 1991; see chapter 1). The present water quality was compared to values given for the Ist class of water quality in this Law (table 3.1).

Table 3.1 Values of some pollution indicators for the first class inland surface water class according to Polish State standards

	Unit	Range		Unit	Range
Temperature	^{o}C	22 and lower	Sodium	mgNa/l	100 and lower
Reaction	PH	6.5 – 8.5	Potassium	mgK/l	10 and lower
Conductivity	µS/cm	800 and lower	Iron	mgFe/l	1.0 and lower
Ammonium nitrogen	mgN_{NH_4}/l	1.0 and lower	Cadmium	mgCd/l	0.005 and lower
Nitrate nitrogen	mgN_{NO_3}/l	5.0 and lower	Manganese	mgMn/l	0.1 and lower
Dissolved phosphate	mgPO4/l	0.2 and lower	Copper	mgCu/l	0.05 and lower
Chlorides	mgCl/l	250 and lower	Lead	mgPb/l	0.05 and lower
Sulphates	mgSO4/l	150 and lower	Zinc	mgZn/l	0.2 and lower

Source: Water Classification, 1991

As is shown in table 3.2, the concentrations of metal ions and sulphate were within the ranges of first-class water quality along the entire river, except for the upper course where there are high levels of iron and manganese, possibly the result of natural chemical weathering (Mioduszewski, 1997). The monthly (seasonal) variation in concentrations also remains within acceptable ranges.

Table 3.2 Mean annual concentrations of some selected ions[a] ($mg\,l^{-1}$) at selected locations along the main course of the Narew river in the period 1996-1997

	Position[b]	Cd	Fe	K	Mn	Na	SO_4
Bondary	431.7	0.003	1.02	1.98	0.22	4.13	17.99
Narew	410.0	0.004	1.05	1.78	0.18	4.57	20.60
Suraz	355.3	0.005	0.86	2.37	0.11	6.47	24.64
Zoltki	303.3	0.004	0.56	3.00	0.10	8.56	27.79
Strekowa Gora	261.7	0.005	0.54	3.06	0.08	11.75	29.99
Wizna	245.9	0.005	0.45	3.06	0.09	9.63	31.09
Czarnocin	203.6	0.005	0.50	3.18	0.09	9.98	31.21
Nowogrod	180.3	0.005	0.42	3.05	0.07	9.53	31.51
Ostroleka	146.8	0.005	0.45	3.16	0.08	9.42	32.99
Rozan	116.8	0.004	0.46	3.01	0.08	9.26	33.35
Zambski Koscielne	81.1	0.004	0.52	3.13	0.09	9.03	34.40

[a] Concentrations of copper, lead and zinc are below detection limits in more than 60% of measurements,
[b] "Position" means kilometres from the mouth of the Narew river.
Source: author's data, Gromiec (eds.), 1992

Measured concentrations of nutrients (and chloride, as a pollution indicator) in surface water in the basin show (table 3.3) that the concentrations of orthophosphate along the entire river are too high for the water to be ranked as first-class quality.

Table 3.3 Mean annual concentration of nutrients and chloride ($mg\,l^{-1}$) at selected locations along the main course of the Narew river in the period 1996-1997

	Position[a]	PO_4	NH_4	Cl	NO_3
Bondary	431.7	0.487	0.408	8.258	2.024
Narew	410.0	0.456	0.374	8.093	2.578
Suraz	355.3	0.509	0.345	10.01	3.911
Zoltki	303.3	0.549	0.696	12.80	4.758
Strekowa Gora	261.7	0.782	0.463	15.38	6.256
Wizna	245.9	0.555	0.369	13.17	4.132
Czarnocin	203.6	0.606	0.384	13.43	4.486
Nowogrod	180.3	0.555	0.345	12.82	4.301
Ostroleka	146.8	0.521	0.387	13.64	3.921
Rozan	116.8	0.571	0.465	13.97	3.950
Zambski Koscielne	81.1	0.600	0.315	12.98	3.819

[a] "Position" see table 3.2
Source: author's data, Gromiec (eds.), 1992

The concentration of orthophosphate exceeded the first-class limit throughout the year and along the entire course of the Narew river and its main tributaries, the Biebrza and the Pisa rivers. The concentrations of nitrate-nitrogen also exceeded the first-class limit along the Narew river downstream from Suraz and along the Biebrza river, although only during the first half (November – April) of the hydrological year. The rest of the time the nitrate-nitrogen concentrations were within the limits accepted for first-class quality (figure 3.2).

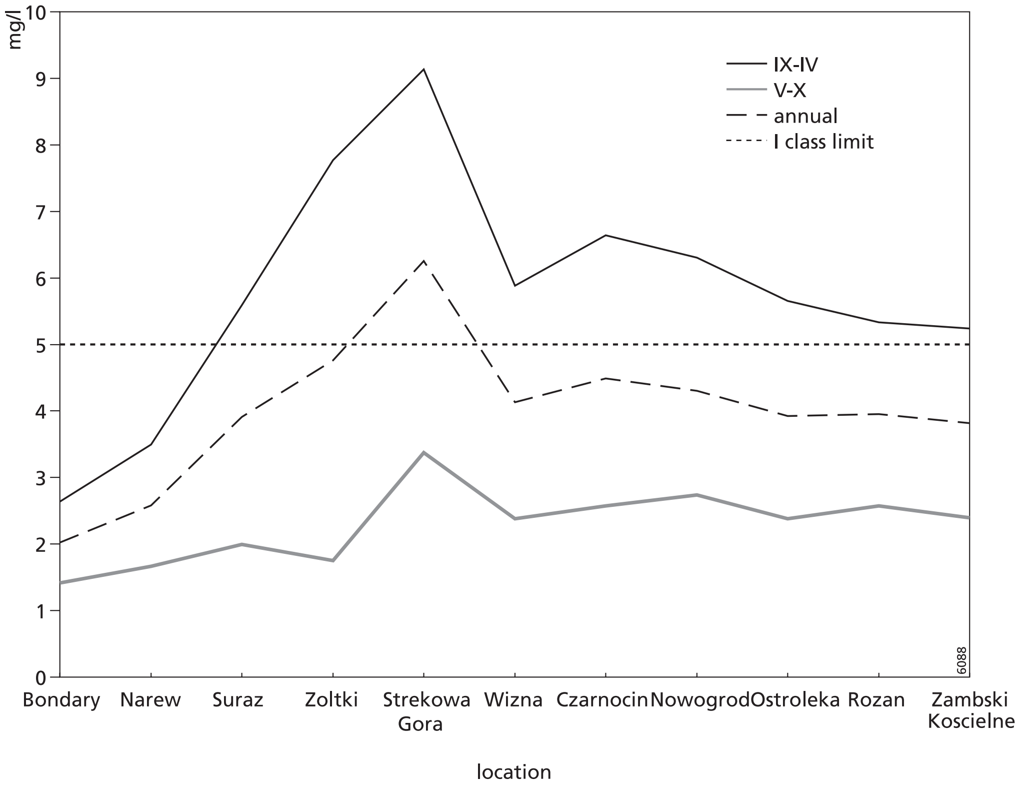


Figure 3.2 Mean concentration of nitrate along the Narew river for the hydrological years 1996-1997

The water quality data, collected within the two hydrological years 1996 and 1997, confirm earlier investigations of surface water quality in the basin (Abrahamsen & Nielsen A/S, 1994). The latter study revealed that Narew water was not of the highest quality mainly because it contains a high concentration of nutrients. On the other hand, the concentrations of heavy metals and sulphur compounds in the Narew River Basin did not exceed the limits for first-class water quality.

3.3.2 Spatial distribution of nutrient concentrations

The median values for ammonium, nitrate and orthophosphate were ranged in four classes according to percentile limits (see section 3.2). The class limit concentration values for each class are given in table 3.4.

Table 3.4 Concentration ranges for ammonium, nitrate and orthophosphate ($mg^{.}l^{-1}$) for classes based on 30th, 60th and 90th percentiles of median values

	Ammonium	Nitrate	Orthophosphate
lt 30	< 0.26	< 2.73	< 0.46
30 to 60	0.26 - 0.30	2.73 - 4.27	0.46 - 0.56
60 to 90	0.31 - 0.37	4.28 - 6.54	0.57 - 0.77
gt 90	> 0.37	> 6.54	> 0.77

Comparing the data shown above with the Polish State standards for water quality classes (Water Classification, 1991) (table 3.5) shows that generally the surface waters of the Narew River Basin are of a relatively high quality.

Table 3.5 Concentration ranges for ammonium, nitrate and orthophosphate ($mg^{.}l^{-1}$) for water quality classes based on Polish State standards

	I Class	II Class	III Class	NON Class
Ammonium	1.0 and lower	3.0 and lower	6.0 and lower	greater than 6.0
Nitrate	5.0 and lower	7.0 and lower	15.0 and lower	greater than 15.0
Orthophosphate	0.2 and lower	0.6 and lower	1.0 and lower	greater than 1.0

Source: Water Classification, 1991

Ammonium concentrations (figure 3.3) were generally low throughout the basin. There were no coherent spatial patterns of ammonium concentrations in the basin, although they were slightly elevated (with a maximum of 0.35 $mg^{.}l^{-1}$ NH_4 at Burzyn) in lower courses of some tributaries in the middle (the Biebrza river) and lower (the Omulew, Orz and Orzyc rivers) parts of the basin. As a result of point sources (respectively cities of Bialystok, Elk and Zambrow) ammonium concentrations were high (with a maximum of 0.81 $mg^{.}l^{-1}$ NH_4 at Fasty) in some tributaries in the upper (the Suprasl river) and middle (the Elk and Gac rivers) parts of the basin.

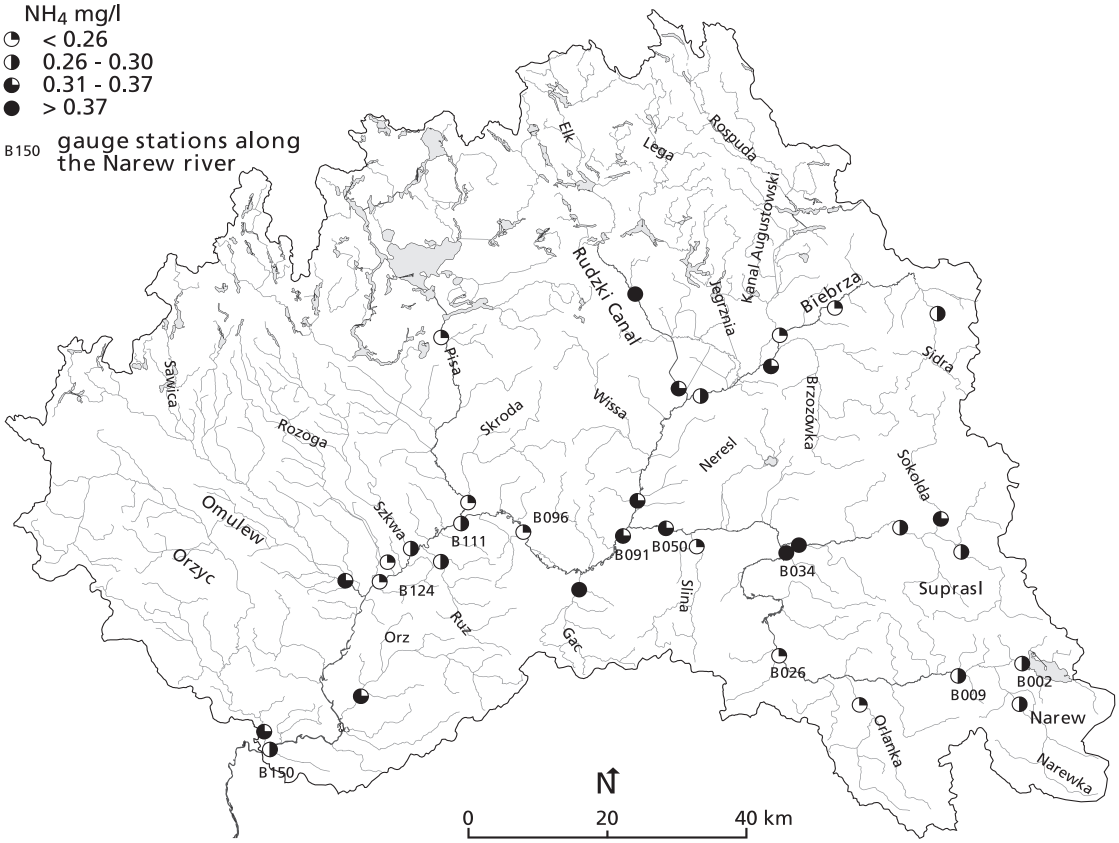


Figure 3.3 Spatial distribution of median ammonium concentration in the Narew River Basin

Nitrate concentrations (figure 3.4) were also generally low in the basin but had a slight tendency to increase downstream. Sites in the middle and lower sub-catchments of the Narew river had somewhat higher concentrations than sites in the upper sub-catchments. However, there were several sites in the upper basin (the Orlanka, Sokolda and Suprasl rivers) with high nitrate concentrations (with a maximum of 12.6 $mg \cdot l^{-1}$ NO_3 at Fasty) coming from point sources (respectively cities of the Bielsk Podlaski, Sokolka and Bialystok).

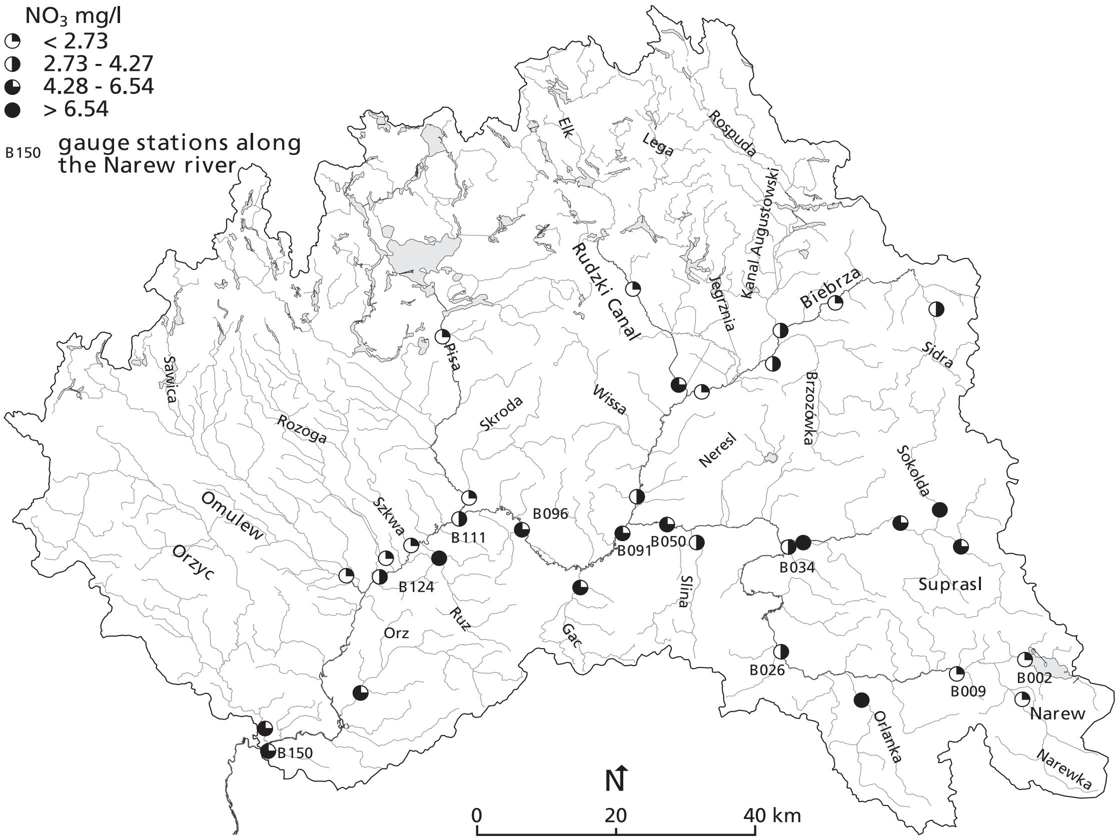


Figure 3.4 Spatial distribution of median nitrate concentration in the Narew River Basin

Orthophosphate concentrations (figure 3.5) were relatively high over the whole basin. Similarly to other ions, the concentrations of this ion were somewhat higher (with a maximum of 0.73 mg·l^{-1} PO_4 at Bialobrzeg Blizszy) in the lower basin, especially in some lower basin tributaries (the Omulew, Orz and Orzyc rivers). As for the other nutrients, for orthophosphate also, point sources, respectively the cities of Bielsk Podlaski, Bialystok, Grajewo and Zambrow contributed to increased concentration values (with a maximum of 1.85 mg·l^{-1} PO_4 at Fasty) at some sites in the sub-catchments in the upper (the Orlanka and Suprasl rivers) and middle (Rudzki Canal and the Gac river) parts of the basins. In some sites in the upper part of the basin, where the discharge in the stream is relatively low, all nutrient concentrations were higher as a result of point sources. Some sites in the very upper course of some of the Narew river tributaries (the Narewka and Pisa rivers), representing areas of very extensive land use, had very low concentrations (with a minimum of 0.22 mg·l^{-1} PO_4 at Pisz) of the variables analysed.

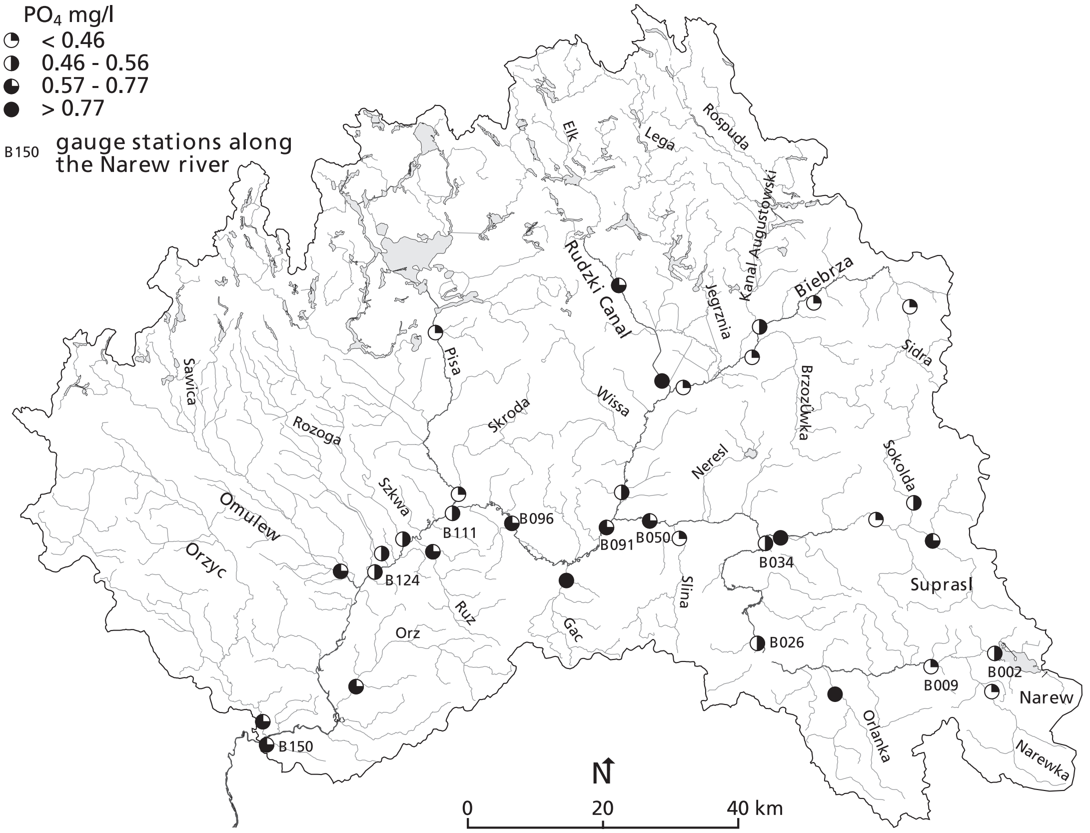


Figure 3.5 Spatial distribution of median orthophosphate concentration in the Narew River Basin

Data were analysed in more detail from 10 selected sites (Bondary, Narew, Suraz, Zoltki, Strekowa Gora, Wizna, Czarnocin, Nowogrod, Ostroleka and Zambski Koscielne) along the main course of the Narew river for elaboration of the spatial distribution of the nutrient concentrations in the basin. The results are shown by "multiple-box-and-whisker" plots (Podgorski, 1996) in figure 3.6. Concentrations of ammonium did not show any spatial trend and were concentrated in a very narrow range from 0.24 $mg{\cdot}l^{-1}$ to 0.28 $mg{\cdot}l^{-1}$, except for the site at Zoltki (B034) where the concentration value was elevated to 0.38 $mg{\cdot}l^{-1}$ as a result of point source discharge from the town of Choroszcz.

Concentrations of nitrate and orthophosphate generally show different trends in the upper reaches, as compared to the lower reaches in the river. Concentrations of both ions, but especially of orthophosphate, increased from the upper most site at Bondary (B002, 1.48 $mg{\cdot}l^{-1}$ NO_3 and 0.44 $mg{\cdot}l^{-1}$ PO_4) up to the site at Strekowa Gora (B050) to reach their absolute maximum (6.28 $mg{\cdot}l^{-1}$ NO_3 and 0.74 $mg{\cdot}l^{-1}$ PO_4). Downstream of this site, where the Biebrza river enters the Narew river, the ion concentrations was lower due to a dilution effect (site B091). Further downstream, nitrate and orthophosphate concentrations fluctuated slightly but both within very narrow ranges (4.24 - 4.96 $mg{\cdot}l^{-1}$

NO_3 and 0.52 - 0.59 $\mathrm{mg \cdot l^{-1}}$ PO_4) with a characteristic dilution after the confluence of the Pisa and Narew rivers (site B111).

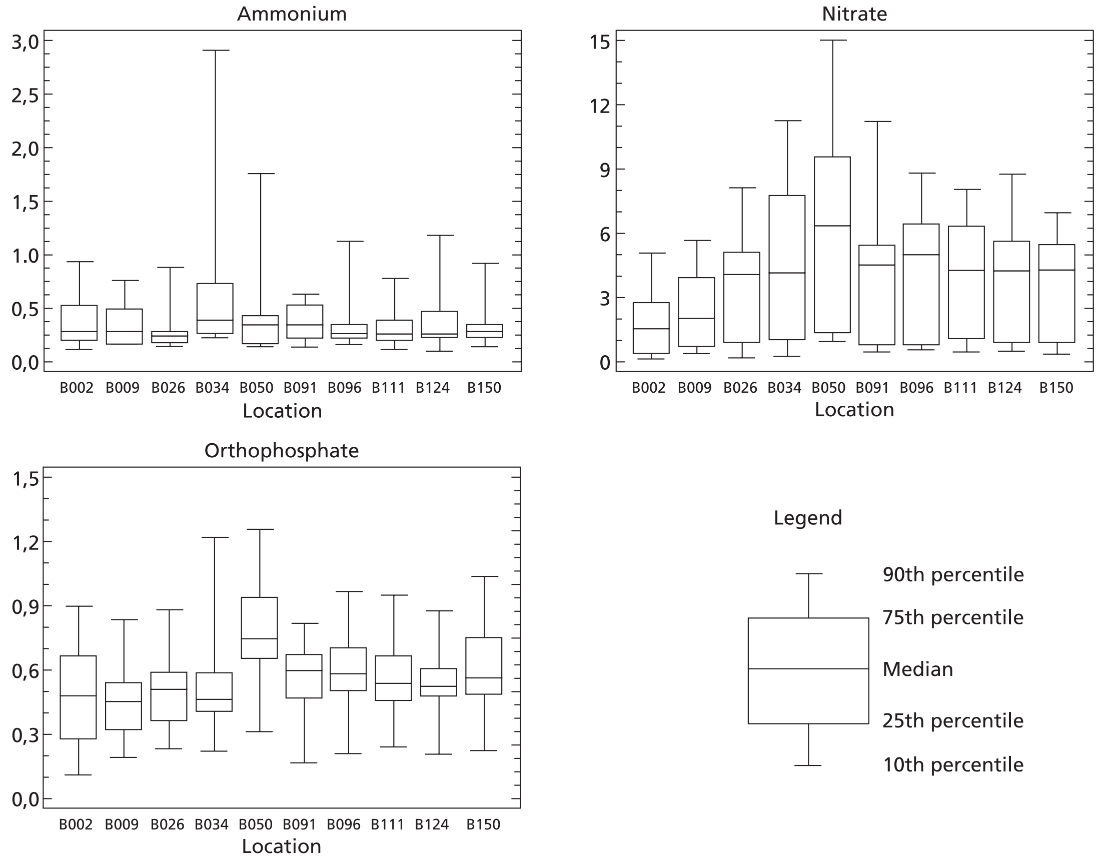


Figure 3.6 Nutrient concentrations at selected sites along the Narew river (for locations see figures 3.3, 3.4 and 3.5)

3.3.3 Nutrient concentrations and land use types

The relation between nutrient concentrations and predominant land use type in sub-catchments was studied separately. All sub-catchments were classified to one of three groups characterised by the most significant land use type and characteristic values of nutrient concentrations were calculated for those groups (see section 3.2.2). In figure 3.7 the distribution of concentrations for each group is shown by “multiple-box-and-whisker” plots.

Ammonium concentrations were low in all groups. The concentrations in the urbanisation group (median about 0.40 $\mathrm{mg \cdot l^{-1}}$) were slightly higher than concentrations in two other groups (median about 0.3 $\mathrm{mg \cdot l^{-1}}$). From all three variables nitrate concentrations were the most differentiating among the groups. The concentrations were the lowest in the forest group (median about 2 mg·l^{-1}), a little higher for the agricultural group (median about 3.6 mg·l^{-1}) and the highest for the urbanisation group (median about 8 mg·l^{-1}). Orthophosphate concentrations were a little higher in the agriculture and forest groups and relatively high in the urbanisation group. The agriculture group did not differ very much from the forest group: median about 0.5 mg·l^{-1} for the forest group and median about 0.55 mg·l^{-1} for the agriculture group, whereas the median value for the urbanisation group was about 1.2 mg·l^{-1}.

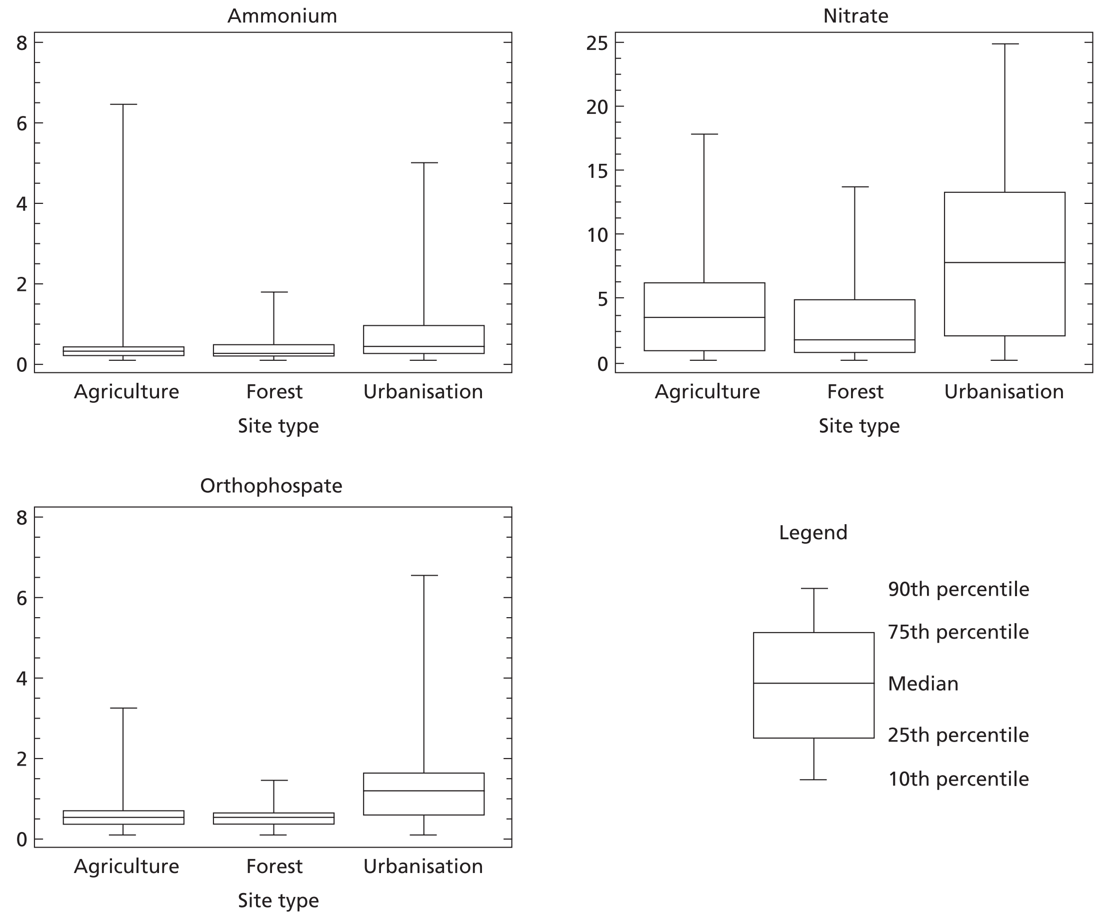
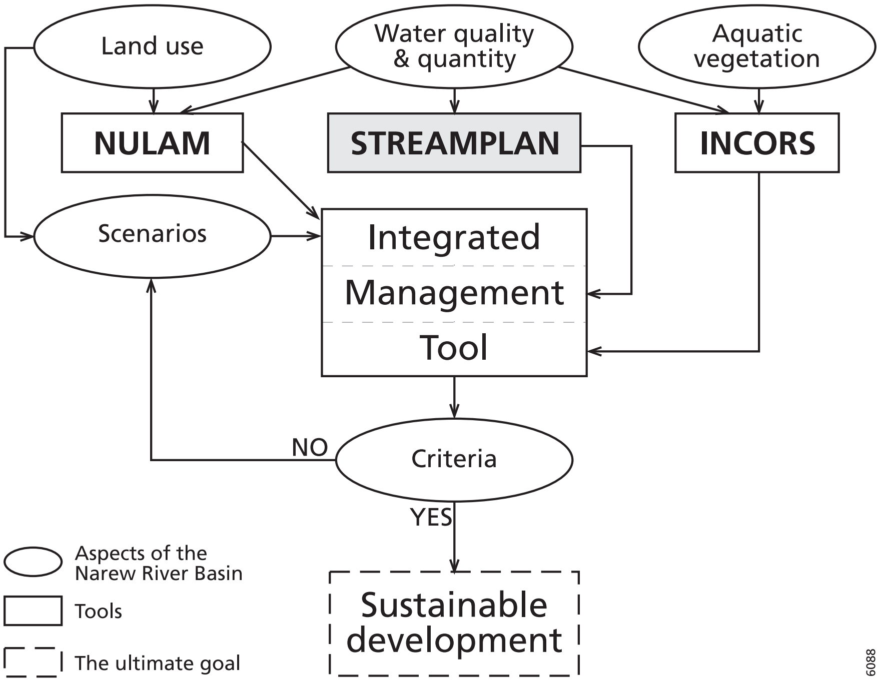


Figure 3.7 Nutrient concentrations for different site types

3.4 Conclusions

This basin wide analysis of the spatial distributions of nutrient concentrations associated with land use types provided a general insight into the concentration ranges and patterns within the basin. Generally, spatial distributions of nutrients showed increased concentrations in the downstream direction and in sub-catchments influenced by an effluent from point sources. The concentrations were slightly higher in the lower and middle parts than in the upper parts of the basin although the concentrations of the mainstream in the middle basin decreased due to a dilution by tributaries with lower concentrations (the Biebrza and Pisa rivers). Remarkably, agriculture is currently not a significant pollution source. The differences in concentration of nutrients between agricultural and forested areas were very small, which may result from the typical land use pattern in the Narew River Basin. As most arable lands are relative remote from the rivers and tributaries, their effect on water quality is less noticeable. The very extensively used grasslands (mostly for hay-making) do not bring nutrient input to the rivers either. A significant impact of point sources was observed in the basin, although downstream a remarkable decrease in nutrient concentrations occurs probably because of a combination of dilution, uptake by aquatic vegetation, aquatic soil adsorption and bio-chemical degradation processes (see also van der Perk, 1996).

At the basin scale the surface waters in the Narew River Basin were found to be of high quality when referred to water quality standards and ecological characteristics of the aquatic vegetation (Barendregt & Gielczewski, 1998), despite, an increase of nutrient concentrations in the downstream direction and downstream from point sources.


Land use
Water quality & quantity
Aquatic vegetation
NULAM
STREAMPLAN
INCORS
Scenarios
Integrated Management Tool
Criteria
NO
YES
Sustainable development
Aspects of the Narew River Basin
Tools
The ultimate goal
6088

4 ADAPTING AN IN STREAM WATER QUALITY MODEL FOR THE NAREW RIVER BASIN – STREAMPLAN

4.1 Introduction

This chapter describes a methodological approach to be used for predicting changes in the concentration of nutrients in the larger rivers in the Narew River Basin so that they can be linked to the Integrated Management Tool (IMT). Increasing nutrient concentrations are frequently reported as the major factor negatively influencing the quality of running waters (e.g. Tonderski, 1997; Van Dijk & Marteijn, 1993; Vollenweider et al., 1974; Vollenweider, 1968). Prediction of the changes in nutrient concentration in surface water expected with implementation of different basin management scenarios requires proper and sufficient tools, such as water quality computer models.

The range of computer codes for modelling surface water quality available today is enormous. Models exist for issues such as chemical transport or planning and the management of pollution sources; they cover different scales from a single field up to large river basins (Haith, 1982). In recent years there has been rapid development of water quality models such as CREAMS (Knisel, 1980), HSPF (Johanson & Kittle, 1983), QUAL2EU (Brown & Barnwell, 1987), AGNPS (Young et al., 1989), MIKE 11 (Havno et al., 1995), TRANS (Kronvang et al., 1999) and PolFlow (De WIT, 1999), to mention only a few.

For the present study I had to decide whether to use an existing model or to develop an entirely new one. I decided to adapt an existing model for the Narew River Basin since the aim of the study is to develop and implement an Integrated Management Tool, in which the water quality model is just one element. Therefore, for modelling, I use STREAMPLAN, a mathematical model, developed by an international team of researchers at the International Institute for Applied Systems Analysis in Laxenburg, Austria (STREAMPLAN Home page). This model was adapted, identified, calibrated and validated for the Narew River Basin.

STREAMPLAN is supposed to be “ready-to-use” with regard to fulfilling the defined goals designed for the water quality modelling part of this study (see chapter 1). The “ready-to-use” status could be given to the model due to:

(i) the incorporation in its structure all of three nutrient ions (ammonium-nitrogen, nitrate-nitrogen, phosphate) which were to be investigated,
(ii) its very clear structure based on spreadsheet format [EXCEL] which allows for relatively simple adjustment for a new basin or sub-catchment, an easy way to prepare input data and the possibility to use output data directly in other parts of the Integrated Management Tool,
(iii) relatively limited input data requirements and finally,
(iv) simple and effective way of schematising of river and point sources network.

This chapter presents STREAMPLAN and describes its development and adjustment for the Narew River Basin. First, the main characteristics of the model are given. Second, the characteristics of the collected database are shown and the preparations of the input data for the model are explained. Then the procedure of the model identification, both calibration and verification phases, for the Narew River Basin is elucidated and the results of this procedure are presented.

4.2 Model description

STREAMPLAN (A Spreadsheet Tool for River Environmental Assessment Management and PLANing) was built on the platform of EXCEL 5.0^{TM} program (Microsoft, 1993). It is an integrated, relatively easy to use, code allowing the analysis of alternative scenarios of quality-oriented water management at the level of a river basin. The model was created to assist scientists, water resource managers and policy makers in assessing new regional strategies for water management (De Marchi et al., 1999).

The model comprises of four basic modules: (i) the water quantity and quality simulation model, (ii) the economic model, (iii) the wastewater treatment plants model and (iv) the optimisation model (Jolma et al, 1997). In this thesis only the first module was used and its details are presented. This module was incorporated into an integrated assessment system of the quality of the aquatic environment in the river basin which consists of a GIS-based model of land use NULAM (see chapter 2), the STREAMPLAN simulation model and an eco-hydrological model INCORS (see chapter 6).

The purpose of the STREAMPLAN simulation model is to analyse the behaviour and propagation of water pollution constituents in a river basin system. Two integrated sub-modules: (i) hydraulic of river network and (ii) propagation of water pollution are used for reaching this aim.

A river network is defined as a scheme of hierarchically interlinked segments (river reaches) and nodal points (figure 4.1). The first segment of each modelled river, called in the model 'head reach', represents the head sub-catchment and is not a subject of modelling but carries initial conditions (water quality constituent concentrations and discharge) for the next downstream reach which is the first modelled one.

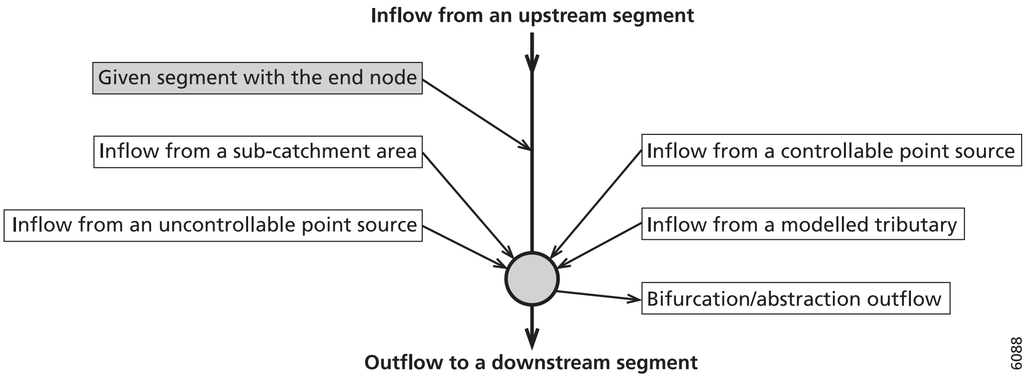


Figure 4.1 River segment concept used in STREAMPLAN model (after: De Marchi et al., 1996)

For each individually treated segment the mean velocity and mean depth in a cross-section are calculated. Additionally it is assumed that a cross-section can be described by one of two shapes: trapezoidal or semi-circular and is uniform over the whole segment. However, different shapes can be used for different segments. Calculations are performed following an assumption that the mass balance of water in the system is conserved and that flow is steady and uniform.

The second sub-module simulates up to five water quality constituents: (i) biochemical oxygen demand (BOD), (ii) dissolved oxygen (DO), (iii) ammonium nitrogen (NH_4-N), (iv) nitrate nitrogen (NO_3-N) and (v) phosphate (PO_4-P). The model is one dimensional, linear and stationary. This implies that both discharges and pollution emissions are also stationary. Several additional assumptions were made: (i) the downstream transport of pollutants is only advective with no dispersion (1-Dimensional), (ii) distributed flows and pollutant emissions such as surface and subsurface runoff and non-point source pollution are modelled indirectly as point sources, (iii) the total volume of water is completely mixed and (iv) the discharge and concentration of water quality constituents values, resulting from modelling, are calculated only for a nodal point closing a given segment. The quality model is based on the extended Streeter-Phelps equations (Thomann & Mueller, 1987). These are one of the simplest and at the same time the most often used formulas in water quality models (Kularathna & Somlyody, 1994). According to these formulas the decay of organic material (BOD), oxidation of ammonium, natural re-aeration and sediment oxygen demand are the key factors influencing the level of dissolved oxygen. The concentrations of phosphate and ammonium decrease respectively due to sediment settling and nitrification. The level of nitrate results from the balance between nitrification and denitrification.

Three different sources of water pollution are modelled: (i) industrial sources, (ii) municipal sources and (iii) non-point sources. They are represented by a single value at the end node of the reach.

The detailed description of the two simulation modules and the remaining system modules is given in the STREAMPLAN program manual (De Marchi et al., 1996).

4.3 Database

4.3.1 Water quality and quantity data

For two hydrological years (1996 and 1997) I carried out an extended water quality monitoring program, consisting of monthly water sampling at ninety four locations scattered all over the Narew basin river network. At the nine biggest pollution point sources additional water samples were taken and discharge was measured. The results of these measurements were used as the basic elements to calibrate and verify the STREAMPLAN model. The database was supplemented by data obtained from the Polish Weather Service (IMiGW). These included geomorphological characteristics of 51 cross-sectional profiles, water level and discharge data measured in these profiles on the same days when the water quality samples were collected.

During this monitoring program water samples were collected twenty times at each location. Twenty one water quality parameters were determined in these samples. These data and the pattern analysis of surface water quality (see chapter 3 and Gielczewski et al., 1998a,b) revealed that the main reason for the non satisfactory quality of surface water in the Narew River Basin, were too high concentrations of nutrients, either seasonal (NO_3) or continuous (PO_4). This matches the water quality status in the Narew River Basin observed in earlier investigations (Abrahamsen & Nielsen A/S, 1994).

From the twenty one analysed ions and chemical compounds three nutrient ions: (i) nitrate-nitrogen (NO_3), (ii) ammonium-nitrogen (NH_4) and phosphate (PO_4) were selected for further analysis and modelling. The analysis was dictated by three principal reasons: (i) for a great part of the basin, nutrient concentrations exceeded the limits allowed for water to be classified as first quality class according to Polish national standards (Water Classification, 1991), (ii) the most suitable and expected development of agriculture and tourism as the main factor of regional economical development (Taraszkiewicz, 1994) will largely influence future levels of nutrients in surface waters and (iii) development of aquatic ecosystems and their conditions depends, significantly on nutrient concentration levels in surface waters.

For calibrating and verifying the STREAMPLAN model for the Narew River Basin, data were selected of both quality (concentrations) and quantity (water levels and discharges) for two months, September 1997 and September 1996. The dataset for the first month was used to calibrate the model, and the September 1996 data were used to validate it. The chosen months were characterised by the lowest discharges among all months during the monitoring period. Thus they represented conditions of low flow during the period of vegetation growth, which are often used for modelling water quality (e.g. Drolc & Zagorc Koncan, 1996), since they reflect one of the most stressing circumstances for an aquatic ecosystem (Dakova et al., 2000).

4.3.2 Modelled river network

According to the requirements of STREAMPLAN segment concept (see figure 4.1), the entire river network of the Narew River Basin was organised into a hierarchical interlinked set of reaches with nodal points (where concentration values of water quality constituents are calculated), tributaries and point sources. The Narew basin’s river network, consisting of a dense network of rivers and tributaries, had to be simplified prior to implementation into the STREAMPLAN model. An implementation of all streams was not necessary to set up a model that allows for reaching the study aims. Additionally, it would require even a more extensive data monitoring program and cause a significant increase of computation time. Before this schematisation was done three questions had to be answered: (i) which rivers should be incorporated into the set of the directly modelled rivers, (ii) which other rivers should be taken as a separate tributaries and finally (iii) which point sources should be included into the model?

Directly modelled rivers

For modelling purposes, it was important to choose a sufficiently large part of the river network within the entire basin. The river network was seen as a set of rivers on which the model was based. The set was the result of a combination of model requirements and the assumptions made in connection with the sustainability approach. The set consisted of the Narew river itself and its three largest tributaries: the Biebrza, Pisa (downstream from the Great Mazurian Lakes District) and Suprasl rivers and two smaller tributaries: Orzyc and Omulew (figure 4.1 and table 4.1). This basic structure reflects sufficiently the character of the basin's river network and allows best for attaching the model results with the other parts of the Integrated Management Tool (NULAM see chapter 2 and INCORS see chapter 6).

Obviously, the set had to include the largest tributaries because they discharge so much water into the Narew river and therefore have a significant impact on its water composition. Moreover, the most valuable aquatic ecosystems are situated along some stretches of these rivers. These extend along almost the entire course of the Biebrza river (Wassen, 1995) and the south-north stretch of the upper course of the Narew river (Banaszuk, 1996) and some stretches of the Pisa river.

Table 4.1 Mean annual discharge ($m^{3\cdot}s^{-1}$)of the Narew river and its main tributaries in the period 1951 – 1980

	Location	Narew	Tributaries
Narew	upstream from Suprasl	19.82	
Suprasl	Zoltki		8.61
Narew	upstream from Biebrza	33.62	
Biebrza	Burzyn		33.36
Narew	upstream from Pisa	75.13	
Pisa	Dobrylas		26.73
Narew	upstream from Omulew	110.00	
Omulew	Bialobrzeg Blizszy		10.89
Narew	upstream from Orzyc	128.38	
Orzyc	Makow Mazowiecki		9.81

Source: Gromiec (eds.), 1992

The smaller tributaries were chosen for completely other reasons. Firstly, they were more polluted compared to the main river, the differences in concentration values being most significant during low flow periods (table 4.2). Thus their negative influence on the water quality was relatively large, despite their low discharge. Secondly, they discharge into the lower course of the Narew close to the outlet where drinking water abstraction is planned.

Table 4.2 Concentrations of phosphate and nitrate-nitrogen ($mg \cdot l^{-1}$) at the mouths of the Omulew and Orzyc rivers and in the Narew river before confluence with those rivers (hydrological years 1996-1997)

	Location	PO_4	NO_3	PO_4
		annual	annual	IX 1997
Narew	Ostroleka	0.521	3.921	0.497
Omulew	Bialobrzeg Blizszy	0.745	1.851	0.935
Narew	Nowy Lubiel	0.583	3.423	0.497
Orzyc	Magnuszew Maly	0.706	4.833	0.715

The courses of rivers selected for modelling were split into reaches based on the location of gauge stations from the National Weather Service network placed along these rivers. The set of monitored locations (see section 4.3.1) included all of the splitting points. Thus, for all these locations cross-sectional profile, discharge and water quality data were available.

Point sources

Point sources to be included in the model were selected according to two successive conditions: (i) location in relation to rivers chosen for modelling and (ii) the size of the point source. Point sources discharging directly to modelled river reaches were selected to be included in the model structure. Only these points could be effectively modelled in the STREAMPLAN model. For the second condition the threshold was set for 10000 inhabitants connected to a point source. This number was relevant for the Narew river basin since smaller point sources had a very distance-limited impact on the water composition of relatively larger rivers compared to those selected for modelling (van der Perk, 1996; Abrahamsen & Nielsen A/S 1994). Finally, nine of the largest point sources were selected (table 4.3).

Table 4.3 Point sources selected for the modelling

	Discharge	Population connected
	$m^3 \cdot s^{-1}$	1000 person
Lapy	0.1	35.5
Bialystok	0.85	225.5
Elk	0.28	55.0
Grajewo	0.12	18.5
Lomza - Piatnica[a]	0.14	61.5
Pisz	0.04	16.0
Ostroleka	0.47	50.5
Makow Mazowiecki	0.04	10.5

[a] Two points sources discharging at one location

Separate tributaries

For selecting the remaining rivers to be included in the modelling as separate tributaries the size of a sub-catchment was taken as a criterion. This threshold was arbitrarily set for 1% of the total basin area, which equals ca. 270 km^2. There was one exception to this rule. The river Biala, in spite of not fulfilling the above requirement, was included in the set of selected tributaries due its importance for overall water quality composition. This is because the biggest city in the whole Narew basin, the city of Bialystok, covers almost the entire sub-catchment of the Biala river. All together this resulted in the selection of 18 rivers (table 4.4).

Table 4.4 Tributaries with a sub-catchment larger than 270 km^2 selected as separate tributaries

	Sub-catchment size in km^2	River length in km
Narewka	365.47	35.6
Orlanka	477.48	33.4
Sokolda	463.19	39.4
Biala[a]	108.02	29.9
Neresl	278.67	38.4
Slina	467.78	34.4
Sidra	226.17	21.3
Rospuda – Augustowski Canal	1347.74	85.5
Brzozowka	694.45	52.0
Lega – Jegrznia	857.63	109.7
Wissa	516.66	41.6
Gac	442.75	36.7
Skroda	380.77	48.7
Ruz	305.74	30.5
Szkwa	487.06	69.5
Rozoga	491.48	74.8
Sawica	403.94	46.6
Orz	616.81	57.3

[a] Included because it is the drainage area for the city of Bialystok

Rivers with their sub-catchment areas below the set limit were included into differential sub-catchments (see section 4.3.3) of particular reaches of modelled rivers.

The final set consisted of in total 27 modelled river reaches and 7 head reaches representing the main streams of the Narew River Basin river network i.e. the Narew river itself as well as its main tributaries Suprasl, Biebrza together with Elk (named Rudzki Canal in the downstream reach), Pisa. Omulew, Orzyc rivers and 18 the biggest of remaining tributaries and also the nine biggest pollution point sources, Lapy, Bialystok, Elk, Grajewo, Lomza - Piatnica, Pisz, Ostroleka, Makow Mazowiecki (figure 4.2).

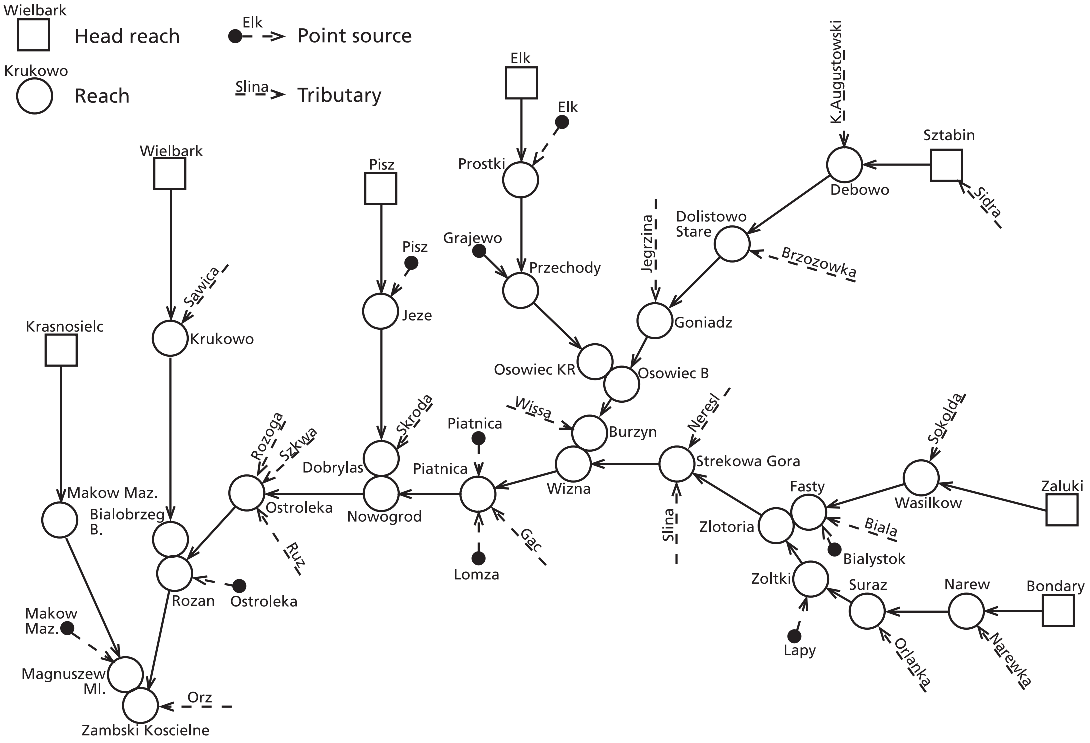


Figure 4.2 Scheme of reaches in the river network of the Narew River Basin used in the STREAMPLAN model

4.3.3 Differential sub-catchment calculations

The next step to build the database for the modelling exercise (model calibration and verification) was to calculate nutrient concentration values in and discharge of water flowing from the differential sub-catchment of a given reach. For a given reach, areas adjacent to it with water flowing directly into it and sub-catchments of tributaries not selected for modelling (see section 4.3.2) were understood as being a differential sub-catchment. To carry out these calculations mass conservation of nutrient loads including self-purification processes (denitrification, sediment settling) in a given reach was assumed (Jarzabek & Twarog, 1998). The equations describing this relation were:

$$C_r Q_r = k(C_u Q_u + C_t Q_t + C_p Q_p) + C_d (Q_r - Q_u - Q_t - Q_p) \tag{4.1}$$

and

$$Q_d = Q_r - Q_u - Q_t - Q_p \tag{4.2}$$

where:

C_r, C_u, C_t, C_p – concentrations measured respectively: at the end node of a given reach (r), at the end node of the upstream reach (u), at the mouth of the tributary (t), and on the point source effluent (p), ($\mathrm{mg \cdot l^{-1}}$).

Q_r, Q_u, Q_t, Q_p – discharges measured respectively: at the end node of a given reach (r), at the end node of the upstream reach (u), at the mouth of the tributary (t), and on the point source effluent (p), ($m^3 \cdot s^{-1}$).
k – parameter describing natural biodegradation (self-purification) process.
C_d, Q_d – requested values of, respectively, nutrient concentration and discharge inflow from differential sub-catchment between the end node of the upstream reach (u) and the end node of the given reach (r).

When carrying out these calculations certain difficulties arose relating to the unsatisfactory quality of discharge measured in the gauge station profiles, i.e. non-balancing of discharges in the main stream and tributaries. This was in particular a problem in the middle course of the Narew river, from Zoltki gauge station to Wizna gauge station, as well as in the middle course of the Biebrza river, the area where this river joins the Jegrznia river and the Rudzki Canal. Balance discrepancies have been earlier observed and reported for these sub-catchments (Herbst, 1971). The Polish Committee of Scientific Research has a current project to find and explain the reasons for this problem (KBN, 1998). In this thesis this problem was solved using suggestions made by the unit of Polish Weather Service in Bialystok, the discharge data provider (Dobrowolski, 1994). The assumption is that within +/- 10% limit of measured discharge the probabilities of discharge are the same. Application of the above described assumption, following equations (4.1) and (4.2), resulted in balancing the nutrient loads for all modelled reaches. However, the results achieved in adjusted reaches (referred in the text as so-called “corrected”) should be treated with caution.

4.3.4 Cross-sectional data

The final step in creating the database was to calculate the characteristics, the base length and the slope of sides, of trapezoidal approximations of cross-sectional profiles of the river beds required by the STREAMPLAN model. The trapezium base length for each gauge station profile was measured based on a digital picture of the cross-sectional profile with the measured water level. Then following the principle of conservation of area of wetted cross-sectional profile, an angle of the slope sides for given the base length was calculated. The results of these calculations are given in Appendix A.2.

4.4 Model calibration and validation

Calibration of the STREAMPLAN model was done to determine the values of the parameters of the equations that describe the changes in concentration of the ions analysed.

Considering that a column of water contains n water quality constituents characterised by concentrations $C_1, C_2,\ldots, C_n$, in STREAMPLAN it is assumed that the rate of change of the concentration of constituent i is a linear function of concentrations of all water quality constituents. The general form of this function is described by the following equation:

$$\frac{d\overline{C}(t)}{dt} = \overline{k} \cdot \overline{C}(t) \tag{4.3}$$

where:

$\overline{k}$ - the parameter matrix containing coefficients for water quality constituents

$\overline{C}(t)$ - the concentration vector.

The form of the function that describes changes in concentration of a particular water quality constituent is an explicated and modified form of equation (4.3). Since, the STREAMPLAN model was used to analyse the behaviour of ammonium nitrogen, nitrate nitrogen and phosphate in the river network three new relation functions (equations 4.4, 4.5 and 4.6) describing the changes in the concentration of these ions were developed. They take the following form:

$$\frac{dC_1(t)}{dt} = -k_1 C_1(t) \tag{4.4}$$

$$\frac{dC_2(t)}{dt} = k_1 C_1(t) - k_2 C_2(t) \tag{4.5}$$

$$\frac{dC_3(t)}{dt} = -\frac{1}{H} k_3 C_3(t) \tag{4.6}$$

where:

$C_1(t)$ - the concentration of ammonium nitrogen,

$C_2(t)$ - the concentration of nitrate nitrogen,

$C_3(t)$ - the concentration of phosphate,

k_1 - the decay rate of ammonium nitrogen, due nitrification process,

k_2 - the loss rate of nitrate nitrogen, due to denitrification process,

k_3 - the loss rate of phosphate, due to sediment settling process,

H - mean depth of cross-sectional profile

From equations (4.4), (4.5) and (4.6) it appeared that calibration of the model required the specification of three parameters: coefficients k_1, k_2, k_3, describing the loss rate of particular water quality constituents in a given reach of the river network.

In the process of model calibration and validation several assumptions were made on the assessment of the model accuracy and the procedure of carrying out calculations:

- for calibration, the loss rate coefficients were optimised for each of the water quality constituents assuming an achievement of +/- 15% agreement level of measured (September 1997) and calculated concentrations in particular reaches;
- for validation, the calculated concentration values, with use of the calibrated loss rate coefficient values, must be in agreement with measured values (September 1996) with a maximum difference of +/- 25%;
- the loss rate coefficients were assumed to be in relation to longitudinal slopes of water level;

- differences between calculated and measured concentrations are allowed to exceed the agreement levels, applied in calibration and validation phases for the “corrected” reaches, affected by large mistakes in loads balancing (see section 4.3.3);
- also the loss rate coefficients could have different values for the “corrected” reaches than those assigned to them according to the value of longitudinal slope of water level in a given reach;
- for nitrogen compounds concentrations of ammonium-nitrogen were calculated firstly and then were followed by calculation of nitrate-nitrogen concentrations.

Used levels of agreement (+/- 15% for calibration and +/- 25% for validation) were arbitrary, since no relevant literature studies could be found. These levels were assumed to be sufficient in case of a relatively large basin area and an event character of the phenomena. However, it might be assumed that the applied agreement levels were in proper relation to those published in literature with reference to water quality modelling but for catchments of other scales (e.g. Johnes 1996; Rousseau et al., 2000).

The values of the loss rate coefficients were related to the longitudinal water level slope in a river. The steeper this slope is the faster the flow is. This implies shorter water retention time in a reach and therefore processes like i.e. denitrification and sedimentation run at slower pace (Heathwaite, 1993; Hill, 1988). Thus, the loss rate of water quality constituents is smaller and concentrations are decreasing at longer distance. The threshold value of the longitudinal water level slope was set to 0.2 for the rivers in the Narew River Basin. The calibrated values of the loss rate coefficients were lower for the reaches characterised by higher slope (table 4.5). For several “corrected” reaches (6 ammonium-nitrogen, 3 for each nitrate-nitrogen and phosphate) applied values of the loss rate coefficients were calibrated at different values (see Appendix A.2) without following the dependence given in table 4.5.

Table 4.5 Calibrated values of loss rate coefficients in relation to longitudinal slope of water level

	Longitudinal slope of water level	
	< 0.2	≥ 0.2
Coefficient k_1 (NH_4)	1.1	0.95
Coefficient k_2 (NO_3)	0.3	0.25
Coefficient k_3 (PO_4)	0.225	0.13

The sensitivity of the model to its parameters was assessed by performing several model runs with different sets of the loss rate coefficients. All the coefficients one at a time were changed all together seven times respectively by 10, 20, 50, 100 and –10, -20, -50 percent of their values estimated in the calibration phase. The concentrations calculated at every run for all modelled locations were compared to concentrations measured at all locations in September 1997 (calibration data set) and the relative errors were calculated for every location. Then, the relative errors were averaged over the entire Narew River Basin and plotted against changes in the loss rate coefficients (figure 4.3).

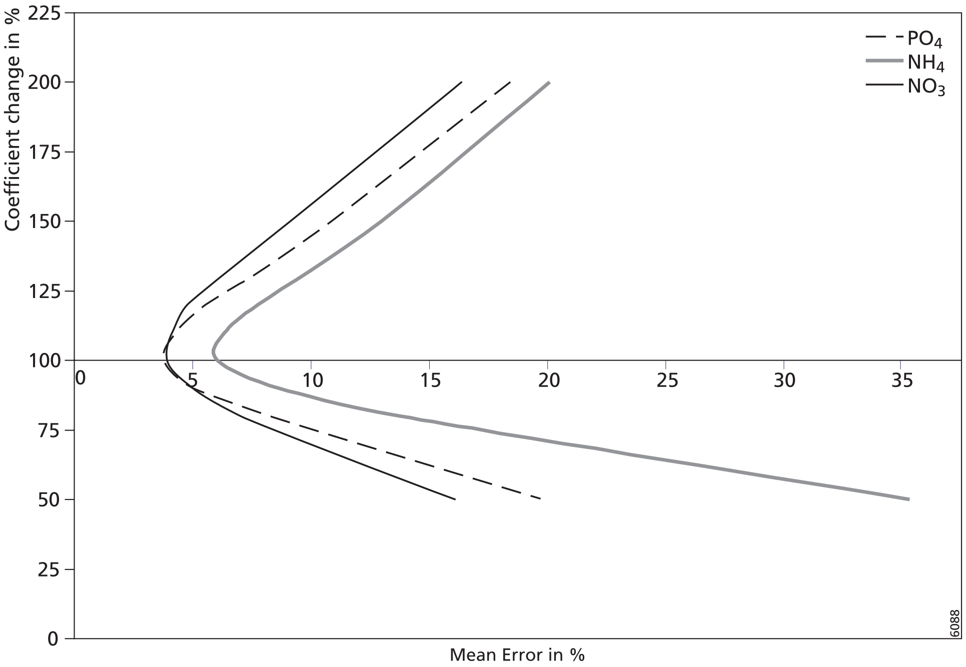


Figure 4.3 Mean error (%) of the measured and calculated concentration values with different sets of the loss rate coefficients

Nitrate-nitrogen was the least sensitive part to the change of the loss rate coefficient. The coefficient change by –50% resulted in decrease of the mean accuracy of the calculated concentrations by 12% (from 4.1% mean error for the calibrated value of the coefficient to 16.1% mean error for the –50% changed coefficient) when for the +100% change of the coefficient the decrease in the mean accuracy was estimated for 12.3%.

Slightly more sensitive to the change of its loss rate coefficient was phosphate, which mean accuracy changed by 15.9% for the –50% change (from 3.8% mean error for the calibrated coefficient value to 19.7% mean error for the changed coefficient) and by 14.6% for the coefficient changed by +100%.

The highest decrease in the accuracy of the results, especially when lowering the loss rate coefficient, was observed for ammonium-nitrogen. The change of this ion loss rate coefficient by –50% reduced the mean calculated concentration results by 29.3% (from 6% mean error for the calibrated value of the coefficient to 35.3% mean error for the –50% changed coefficient). The increase of the coefficient for ammonium-nitrogen had less impact on the results accuracy and was comparable to phosphate with the mean accuracy decrease by 14.1% for +100% value of the loss rate coefficient.

The suitability of the STREAMPLAN model as a relatively reliable tool for the prediction of changes in water quality with reference to nutrients in the conditions similar to those for which the model was verified i.e. summer low flow period was tested by the model identification i.e. calibration and validation results. These results, gathered and shown at the scale of the entire basin, are given in table 4.6. However, it must be noted that significant differences among the three nutrients were observed, despite the results of both model calibration and validation being satisfactory and comparable to results reported in other studies on similar problems and catchment sizes.

Table 4.6 Percentage values of mean comparative difference and standard deviation of measured and calculated concentrations of modelled nutrients for all reaches

		Calibration		Validation	
		Mean diff.	STD	Mean diff.	STD
nitrate nitrogen	27 reaches	3.9	4.8	4.8	4.2
(NO_3)	24 reaches[a]	3.2	4.1	4.1	3.6
ammonium	27 reaches	6.0	15.6	15.6	17.4
nitrogen (NH_4)	21 reaches[a]	4.3	11.1	11.1	12.5
phosphate	27 reaches	3.8	5.3	5.3	8.2
(PO_4)	24 reaches[a]	3.1	3.4	3.4	3.8

[a] Except for “corrected” reaches where non-standard values of loss rate coefficient were used

The best results of the model calibration (see also figure 4.4) were achieved for phosphate with the mean error between measured and calculated concentrations, estimated for 3.8%. In the validation phase the results obtained for phosphate were somewhat worse and the mean difference of measured versus calculated concentrations was 5.3%. For the nitrate-nitrogen the identification of the model was almost as good as for phosphate in the calibration phase where the mean error was estimated for 3.9%. However, for this ion the model performance was the best of all in the validation phase with this phase results (mean error of 4.8%) the most comparable to the calibration results. In case of ammonium-nitrogen the model performed less accurately than for phosphate and for nitrate nitrogen, considering the agreement level of measured and calculated concentration and the results achieved in calibration and validation phases. It was particularly evident for the validation phase that the results were apparently worse than the calibration phase results and only just fell within the assumed agreement levels in the model.

A substantial effect on the accurateness of results, at the scale of the entire basin, was achieved by the rejection of “corrected” reaches. The rejection attempt is justified by a number of uncertainties concerning reliability of available input data (see section 4.3.3) and by calibration of the loss rate coefficients with non-standard values. The exclusion of these reaches gave the best improvement of the model performance for ammonium-nitrogen and especially within the validation phase. Omission of “corrected” reaches was less important with regard to phosphate and nitrate-nitrogen parts of the model, mainly due to good model performance already for all reaches. However, the results of the validation phase for phosphate were improved considerably when “corrected” reaches were excluded from calculations.

Equally important to assess the usefulness of the model is to analyse the results achieved for particular reaches of the river network. Figure 4.4 shows the findings of such analyses in reaches of the Narew river, from the first modelled nodal point Narew until the most downstream nodal point Zambski Koscielne, which is the main axis of the whole basin.

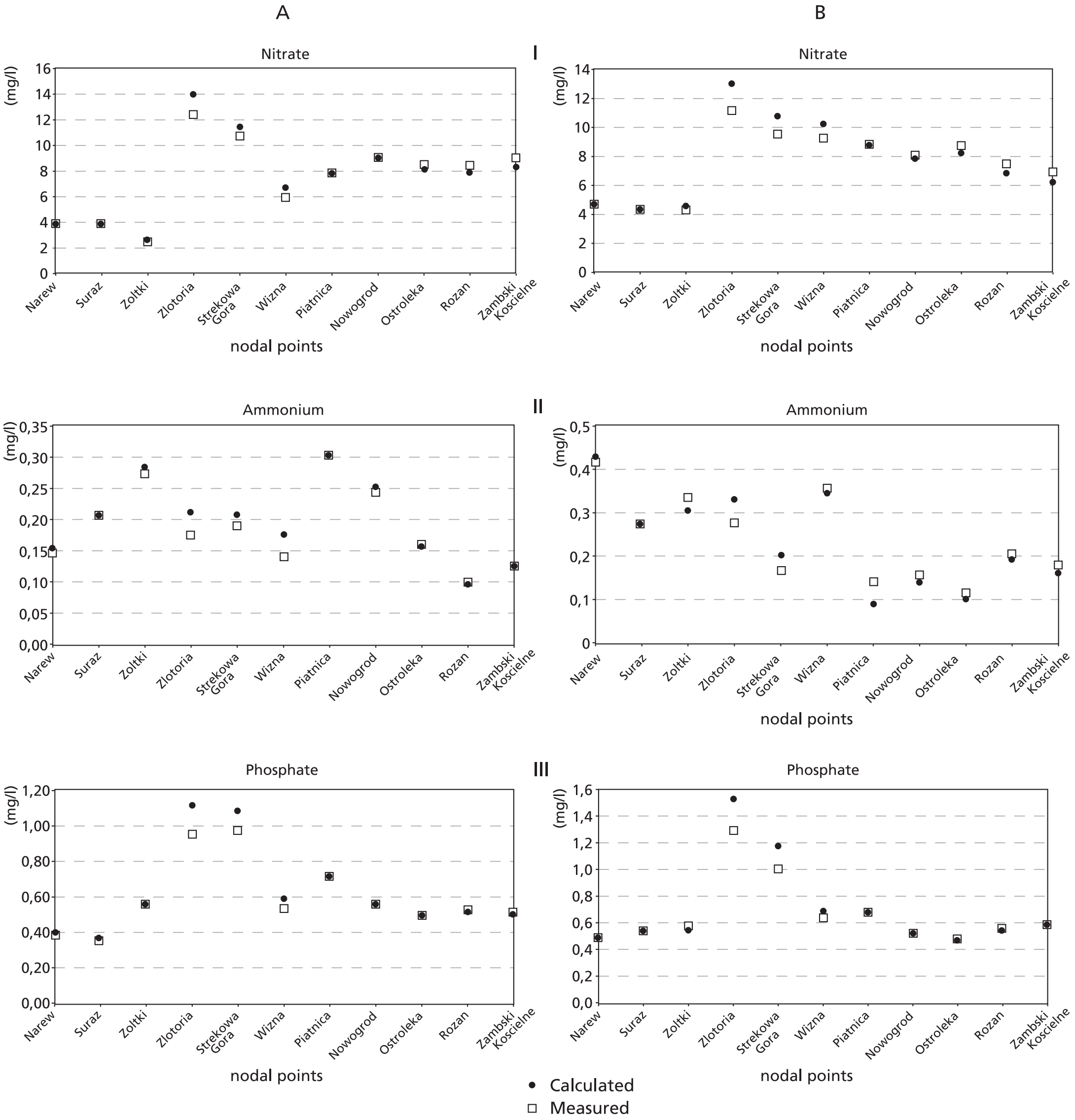


Figure 4.4 Results of STREAMPLAN model identification at nodal points along the Narew river: A) calibration: (I) nitrate, (II) ammonium, (III) phosphate; B) validation: (I) nitrate, (II) ammonium, (III) phosphate

For all three ions the calibration of the model gave the best results for the upper course of the river (between nodal points Narew and Zoltki) and for the lower courses (downstream of Piatnica nodal point), with well matched calculated and measured concentrations. For the rest of the Narew river (between nodal points Zlotoria and Wizna) calculated concentrations were overestimated compared to measured ones. The possible explanation of the worse results in this stretch is that it consists of “corrected” reaches. Moreover, Zlotoria and Wizna reaches receive the input from respectively the Suprasl and the Biebrza rivers which themselves contain some of the “corrected” reaches. The same pattern as in the calibration results was observed only for phosphate in the results of the model validation. The differences in measured and calculated concentration of nitrogen ions were in general overestimated in the upper course (between Narew and Wizna nodal points) and underestimated in the entire river stretch downstream of Wizna (between nodal points Piatnica and Zambski Koscielne). The model appears to estimate the concentrations correctly, in particular the low range concentrations are modelled fairly well.

The graphs of figures 4.5, 4.6 and 4.7 present relative errors (%) of measured and calculated concentrations for both calibration and validation phases of the STREAMPLAN model identification at nodal points along the Narew river. For all three water quality constituents it might be concluded that the best results (the smallest errors) were achieved for the upper and for the lower course of the Narew river. For these reaches the calibration errors stayed within +/-10% range for nitrogen compounds and +/-5% range for phosphate. Respectively the validation errors were observed within +/-15% range for ammonium and nitrate and +/-10% range for phosphate. For the middle course of the river, from the nodal point of Zoltki to the nodal point of Wizna, the model results were poorer which was caused by troubles with the water discharge balance and the resulting discharge corrections applied for some of the reaches (see section 4.3.3).

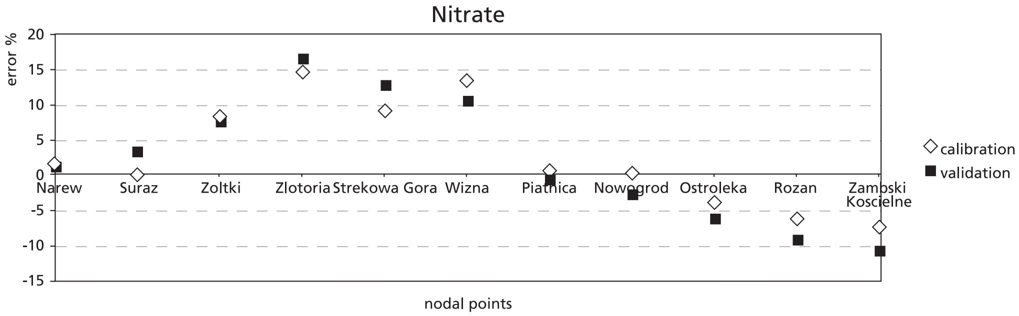


Figure 4.5 Comparison of relative errors (%) of measured and calculated nitrate concentrations between calibration and validation phases of the STREAMPLAN model identification at nodal points along the Narew river

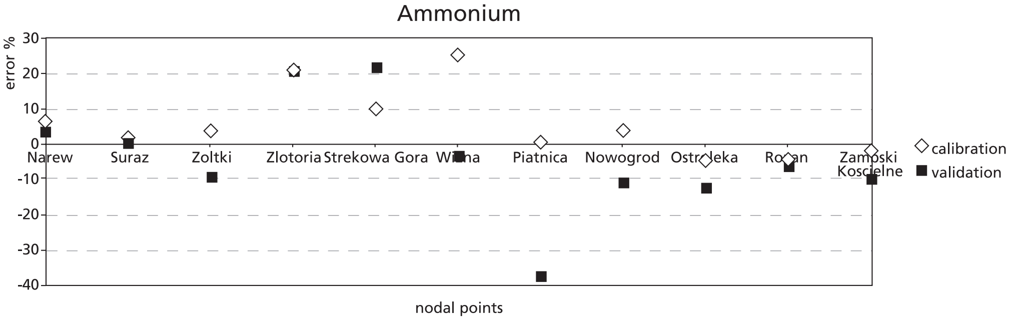


Figure 4.6 Comparison of relative errors (%) of measured and calculated ammonium concentrations between calibration and validation phases of the STREAMPLAN model identification at nodal points along the Narew river

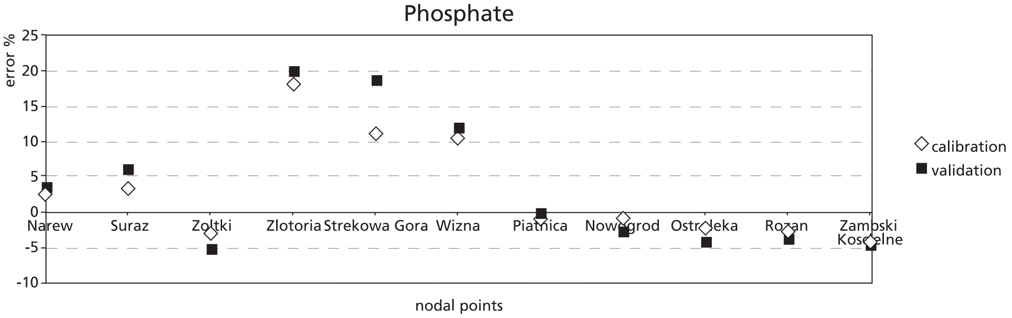


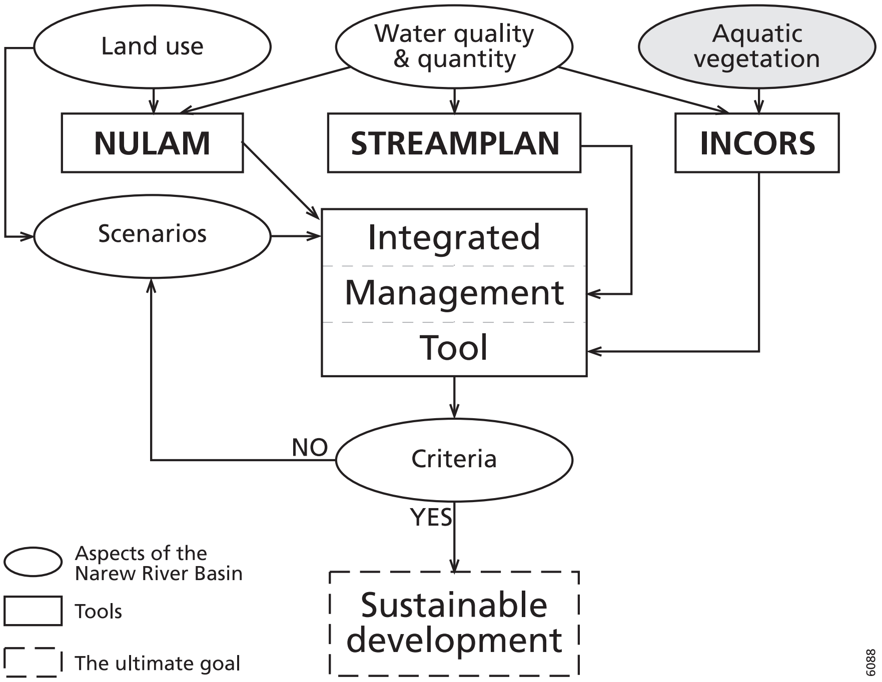
Figure 4.7 Comparison of relative errors (%) of measured and calculated phosphate concentrations between calibration and validation phases of the STREAMPLAN model identification at nodal points along the Narew river

Based on the analysis of all graphs several general conclusions concerning the whole modelling procedure could be drawn:

- the accuracy of the assumptions for both calibration (+/- 15% difference between measured and calculated concentration values) and validation (+/- 25% difference of values) phases were borne out, except for the “corrected” reaches;
- distinctly better model results were obtained in the upper course (between Narew and Zoltki nodal points) and in the lower course (between Piatnica and Zambski Koscielne nodal points) than in the middle course of the river, between Zlotoria and Wizna nodal points. The middle course is the part of the river with the largest quality problems in the available data;
- the general tendency of overrating calculated concentration values in the upper course of the river and underestimating these values in the lower course was observed;
- the model performed best with regard to phosphate and slightly poorer for nitrogen ions, which fits the tendency observed for the whole catchment area (table 4.6).

4.5 Discussion

To design and realise water management aiming at sustainable development of the basin requires proper tools suitable for the assessment of the influence of applied water management on water quality and the aquatic ecosystems. One of the essential elements in this is the possibility to model water quality. The STREAMPLAN model fulfilled the requirements of this study and appeared to be an appropriate tool. It was used to model the nutrient concentrations in low flow summer conditions in the Narew River Basin and might be applied to other basins characterised by similar hydrological, climatic and geomorphologic features. The confirmation of this possibility is given by the model identification results which were in agreement with the published results on the application of the model for water quality modelling in other large European rivers such as the Rhine and Elbe (De Wit, 1999), Sava (Drolc & Zagorc Koncan, 1996), Nitra (Breithaupt & Somlyody, 1994), or Zala (Somlyody, 1986). Additional factors to chose this model are a clear structure based on a commonly used spreadsheet program, a relatively small number of required input data, a simple concept of given river network schematisation and a limited number of calibration parameters. Thus, it fulfilled the demands for the water quality model to be part of an integrated management tool (IMT) proposed in this thesis especially for the planning and scenario studying purposes.


Land use
Water quality & quantity
Aquatic vegetation
NULAM
STREAMPLAN
INCORS
Scenarios
Integrated
Management
Tool
Criteria
NO
YES
Sustainable development
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5 LINKING ENVIRONMENTAL VARIATION WITH VEGETATION IN THE NAREW RIVER BASIN

(Adapted from A. Barendregt & M. Gielczewski “Linkage of environmental variation with vegetation in the catchment area of Narew River” PAN 458, Warsaw, 1998)

5.1 Introduction

An essential element in the procedure for preparing the hydro-ecological component of the Integrated Management Tool (IMT) was information on the present condition of aquatic ecosystems in the Narew River Basin. Aquatic ecosystems were assessed by biodiversity and the abundance of aquatic plants and by the investigation of spatial relationships in situations where certain aquatic ecosystems were found. The biotic variation in the aquatic vegetation was assessed and a study was made of the environmental variation in landscape, water quality and quantity and the linking of vegetation to this environmental variation.

In this chapter a database of water quality and other abiotic variables and aquatic vegetation is analysed and discussed in relation to the question: which spatial patterns in vegetation and abiotic site factors of riverine aquatic vegetation are current in the Narew River Basin? The database is also used to develop an empirical statistical species response model (see chapter 6).

Many lowland rivers in Europe are contaminated and have lost their characteristic biodiversity. This might be due to a physical change in the water system by diking the river and digging channels or due to chemical water pollution (Moss, 1988). The chemical shift can have different causes: (i) polluted waste water from industry, (ii) nutrients in sewerage water from housing, (iii) nutrients and pesticides from agricultural areas and (iv) nutrients from drained organic soils with mineralization. In most rivers in Europe these problems are co-exist, so that the different causes and their results cannot be separated.

The Narew River Basin, where industry is scarce and the population is low, provides a good opportunity to investigate relatively undisturbed relations in a lowland river. In national and regional policy it is aimed to preserve these undisturbed conditions, by establishing a region favourable for sustainable land use (‘the Green Lungs of Poland') (Taraszkiewicz, 1994). The many National Parks and extensive nature areas in the catchment of river Narew, coupled with almost the absence of human impact in the physical hydrologic river system, ensure that the Narew is a fine example of an undisturbed lowland river.

Because, the Narew is an example of a relatively undisturbed river in a landscape rich in nature, it offers the opportunity to determine the variation in vegetation in relation to the environmental conditions and how the origin of this variation can be explained by natural processes or by human influences.

To investigate those variations, data were collected on vegetation (see section 5.3.1) and on water chemistry (see section 4.3.2); these were examined and analysed and according to the collected data a new classification of vegetation composition was proposed that provided a useful input to the IMT.

5.2 Methods

All watercourses of the Narew River Basin were visited in the first week of July 1997, excluding the Great Mazurian Lake area since these locations represent lake systems and not river ecosystems. At 116 locations (see figure 5.1) full descriptions of the conditions in the river were made along a 50 metre section of the river, including both shorelines. These locations were chosen to include the full range of the spatial and ecological variation present in the catchment area and were considered to represent the total variation. Sampling sites in the former river beds (oxbows) along the rivers, where many times Watersoldier (*Stratiotes aloides*) (taxonomy in this thesis according to Van der Meijden et al., 1990) dominates and nutrient rich conditions prevail (Gepp et al., 1985; Barendregt & Wassen, 1994) were excluded, since they do not contain flowing river water.

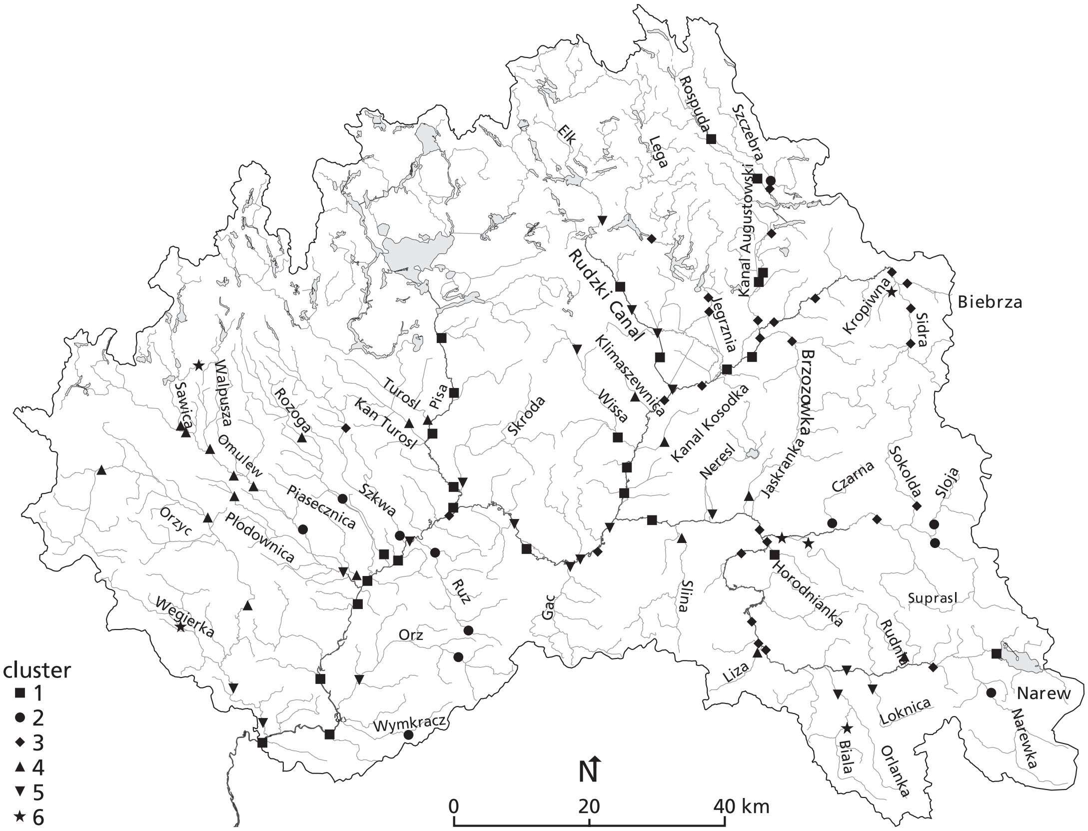


Figure 5.1 Vegetation clustering in the Narew River Basin

At the 116 sites sampled water samples were taken from the stream and analysed in the laboratory for acidity and major ions, including the mineral nutrients, with a Continuous Flow Auto-analyser and Inductivity Coupled-Plasma analysis (see chapter 3). The recording of the vegetation was done in two categories: (i) the aquatic vegetation in the streaming part of the river (excluding the shore), and (ii) the vegetation at the shore lines still in contact with the surface water. The vegetation recordings included the hydrophytes and phreatophytes (cf. Londo, 1988), as these are directly dependent on groundwater or surface water present in the rooting zone. The abundance of all species present was recorded according to the Tansley-scale. The collected vegetation data were clustered with the program FLEXCLUS (Van Tongeren, 1986). In addition, values in discharge and stream velocity were derived from data taken from fifty five locations monitored by the Polish Weather Service and from data recorded during the field work devoted to collecting data for an unit areal discharge calculations used in modelling of nutrient loads in the sub-catchments. (see chapter 2).

5.3 The biotic variation in the aquatic vegetation

Several investigations have been carried out to determine which macrophytes are present in Polish rivers (e.g. Pachuta, 1990; Dabkowski & Pachuta, 1990). From these studies the patterns of frequency occurrence of these species are known. In addition, the life strategies of the macrophytes are also known. However, a distinct description of the types of aquatic vegetation in different parts of a river and the influence of pollution could not be found.

For this reason we have created a new classification with the collected vegetation data. In total 109 species are present in the final datasets. The vegetation data were clustered with the program FLEXCLUS and the resulting clusters from the dataset with the vegetation in the stream were comparable with the clusters from the shorelines. Since the cluster sets resulting from both datasets resembled each other and to reduce the information to a primary classification, the two datasets were united by taking the highest Tansley-value for each present species at the location in the datasets. The clustering was continued until six internal and external homogeneous clusters remained. These clusters are plotted in figure 5.1 and have been summarised in table 5.1.

The clusters appeared to describe three groups of vegetation types: clusters 1, 3 and 5, clusters 2 and 4 and isolated cluster 6. Cluster 1, 3 and 5 are characterised by the presence of the aquatic species *Nuphar lutea* (Yellow Water-lily) and the semiaquatic species *Butomus umbellatus* (Flowering-rush). These three clusters are well differentiated from each other. Cluster 5 is poor in species (average 12.2) compared to the others (17.9 and 17.2) and has no own characteristic species. It appears to be the cluster without the characteristic species such as *Potamogeton perfoliatus* (Perfoliate Pondweed) and *Myriophyllum verticillatum* (Whorled Water-milfoil).

Table 5.1 Indication of the vegetation types (clusters) by a selection of plant species with their weight in clustering (characteristic species bold; only values > 0.15 are shown)

Cluster	1	3	5	2	4	6
Number of relevées	28	30	20	13	19	6
Mean number of species	17.9	17.2	12.2	14.3	14.5	14.3
Nuphar lutea	**1.46**	**3.03**	**1.55**	0.85	0.68	-
Butomus umbellatus	**1.93**	**1.47**	**1.50**	-	0.63	0.67
Potamogeton perfoliatus	**1.36**	**1.73**	-	-	-	0.33
Ceratophyllum demersum	**0.57**	**0.63**	-	-	-	0.17
Myriophylum verticillatum	**0.36**	**0.23**	-	-	-	-
Hydrocharis morsus-ranae	**0.46**	**0.33**	-	-	0.16	-
Ranunculus fluitans	**0.57**	-	-	-	-	-
Potamogeton nodosus	**0.71**	-	-	0.23	-	-
Potamogeton trichoides	**0.32**	-	-	-	-	-
Potamogeton lucens	0.89	**1.93**	-	0.31	-	-
Phragmites australis	0.29	**1.53**	0.35	-	-	0.67
Acorus calamus	0.61	**1.20**	-	-	0.21	0.50
Typha angustifolia	-	**1.13**	-	-	-	-
Nymphaea alba	-	**0.40**	-	-	-	-
Elodea canadensis	0.50	0.50	0.55	**2.38**	**2.84**	0.33
Lemna trisulca	0.68	0.50	-	**1.15**	**1.79**	-
Ranunculus circinatus	0.25	-	-	**1.08**	-	-
Callitriche species	-	-	-	**0.92**	-	0.83
Carex rostrata	-	-	-	**0.31**	-	-
Equisetum fluviatile	-	0.27	-	**0.84**	-	-
Glyceria fluitans	0.54	0.37	-	0.69	**2.21**	0.17
Berula erecta	-	0.40	0.25	-	**1.68**	-
Oenanthe aquatica	-	-	0.30	-	**0.32**	-
Scirpus sylvaticus	-	-	-	-	**0.42**	-
Carex riparia	-	-	-	-	0.26	**0.50**
Urtica dioica	-	-	-	-	-	**0.67**
Typha latifolia	-	0.17	-	-	0.16	**0.50**
Potamogeton crispus	0.50	0.50	-	0.62	-	**1.50**
FLAB[a] (= algae)	**1.71**	0.97	0.35	0.23	0.95	**3.50**
Potamogeton pectinatus	**2.39**	0.30	-	0.46	0.37	**1.83**
Potamogeton natans	0.71	1.03	-	0.54	0.68	1.17

[a] FLAB – floating algae biomass

They are differentiated by the presence of e.g. *Ranunculus circinatus* (Fan-leaved Water-goosefoot) and *Equisetum fluviatile* (Water Horsetail) in cluster 2, and by *Glyceria fluitans* (Reed Sweet-grass) and *Berula erecta* (Lesser Water-parsnip) in cluster 4. Cluster 6 incorporates some species from the former clusters, however, owns characteristic species such as *Carex riparia* (Greater Pond-sedge) and *Potamogeton crispus* (Curled Pondweed).

5.4 The environmental variation: landscape, water quantity and quality

When geographical data of the distribution of the members of the clusters are incorporated, distinct differences can be obtained. Clusters 1, 3 and 5 are from the lower parts of the river, whereas cluster 1 is almost exclusively from the lowest parts and cluster 3 is relatively more up-streams; cluster 5 is present in all lower parts of the river. Clusters 2, 4 and 6 are distinct representatives from the up-stream parts of the river. Cluster 2 derives mostly from the upstream eastern parts in the basin area where soil is a morainic clay, whereas cluster 4 mostly represents the northern parts of the basin area in the sandy out-wash plain south of the Great Mazurian lakes, when cluster 6 is connected to sites located directly downstream of the pollution point sources (see figure 5.1).

If we accept that this analysis provides an accurate description of the variation in vegetation, since the vegetation reflects the conditions in the environment, the mean environmental data according to the members of the clusters can be calculated. In table 2 some important environmental characteristics of the vegetation typology are incorporated. Indeed it appeared that clusters 1, 3 and 5 inform about the lower parts of the river, where discharge and stream velocity are higher and the dimensions of the river (width, depth) increase; clusters 2, 4 and 6 describe locations with smaller dimensions.

With salinity and nutrient levels other dimensions can be pointed out, related to the human production of wastewater and agricultural run-off. Higher ion-concentrations such as in Cl, Na and SO_4 indicate the addition of human waste or mineralising organic soils. Since Cl is a conservative substance, only dilution with clean water affects the Cl concentration, it is a perfect indicator for pollution. In the three clusters from the down-stream parts of the river, the locations of cluster 3 have the lowest concentrations; the other two partly show pollution. In the three clusters from the up-stream parts, cluster 2 has the lowest concentration; cluster 4 has some increased values, however, cluster 6 has very high concentrations.

The origin of nutrients in river water is partly from sewage water and partly from agricultural run-off and mineralization. Table 5.2 presents the concentrations in orthophosphate, potassium, nitrate and ammonium. These concentrations are influenced through removal by adsorption or biochemical processes (Van der Perk & Bierkens, 1997) and removal through uptake by algae and aquatic macrophytes (Barendregt & Wassen, 1994). The same ranking of the clusters as by salinity can be indicated. In the down-stream parts cluster 3 has the lowest nutrient concentration, cluster 1 has some increased levels and cluster 5 somewhat higher; in the up-stream parts cluster 2 has the lowest mean concentrations, cluster 4 is affected by higher concentrations, whereas cluster 6 is on the same high nutrient level as cluster 4.

The conclusion is that the locations of the members of vegetation clusters show a subdivision related to the dimension of the river and that in each subdivision a range in nutrient and salinity concentrations can be found.

Table 5.2 Some average data on the environmental variation in the vegetation clusters

	1	3	5	2	4	6
number of locations	28	30	20	13	19	6
mean discharge in m$^{3\cdot}$sec	19.7	6.8	9.0	1.2	1.1	1.2
mean stream velocity m·sec	0.32	0.21	0.30	0.24	0.29	0.26
mean width river (m)	48	27	25	8	8	6
mean depth river (m)	2.2	1.6	1.4	0.7	0.7	1.1
mean Cl mg·l^{-1}	11.6	9.4	12.6	9.4	15.1	35.4
mean Na mg·l^{-1}	8.7	7.1	10.2	6.5	12.7	30.0
mean SO_4 mg·l^{-1}	30.3	25.8	29.5	30.4	32.0	39.6
mean mineral P-total mg·l^{-1}	0.2	0.1	0.4	0.2	0.8	1.1
mean mineral N-total mg·l^{-1}	0.4	0.3	1.2	0.4	2.6	2.3
mean K-total mg·l^{-1}	2.8	2.5	3.4	2.1	4.4	5.8
$N\text{-}NO_3$ / $N\text{-}NH_4$	0.58	0.72	0.20	2.19	0.08	0.36

5.5 Linkage of vegetation with environmental variation

The first conclusion is that there is a distinct difference in the Narew River Basin between the up-stream and down-stream parts. Environmental conditions in the up-stream part are quite different: in width and depth of the river, discharge and stream velocity. The three up-stream clusters show the same type of dimension and can be separated by water chemistry. Cluster 2 is characterised by species known from unpolluted conditions such as *Carex rostrata* (Bottle sedge) and *Equisetum fluviatile* (Water Horsetail). Relatively (absolutely, compared with Western Europe) the salinity and nutrient concentrations are low at these locations. This is not surprising since the origin of the water in cluster 2 is in many cases a nature area. This differs from the locations of cluster 4: most locations are in a sandy area, where agriculture dominates, represented by higher concentrations in salinity and nutrients. Vegetation is dominated by e.g. *Oenanthe aquatica* (Fine-leaved Water-dropwort) and *Glyceria fluitans* (Reed Sweet-grass), species known to be tolerant to pollution. Proportionally the share of non-oxidised ammonium is very high (see table 2). Cluster 6, characterised by e.g. *Urtica dioica* (Common Nettle) and *Carex riparia* (Greater Pond-sedge), is indicated by extreme high concentration in salinity. Discharge of sewage close to towns is very likely and it illustrates what will happen when no protection is formulated.

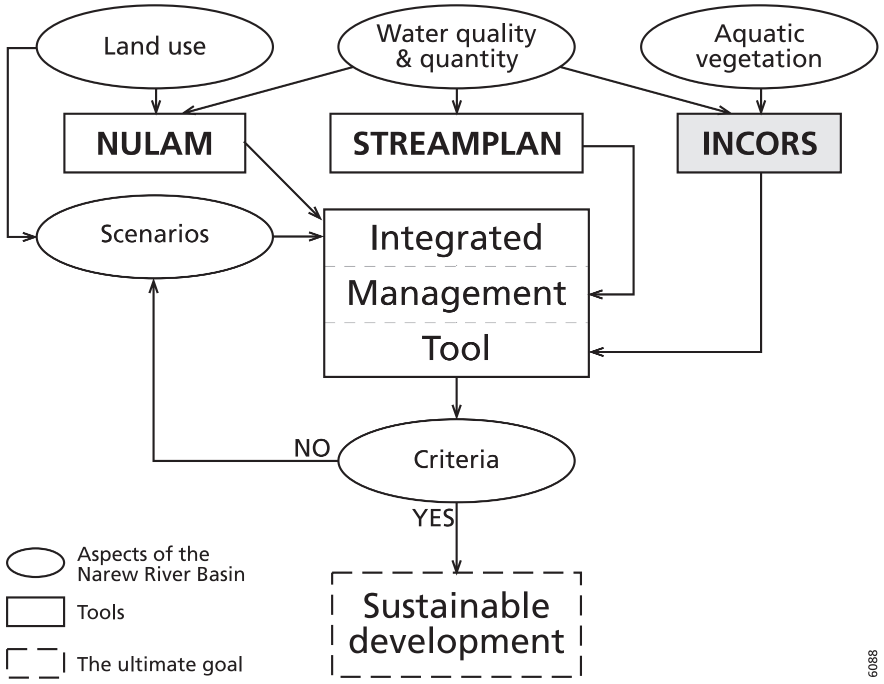
The three clusters from down-stream locations in the basin area differ by stream velocity. Cluster 3 with e.g. *Phragmites australis* (Common Reed) and *Acorus calamus* (Sweet-flag) is characterised by many species known from aquatic succession. Moreover the salinity and nutrients are on a low level, indicating optimal conditions. Clusters 1 and 5 show higher discharges and can be separated by nutrient concentrations. In cluster 1 with e.g. *Potamogeton nodosus* (Long-leaved Pondweed) and *Ranunculus fluitans* (River Water-crowfoot) these concentrations are lower; the proportional share of ammonium is low (see table 5.2). Cluster 5 is also mostly on main river stream, without characteristic species illustrates what happens when no purification is present.

5.6 Discussion

From this study we learn that the variation in the river ecosystem is due to two factors. The first is the natural variation from the source to the mouth, which is the basic variation. Next to that, the human population influences the water chemistry and in that way the river ecosystem. The source of the chemical pollution can be diffuse from agricultural areas, as could be stated from the comparison between clusters 2 and 4 or can be well-defined point-pollution from sewerage water (cluster 6).

The effect of the pollution is that the characteristic type of vegetation is changed to another type, mostly without important species. In general it is a shift of the vegetation types toward cluster 6. The optimistic view is that after 20 km of streaming water the pollution is removed by biochemical processes (Van der Perk & Bierkens, 1997; Barendregt & Wassen, 1994). Moreover, down-stream parts of the river are partly prevented of algae bloom by the high stream velocity (Remy, 1991). The problem remains that with a constant loading with nutrients (agricultural areas) the system cannot recover.

Although the Narew appears to be a lowland river without physical disturbance and limited pressure from the human population contamination can be observed and detected. However, now that the point and diffuse sources have been identified, a sustainable management can be developed to preserve this river.


Land use
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6 BUILDING THE HYDRO-ECOLOGICAL MODEL (INCORS) FOR THE NAREW RIVER BASIN

6.1 Introduction

In chapter 5 I investigated and explained the links between water quality and natural vegetation in the Narew River Basin. This chapter takes the study a step further by encapsulating the understanding of vegetation – water relationships into a hydro-ecological model. This species response model was developed to be used for assessing the impact of changes in land use and in water management in the basin on the aquatic ecosystems of the Narew river and its tributaries.

The model is based on the empirical statistical approach. This is reflected in the name INCORS: Influence of Nutrient Concentrations On the Response of Species. The data used for this empirical logistic regression model are records of non-biotic variables (mainly nutrients) and on species composition of the vegetation. The model is based on the ICHORS concept (Influence of Chemical and Hydrological factors On the Response of Species (Barendregt, 1993) and on several versions of the ICHORS model developed at the Department of Environmental Sciences, Utrecht University, The Netherlands (Barendregt & Nieuwenhuis, 1993). To achieve the research aims within the logistic limitations of the study the proposed model had to be characterised by several required features such as (i) use of data that explain the variation of vegetation, (ii) use the data produced by the water quality model (see chapter 4) to allow scenario exploration (see chapter 7), (iii) use of data that are easy to collect and (iv) the precondition that the model must be computationally tractable (i.e. reasonable computing times). The procedure is based on a computational and theoretical framework of Generalized Linear Models (GLM) proposed by Nelder and Wedderburn (1972) which has been successfully applied in many ecological studies (e.g. Austin et al., 1984; Margules et al., 1987) to predict species response to a variety of environmental data using linear parameter response models (Yee & Mitchell, 1991). In principle, for each plant species present in the data set a regression model can be calculated which describes the response of the species to the values of the explaining variables. When the model is applied, the model output consists a set of probability values for the presence of the modelled species with respect to a certain set of non-biotic variables. After defining different input sets of abiotic values, for instance one defining the present conditions and one defining the conditions after a certain change in land use has been realised, comparison of the two sets of output (probability values for species) gives insight into the potential changes in species presence that might be the result of implementing such a scenario.

The following sections explain the choice of the variables that must fit the water quality model, the characteristics of the collected database and the modelling technique. The Results section presents the regression models obtained. Finally, the chosen approach and the applied modelling technique are discussed.

6.2 Variables

6.2.1 Dependent variables

In this study the restriction was made to consider plant species as the dependent (response) variables under the assumption that vegetation composition of aquatic ecosystems is a good indicator of the state of the ecosystem in terms of completeness and biodiversity. Furthermore, it is assumed that vegetation is a structuring component important in determining for other kind of biological functions, including a habitat for fauna.

6.2.2 Explaining (independent) variables

Chosen explaining variables should (i) reflect relevant conditions of an ecosystem e.g. the environmental factors influencing the existence of a biotic ecosystem component (flora, fauna) the most (key environmental factors) and (ii) include environmental factors which are affected by changes in policy and management considered in the present study.

Previous studies on plant species response to changes in environmental conditions (Barendregt, 1993 (ICHORS); Ertsen, 1995 & 1998 (ITORS)) attempted to find which were the most important biochemical (water chemistry) and biophysical (morphology, soil and hydrology) variables for describing species presence using logistic regression. For example, Ertsen (1998, p. 38, table 2.4) collected data on 17 chemical variables, 8 hydrological variables and 3 management variables. It turned out that of these 28 variables, only 10 proved to be significant. These included the major nutrient supplies (nitrogen and phosphorus), organic matter percentage and groundwater (Ertsen, 1998, p. 41, table 2.5). The advantage of the approach including a vast number of variables is that it gives insight in which variables are best correlated to species response. Thus, it offers the opportunity to formulate hypotheses on key environmental variables in certain ecosystems. A disadvantage is that running such empirical models requires the definition of a large number of variables and thus collection of large datasets. According to Olde Venterink and Wassen (1997) who analysed features of several of such models, the data, time and computation demands seriously restrict the applicability of this type of models. This is especially valid in case of a vast region like the Narew River Basin, with a surface area of 28000 km^2. In this study the choice of variables also differs from the ICHORS/ITORS models in another respect. In contrast to these above mentioned studies the building of an ecological model is here not an objective in itself. The ecological model is part of an integrated management tool (IMT, see chapter 1) also containing a nutrient emission module (see chapter 2) and a water quality model (see chapter 4). Thus, the selected variables in the ecological model should match the variables incorporated in the nutrient emission module and the water quality model: nitrogen (nitrate and ammonium) and phosphorus (orthophosphate).

On the basis of these experiences, and because I was attempting to construct a useful model instead of testing a complete set of environmental variables on its ecological significance, I decided to collect data on the 4-5 most important attributes indicated by Ertsen (1998) and Barendregt (1993), namely nutrients (nitrogen and phosphorus). Since the river dimensions importance for vegetation composition was revealed when analysing the linkage between vegetation patterns and environmental features (see chapter 5) an incorporation of a variable describing river size into response modelling was necessary. Thus, as an addition to variables measured by Ertsen (1998) and Barendregt (1993), I also measured river dimensions, of which river width proved to be the most important and reliable, compared to river depth and discharge as an accurate, indicator of river morphology. Therefore, finally four variables, nutrient concentrations (NO_3-N, NH_4-N, PO_4-P) and river width, were chosen to be incorporated into regression equations. The reasons why they are incorporated are: (i) their importance for plant species existence and growth, proved by previous studies (Ertsen, 1998 and Barendregt, 1993), (ii) they are constituents that are most influenced by development of agriculture (manure, fertilisation) and tourism (sewage), which are proposed and designed as the main, sustainable soundly, directions of socio-economical development of the region (Taraszkiewicz, 1994), (iii) they result from water quality modelling (see chapter 4), allowing for scenario studies (see chapter 7) and finally (iv) at present their concentrations exceed drinking water quality limits (while maintaining a water quality which allows drinking water production is one of the aims of the sustainable development of the Narew River Basin).

6.3 Database

6.3.1 Biotic data

A total of 109 plant species was recorded at all sampling sites (table 6.1). The presence of the plant species varied between 1 (22 species) and 91 (*Glyceria maxima*) observations and had an average value of 17 observations. Forty-six of the recorded species were very rare (presence lower than 5 observation) and only nine had been present at least at half of the sampled locations. The number of species used for further statistical analysis was reduced to 63 by excluding, from the total database species observed less than 5 times.

An extended study on aquatic vegetation in the Narew River Basin, focusing on more detailed insight and analysis of composition and differentiation of vegetation and its linkage to observed environmental variation, is given in chapter 5.

6.3.2 Environmental data

An extended environmental monitoring program, focused on water quality data acquisition for the entire Narew River Basin, was run (see chapter 2). During a two-year long period covering the hydrological years 1996-1997 water quality was sampled monthly at 89 sampling sites. In July 1997 vegetation was recorded at these sites and, additionally, at 27 other sites where water samples were taken also. At each of the sites three water samples were taken from the stream and mixed.

Table 6.1 Species recorded in the Narew River Basin in July 1997 with the number of occurrences

	n		n		n
Achillea ptarmica	1	*Hottonia palustris*	2	***Potamogeton perfoliatus***	**40**
Acorus calamus	**34**	***Hydrocharis morsus-ranae***	**19**	*Potamogeton pusillus*	1
Agrostis stolonifera	2	***Iris pseudacorus***	**10**	***Potamogeton trichoides***	**5**
Alisma plantago-aquatica	**26**	*Juncus articulatus*	4	*Potentilla palustris*	1
Alopecurus geniculatus	3	*Juncus bufonius*	2	***Ranunculus aquatilis***	**6**
Apium nodiflorum	1	***Lemna minor***	**89**	***Ranunculus circinatus***	**12**
Berula erecta	**28**	***Lemna trisulca***	**40**	***Ranunculus fluitans***	**10**
Bidens spec	4	*Limosella aquatica*	1	*Ranunculus repens*	1
Bryonia dioica	1	***Lycopus europaeus***	**6**	***Ranunculus sceleratus***	**6**
Butomus umbellatus	**68**	*Lysimachia nummularia*	4	*Rorippa amphibia*	4
Callitriche spec	**15**	*Lysimachia thyrsiflora*	1	*Rorippa austriaca*	2
Caltha palustris	**5**	*Lysimachia vulgaris*	2	***Rorippa palustris***	**76**
Calystegia sepium	2	*Lythrum portula*	2	*Rumex crispus*	2
Cardamine pratensis	1	***Lythrum salicaria***	**8**	***Rumex hydrolapathum***	**37**
Carex acuta	3	***Mentha aquatica***	**44**	***Sagittaria sagittifolia***	**82**
Carex acutiformis	**40**	*Menyanthes trifoliata*	3	***Scirpus lacustris***	**17**
Carex hirta	1	***Myosotis palustris***	**51**	***Scirpus sylvaticus***	**12**
Carex nigra	1	***Myrophyllum spicatum***	**8**	*Scrophularia umbrosa*	1
Carex riparia	**7**	***Myrophyllum verticillatum***	**10**	***Scutellaria galericulata***	**6**
Carex rostrata	3	***Nuphar lutea***	**73**	***Sium latifolium***	**26**
Carex vesicaria	3	***Nymphaea alba***	**5**	***Solanum dulcamara***	**8**
Catabrosa aquatica	1	*Nymphoides peltata*	3	***Sparganium emersum***	**53**
Ceratophyllum demersum	**19**	***Oenanthe aquatica***	**13**	***Sparganium erectum***	**59**
Cicuta virosa	**18**	***Phalaris arundinacea***	**81**	***Spirodela polyrhiza***	**71**
Eleocharis palustris	**12**	***Phragmites australis***	**26**	*Sponge*[b]	2
Elodea canadensis	**55**	*Poa pratensis*	1	***Stachys palustris***	**15**
Epilobium tetragonum	3	***Polygonum amphibium***	**13**	***Stratiotes aloides***	**6**
Equisetum arvense	1	***Polygonum hydropiper***	**6**	*Symphytum officinale*	1
Equisetum fluviatile	**13**	*Potamogeton compressus*	2	*Trifolium repens*	1
Equisetum palustre	1	***Potamogeton crispus***	**25**	***Typha angustifolia***	**13**
Filipendula ulmaria	1	***Potamogeton lucens***	**33**	***Typha latifolia***	**9**
Flab[a]	**51**	***Potamogeton mucronatus***	**5**	*Urtica dioica*	2
Fontinalis antipyretica	**12**	***Potamogeton natans***	**36**	*Utricularia vulgaris*	1
Galium palustre	2	***Potamogeton nodosus***	**12**	***Veronica anagallis-aquatica***	**34**
Glyceria fluitans	**34**	*Potamogeton obtusifolius*	1	*Veronica beccabunga*	3
Glyceria maxima	**91**	***Potamogeton pectinatus***	**39**	***Veronica catenata***	**8**
Hippuris vulgaris	1				

n = number of positive observations

bold font = species included in modelling

[a] *Floating algae biomass*

[b] Animal organism (*Pozifera*)

Alkalinity and pH were measured in the field. Major ions, including the mineral nutrients were analysed in the laboratory after conserving the samples through acidification. For details on the treatment of the samples and analysing methods see chapter 3.

Since the Integrated Management Tool proposed in this study was designed for vegetation periods with low flow conditions (see chapter 1) the water quality (see chapter 4) and the load emission (see chapter 2) models were developed based on data for months with the lowest average discharge for all gauge stations (September 1996 and September 1997). The recording of aquatic vegetation was done in July 1997. September is too late in the vegetation season for recording aquatic vegetation, plants are already decaying. July 1997 was still a quite low flow period (see chapter 3). To test if nutrient concentrations measured in July 1997 were comparable to those in September, correlations were calculated between concentrations in July 1997 and September 1996 and September 1997 (table 6.2). The concentrations appeared to cover a similar range and correlations were significant. This made the data for July 1997 acceptable for further plant species response modelling.

Table 6.2 Comparison of ranges of nutrient data measured at standard sampling sites (89 locations) in July 1997 and September 1997 and September 1996

	PO_4			NO_3			NH_4		
	Range (mg$^{.}$l^{-1})	Median (mg$^{.}$l^{-1})	Correlation Coefficient[a]	Range (mg$^{.}$l^{-1})	Median (mg$^{.}$l^{-1})	Correlation Coefficient	Range (mg$^{.}$l^{-1})	Median (mg$^{.}$l^{-1})	Correlation Coefficient
July 1997	0.13 – 32.8	0.54		0.16 - 5.77	0.67		0.10 - 51.2	0.20	
September 1997	0.13 – 27.0	0.47	0.97	0.11 - 3.82	0.50	0.76	0.10 – 51.4	0.15	0.97
September 1996	0.13 – 21.9	0.49	0.97	0.33 – 3.4	0.63	0.71	0.11 – 17.5	0.21	0.90

[a] Correlation coefficients are respectively between July 1997 and September 1997 data and July 1997 and September 1996 data

The studied sampling sites were scattered extensively and evenly distributed among all significant streams in the Narew basin river network. Therefore, the whole variation in nutrient concentrations existing in the catchment area was present in the data set. Table 6.3 shows the range of vegetation types and river locations investigated in this study by means of vegetation clustering. The clustering procedure and characteristics of the clusters are presented in chapter 5. Percentile and mean values of the measured nutrients and the river width give information on the trophic level of the studied vegetation types present at certain locations. Generally, nutrient concentrations in the entire basin appeared to be within relatively narrow ranges. Only a few sampling sites, classified in Cluster 6, appeared to be outside the range. Down-stream locations account for two thirds of all sites. Between clusters they differed in river dimensions and showed limited discrimination in all three nutrient constituents concentration levels, but differed especially in nitrate and phosphate levels. Sampling sites located in the up-stream parts of the streams comprised 33% of the total and showed, for all up-stream clusters, the same type of dimensions and larger differences in water chemistry. Sites located close to sewerage effluents (5% of the sites) were characterised by extremely high levels of nutrient concentrations in comparison to all other sites.

Table 6.3 Range for used environmental variables for studied sites (116 locations) with 10-precentile (P10), mean and 90-percentile (P90) values

	Location along river	NH_4 (mg·l^{-1})			NO_3 (mg·l^{-1})			PO_4 (mg·l^{-1})			width (m)		
		P10	mean	P90	P10	mean	P90	P10	mean	P90	P10	mean	P90
Cluster 1[a] (n = 28)	down-stream	0.12	0.33	0.25	0.28	0.77	1.23	0.22	0.65	0.96	13.4	48.0	113
Cluster 2 (n = 13)	up-stream	0.11	0.20	0.23	0.45	1.15	1.68	0.28	0.66	1.03	2.8	8.0	9.6
Cluster 3 (n = 30)	down-stream	0.13	0.23	0.29	0.25	0.69	1.40	0.23	0.44	0.67	10.2	27.0	96.4
Cluster 4 (n = 19)	up-stream	0.16	0.29	0.43	0.29	0.70	1.15	0.38	0.62	0.88	3.0	8.0	16.4
Cluster 5 (n = 20)	down-stream	0.14	0.24	0.35	0.53	0.94	1.34	0.36	0.73	1.10	4.7	25.0	63.0
Cluster 6 (n = 6)	up-stream	0.24	4.17	36.2	0.58	2.68	4.85	2.48	0.16	21.2	2.8	6.0	12.0
All sites (n = 116)		0.13	0.99	0.40	0.27	0.91	1.68	0.26	1.11	1.16	4.0	25.0	60.0

[a] For detailed cluster description see chapter 5

6.4 Modelling the presence of plant species as a function of nutrient availability and river geomorphology

Empirical modelling was done within the framework of generalised linear models (GLM) (Nelder & Wedderburn, 1972; McCullagh & Nelder, 1989), using the statistical software package S-PLUS (version 2000; Mathsoft, 1999).

General multiple logistic regression (Hosmer & Lemeshow, 1989; Dobson, 1990) was used to describe the species response (its presence or absence) in relation to changes in nutrient concentrations. If the probability of a plant species being present is denoted by $P(X_i) = P(Y_i = 1 / X_i)$, where X_i is a set of given environmental variables $X_i = (X_{i0}, X_{i1},\ldots, X_{im})$ and Y_i is the considered plant species, for each of recorded plant species Y_i model regression formulation is as follows:

$$E(Y_i / X_i) = P(Xi),\ \mathrm{logit}[P(X_i)] = \log[P(X_i) / (1 - P(X_i))] = X_i\beta,\ \ i = 1,\ldots,n \qquad (6.1)$$

where X_i is the set of measured environmental variable values corresponding to observation i and $\beta = (\beta_0,\ldots,\beta_m)$ is the parameter vector with unknown regression coefficients.

The regression model was constructed following certain assumptions (i) all selected environmental variables are included in this regression, (ii) the first order terms of each variable are imperative and (iii) the second order terms of each variable are optional in the regression equation. By this the shape of the species' response to each predictor was limited to a first- or second-order model, which at the original presence - absence scale corresponds to a sigmoid or a unimodal symmetric curve, respectively (Jongman et al., 1987).

The modelling exercise was restricted to plant species with a minimum of 5 positive observations in the total database (see table 6.1). For each species all possible multiple regression models containing all of the four predictor variables fitted either by a first- or second-order model were calculated. The most significant of the 16 candidate models was subsequently accepted as the final model for that species, provided it was significant at a 0.1 level. Therefore, the significance of the final regression models was assured during model selection, as only significant models (at $\alpha = 0.01$) were accepted. Model significance was assessed comparing the empty model (with an intercept only) with the multiple regression model by means of a maximum likelihood ratio test (Dobson, 1990). This approach resulted in 16 possible candidate models containing 4 to 8 model terms (table 6.4).

It was decided not to validate obtained response models, because other independent data were not currently attainable and because the available number of recorded relevees was too limited to be divided into a validation and a model set. All available data were, therefore, used for modelling.

6.5 Results

From the total set of 109 plant species, observed at 116 sites during the fieldwork, more than half (58%, 63 species) were recorded at five or more sampling sites (see table 6.1). In view of the multiple regression models described in the previous section statistical analysis was restricted to these plant species. About three fourth of the plant species, with five or more presences (71%, 45 species), were successfully modelled with one of the 16 candidate models applied. In general, only less frequent species resulted in non-significant models and were rejected from further analysis. Of the species resulting in non-significant models only three (*Glyceria maxima*, *Rorippa palustris* and *Veronica anagalis-aquatica*) displayed more than average positive observations in the total data set (i.e. a frequency of plant species presence higher than 28). The group of satisfactorily modelled species covered the whole range of observed abundances including both the least and the most present species and averaging a frequency of 31 observations.

The number of different significant response model types finally obtained for all successfully modelled species was 9, out of the 16 candidate model types. Most plant species (13) were best modelled with the less complex model containing only the first order terms of all four predictor variables. Models containing five terms, with one of the second-order term included, were obtained for more than a half of all species (55%).

Table 6.4 Candidate model formulations

	Imperative terms	Optional terms			
1	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)				
2	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)	$log10(PO_4)^2$			
3	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)		$log10(NH_4)^2$		
4	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)			$log10(NO_3)^2$	
5	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)				$log10(width)^2$
6	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)	$log10(PO_4)^2$	$log10(NH_4)^2$		
7	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)	$log10(PO_4)^2$		$log10(NO_3)^2$	
8	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)	$log10(PO_4)^2$			$log10(width)^2$
9	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)		$log10(NH_4)^2$	$log10(NO_3)^2$	
10	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)		$log10(NH_4)^2$		$log10(width)^2$
11	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)			$log10(NO_3)^2$	$log10(width)^2$
12	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)	$log10(PO_4)^2$	$log10(NH_4)^2$	$log10(NO_3)^2$	
13	log10(PO_4) log10(NH_4) log10(NO_3) log10(width)	$log10(PO_4)^2$	$log10(NH_4)^2$		$log10(width)^2$
14	log10(PO_4) log10(NH_4) log10(NO^3) log10(width)	$log10(PO_4)^2$		$log10(NO_3)^2$	$log10(width)^2$
15	log10(PO_4) log10(NH_4) log10(NO^3) log10(width)		$log10(NH_4)^2$	$log10(NO_3)^2$	$log10(width)^2$
16	log10(PO_4) log10(NH_4) log10(NO^3) log10(width)	$log10(PO_4)^2$	$log10(NH_4)^2$	$log10(NO_3)^2$	$log10(width)^2$

More complex models containing two or three second-order terms were selected less frequently, for only 9% and 6% of all successfully modelled species, respectively. None of the species was modelled best with the most complex candidate model with four quadratic terms present (table 6.5). The large majority of modelled species was, therefore, satisfactorily modelled with relatively simple models.

The number of second-order terms included in the final model formulations varied from 0 to 3, with most frequently one term added. For all environmental variables the quadratic term for river width was most frequently incorporated into final response model equation (in 15 equations). With regard to nutrient constituents, the second-order term for ammonium (NH_4) was the most frequent in the final model equations (occurring 12 times), whereas the quadratic term for nitrate (NO_3) was most seldomly included (in 5 equations). The regression models explained from 5% to 78% of the species' deviances, with an average of 22% of explained deviance.

Table 6.5 Used final models, their frequency and percentage (%) of the plant species modelled by certain model

	Frequency	% of species
log10(PO_4) log10(NH_4) log10(NO_3) log10(width)	13	29
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10(width)*^{2}	9	20
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10*(NH_4)^2	6	13
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10*(PO_4)^2	6	13
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10*(NO_3)^2	4	9
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10*(NH_4)^2 *log10(width)*^{2}	3	7
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10*(NH_4)^2 *log10*(NO_3)^2	1	2
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10*(PO_4)^2 *log10*(NH_4)^2 *log10(width)*^{2}	2	4
log10(PO_4) log10(NH_4) log10(NO_3) log10(width) *log10*(PO_4)^2 *log10*(NO_3)^2 *log10(width)*^{2}	1	2

Out of the species that resulted in non-significant models only, 2 ecologically interesting species, *Ranunculus circinatus* (Fan-leaved Water-goosefoot) and *Sium latifolium* (Greater Water-parsnip) (Van Diggelen, 1998), were studied in more detail, to assess whether omission of one or more predictor terms would result in a significant model. Less complex models for both *Ranunculus circinatus* (with omission of the term log10(PO_4)) and *Sium latifolium* (with omission of the term log(NO_3)) proved to be significant at the 0.1 level. Terms, parameters, significance and explained deviance of the final regression models for all modelled plant species are given in Appendix A.3.

6.6 Discussion

The empirical statistical approach used resulted in a tool for the assessment of the effect of changes in surface water nutrient concentrations on aquatic vegetation composition.

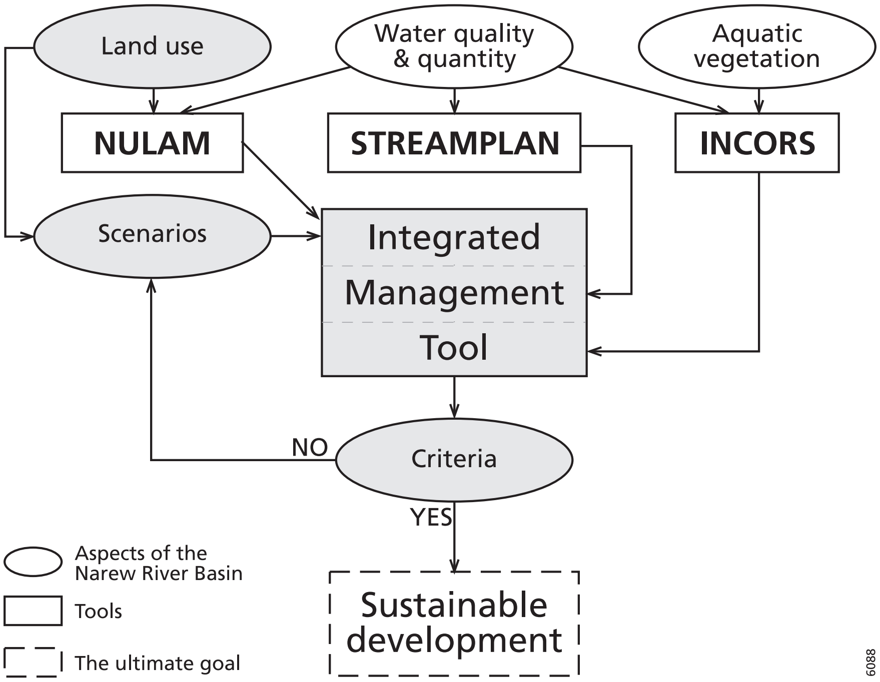
The proposed empirical statistical approach is one of a few possible approaches. One can choose for a deterministic approach in which the key-processes in the studied ecosystems are analysed and modelled. In environmental sciences this approach is not yet possible since the state of our knowledge does not allow us to model complex ecosystems like riverine ecosystems deterministically (Barendregt et al., 1986; Runhaar, 1999). To date, deterministic ecosystem modelling has only proved to be successful for quite simple ecosystems in which few species compete for resources (e.g. Berendse et al., 1992). Deterministic modelling requires an understanding of complex interrelations; frequently such models demand large amounts of precise data and are slow to compute. Faster, and at present more feasible approaches, are either an approach based on expert judgement or an empirical statistical approach. In western European countries the expert approach is often practised and based on indication values for species (e.g. Latour et al., 1993; Runhaar, 1999). For eastern Poland such expert information is not available, and indication values for species valid for central and western Europe were never validated for eastern Poland. Besides the accuracy of these indication values might be doubted for running waters. For these reasons the empirical statistical approach was chosen for this study. An additional reason for this choice was that there is much experience in the research group with this type of modelling (Barendregt, 1993; Ertsen, 1998; Van Horssen et al., 1999; Bio et al., 2002).

Compared to the use of expert judgement such an approach offers a more reproducible, quantitative insight into the effect of different scenarios on plant species response in sense of their chances to occur. Moreover, the model was designed to be linked without problems to the integrated management tool (IMT) for evaluation of the impact of land use planning and water management on surface water quality and status of aquatic nature (described in chapter 1). Ultimately, the type and limited number of predictor variables used, increases the model applicability as decision support system, since INCORS only requires environmental data conventionally measured by, for instance, the national weather services (i.e. Polish National Weather Service). Also, the type of incorporated variables complied with the objective to investigate nutrients, being a key factor for plant growth and being the water composition elements most directly influenced by land use practices.

However, since plant species growth is determined also by many other environmental variables, model predictions should be interpreted as an indication of possible development tendencies in vegetation types when different management strategies are regarded and not as the exact predictions of the change that a certain vegetation type will undergo. Furthermore, the predicted probability for a certain plant species should be considered as relative value of a chance for this plant species to be present and not as an absolute probability. Besides and given that the diagnostic value of a sociological group of species is higher than that of a single species, it is wiser to evaluate the response of sets of certain species groups than interpretation of singular plant species. The total set of response models consists of 11 different variable combinations for the 47 final species regression models.

The fact that in principle all species models were based on the precondition that all nutrient constituents modelled by the water quality model must be included in regression formulation (at least as a first-order term) influenced the achieved models. Possible omission of one or more imperative term could result in significant models of different complexity.

For the INCORS model a number of five positive records per species was chosen as a threshold to accept a species for the empirical regression modelling. The threshold value used was low compared to the number of occurrences taken as a threshold in other studies (n = 15 in Barendregt, 1993 and Ertsen, 1999, n = 20 in Ertsen et al., 1998). Expressed, however, in percentages of the total number of relevees, the threshold of five used is in agreement with those used by others when the number of available sampling sites is considered (n = 116 which is about 20 percent of the number of relevees sampled by the above mentioned authors). I therefore opted for a low threshold taking into account the small number of relevees in our sample.


Land use
Water quality & quantity
Aquatic vegetation
NULAM
STREAMPLAN
INCORS
Scenarios
Integrated Management Tool
NO
Criteria
YES
Sustainable development
Aspects of the Narew River Basin
Tools
The ultimate goal
6088

7 ANALYSIS OF DEVELOPMENT SCENARIOS FOR THE NAREW RIVER BASIN USING AN INTEGRATED MODELLING APPROACH

7.1 Introduction

The main applied aim of this thesis was to propose and examine various scenarios for development of the Narew River Basin and to assess the impact of these strategies on the nutrient emissions, quality of surface water and species composition of aquatic ecosystems. Previous chapters discussed the present situation of the basin with regard to nutrient emissions (chapter 2), surface water quality (chapter 3) and composition of aquatic vegetation (chapter 5). At the same time the methods to model changes in these three fields were developed and described in chapters 2, 4 and 6, respectively. Now that the hydrological, hydrochemical and vegetation components of the Narew River Basin have been determined, and the spatial/dynamic variations have been captured in validated models, it is possible to combine all these into the Integrated Management Tool (IMT).

Once the IMT is in place, I demonstrate its use for scenario modelling, which in turn leads to an evaluation of water quality policies for sustainable water quality in the Narew River Basin. These analyses might be instrumental for policy makers to decide upon efficient measures to direct the basin development into sustainability. Such measures will be needed when Poland joins the European Union since major social and economical changes are foreseen, mainly in agriculture because this is the dominant sector in the region's economy. Proper analysis of the impacts of potential changes in land use, in agricultural practices and in water management on the surface water quality and the aquatic ecosystems is required.

For such analysis a scenario study approach has proved to be the most appropriate and sufficient method. Schoonenboom (1995), and Veeneklaas and van der Berg (1995) have concluded that scenarios and scenario studies in strategic decision-making and planning have the advantage (over expert reports or judgements and other planning approaches) than they force a systematic, consistent approach to studying issues and explain possible uncertainties. Schoute et al. (1995) noticed also that 'the intended benefit of scenarios is that they stretch as well as focus people's thinking', which may be crucial for the decision making. Moreover, the scenario study approach has been widely employed to analyse changes in nutrient emissions (e.g. De Wit & Bendoricchio, 2001; Kronvang et al., 1999), in surface water quality (e.g. Hendriks & van der Kolk, 1995) and in vegetation composition (e.g. Ertsen, 1998; Barendregt, 1993).

In this chapter the scenarios will be designed, described and quantified with the explanation of their foundations. They will be analysed with the IMT. The results of the scenario analyses will be presented and evaluated with focus on the ultimate goal for water quality management in this river basin, that aims at reaching the Ist surface water quality class according to the national standards and preserving the high quality of aquatic ecosystems, which may be a way of achieving sustainable development of the basin.

7.2 Scenarios

The scenario study envisages several ways to explore basin development, which will follow present ideas, premises and perspectives. In the Narew River Basin, two different development schemes may be expected when looking at the present political situation. One assumes that Poland will join the European Union which may lead to rapid intensification of agricultural production and a situation comparable to the high Dutch or German levels of production. The second perspective is based on the much discussed idea of the basin being the core part of the Green Lungs of Poland region, thus undergoing sustainable development, which implies extensive, ecological farming (Taraszkiewicz, 1994). Therefore, by studying the effects of these two scenarios one might get insight in the possible ranges within which future nutrient loads, surface water quality and presence of aquatic vegetation might change. So, it was decided to use the Integrated Management Tool to study the effects of three possible scenarios, with the first one acting as a reference for the others, namely: (i) the current situation, (ii) joining the European Union and (iii) achieving the Ist class of water quality. The scenarios were differentiated by setting changes into land use area, livestock densities, fertiliser application level and sewage effluent purification policies (table 7.1).

Table 7.1 Agricultural characteristics and purification standards used for the scenario calculations

	Unit	Scenario[a]		
		'present'	'EU'	'first'
fertilisation N	$kg \cdot ha^{-1}$	25.2 – 50.8	170	23.3
fertilisation P	$kg \cdot ha^{-1}$	6.9 – 20.4	45	5.2
Cattle	$head \cdot km^{-2}$	11 – 164	90	33.2
Pigs	$head \cdot km^{-2}$	8 – 237	150	53.8
Horses	$head \cdot km^{-2}$	1.3 – 17.6	10	1.9
Sheep	$head \cdot km^{-2}$	0.5 – 17.7	10	0.4
Poultry	$head \cdot km^{-2}$	32 – 565	400	128
Point sources NH_4	$mg \cdot l^{-1}$	0.12 – 46.3	0.12	0.12
point sources NO_3	$mg \cdot l^{-1}$	0.15 – 40.2	0.15	0.15
point sources PO_4	$mg \cdot l^{-1}$	0.5 – 26.5	0.5	0.5

[a] 'EU' denotes 'joining the European Union' scenario; 'first' – denotes 'achieving the Ist class of water quality' scenario

Two common assumptions were made for both future scenarios. For the purification polices it was assumed that waste water purification will be realised at the best available level (table 7.1). For land use the two extreme scenarios were differentiated by assuming that all non-productive land will be available for conversion into another type of land use. The conversion-available, non-productive land acreage varies from 2% of the total area in the Biala river sub-catchment to 24 % of the total area in the Goniadz differential sub-catchment, whereas it is 8% (2110 km^2) on average for the entire basin (figure 7.1).

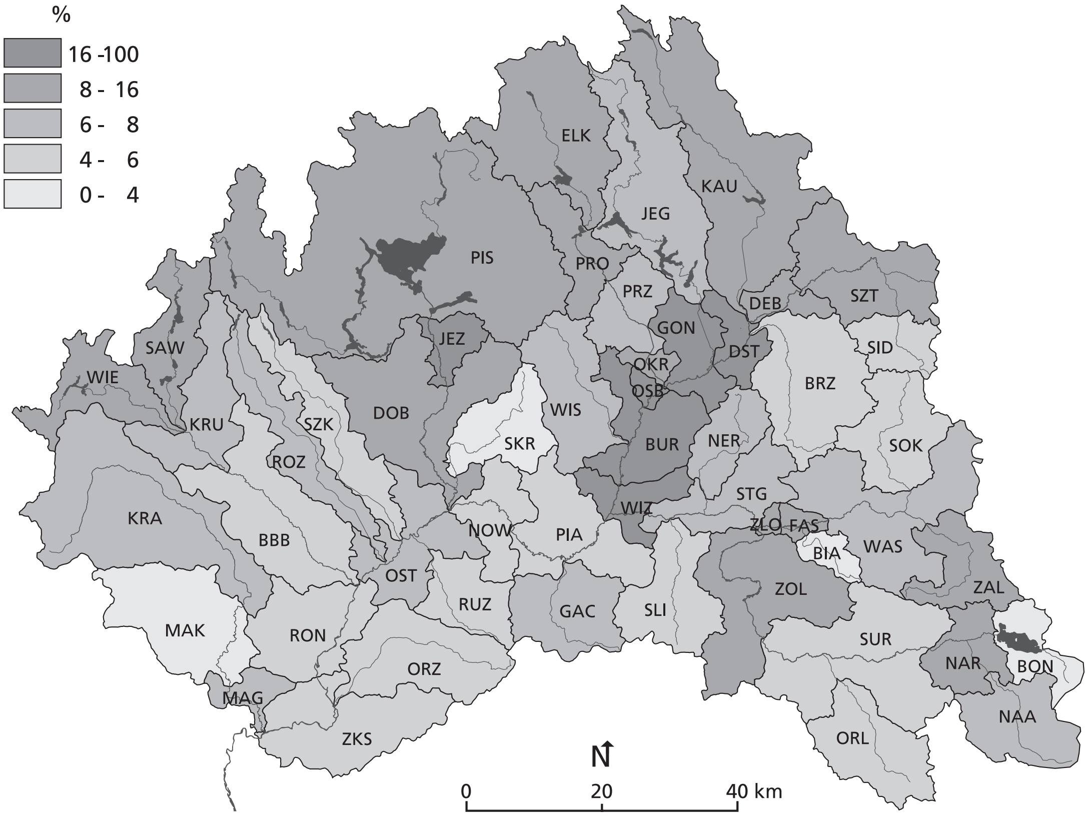


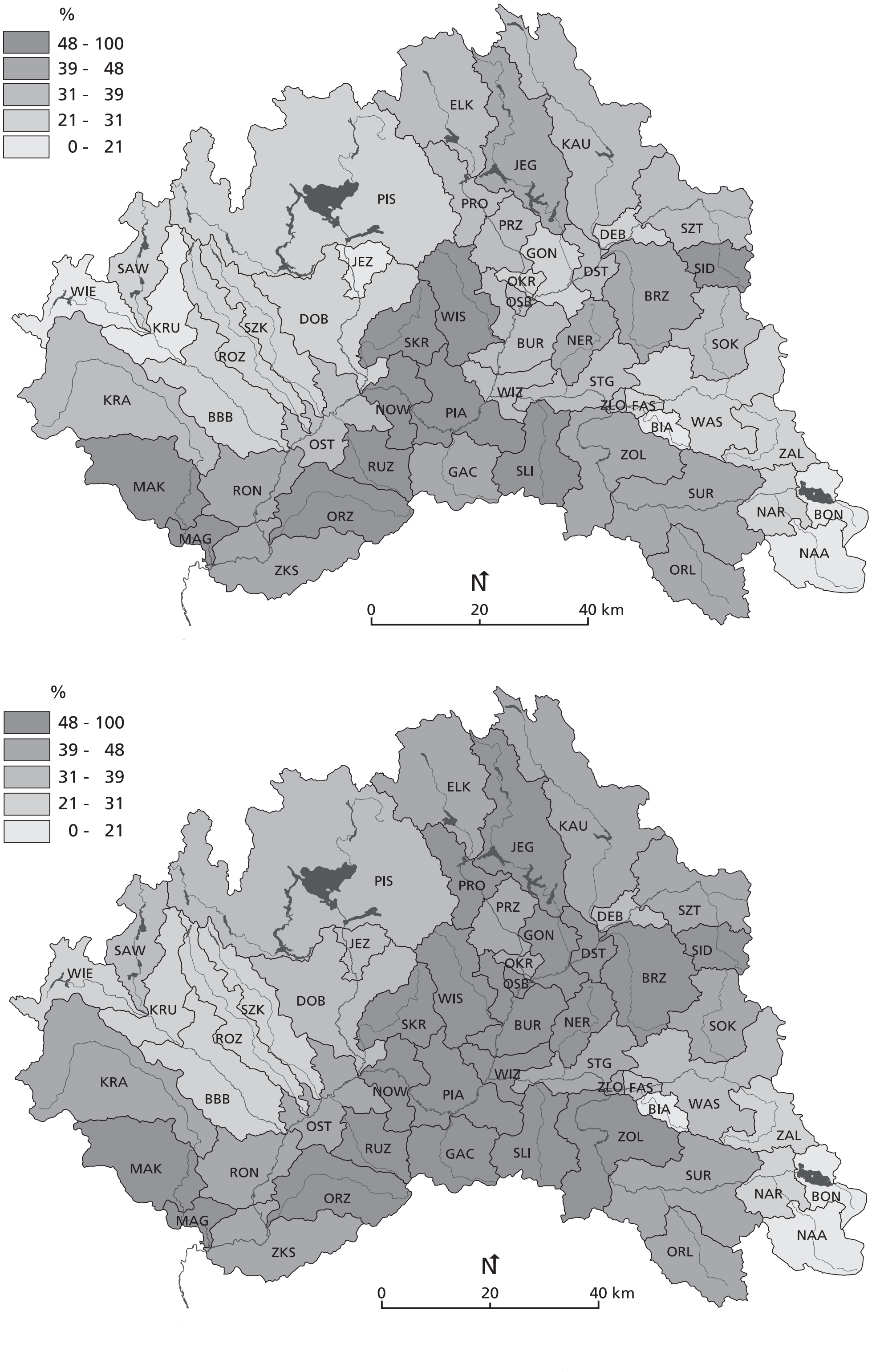
Figure 7.1 Non-productive land acreage (%) in the sub-catchments of the Narew River Basin

7.2.1 Scenario ‘present’

The ‘present’ scenario (current situation) relates to the situation in the Narew River Basin in the years 1996-1997. It was calculated based on data collected (land use, fertilisation and livestock) and measured (point source effluents) in 1997 for which the IMT was calibrated (see chapters 3 and 4).

7.2.2 Scenario ‘joining the European Union’

The ‘joining the European Union’ scenario in the case of agricultural characteristics (livestock and fertilisation levels) relates to respectively levels in German farming of the year 1995 and/or the European Union standards (EU, 1991; GUS, 1996). These levels might be regarded as the maximum foreseen at the moment for the basin. They refer to one of the most intensive forms of European agriculture, characterised by comparable soil and climatic conditions and the standards that coming members of the European Union will have to comply to. The threshold values for parameters applied for the calculation are given in table 7.1.



a)

b)

Figure 7.2 Arable land acreage (%) in the sub-catchments of the Narew River Basin: a) situation in 1997 (scenario 'present'), b) future situation (scenario 'joining the European Union')

When for a certain sub-catchment the present (year 1997) population of a certain animal type was higher than the threshold value the present value was taken for calculation. For this scenario it is also assumed that all available non-productive land will be converted entirely into arable land (figure 7.2).

The term 'joining the European Union' has been used as a convenient surrogate for the upper levels of livestock and fertilisation that were permitted in the industrial agriculture in the European Union in the mid-1990's. The term is not used in an anti-Europe way.

7.2.3 Scenario 'achieving the Ist class water quality'

The agricultural characteristics (fertilisation and livestock) for 'achieving the Ist class water quality' scenario were based on the lowest levels recorded in the first half of the nineteen nineties in voivodeships and communities included in the Narew River Basin (GUS, 1990-1995). These figures might be regarded as the possible minima for the basin. The period of the first couple of years after the fall of the communist system in 1989 brought a dramatic drop in agricultural production and fertilisers usage (Dzikiewicz, 2000). The threshold values for parameters applied for the calculation are given in table 7.1. If in the case of a certain sub-catchment the threshold values for a certain animal type were higher than for the population observed in 1997, the 1997 value was used for calculations for this sub-catchment. Afforestation of all non-productive land areas in the entire basin was assumed for 'achieving the Ist class water quality' scenario (figure 7.3).

7.3 Results

The assumptions made for the different scenarios caused large differences in the initial settings of the model, which are reflected in the results of the IMT.

7.3.1 NULAM

The NULAM module yielded three characteristic values of emitted load: the total load, load originating from land use and load originating from livestock for three scenarios in 52 sub-catchments, head and differential ones. For the analysis of the scenario performance over the entire basin the results for basic head and differential sub-catchments were grouped into seven larger lumped catchment areas. These sub-catchments are the Upper Narew and together the Middle and Lower Narew and the sub-catchments of the Narew river main tributaries (the Suprasl, Biebrza, Pisa, Omulew and Orzyc rivers), modelled in STREAMPLAN (see chapter 4). For each group the total emitted loads for each scenario were calculated and then compared to the loads emitted at present (scenario 'present'), which was set to 100%.

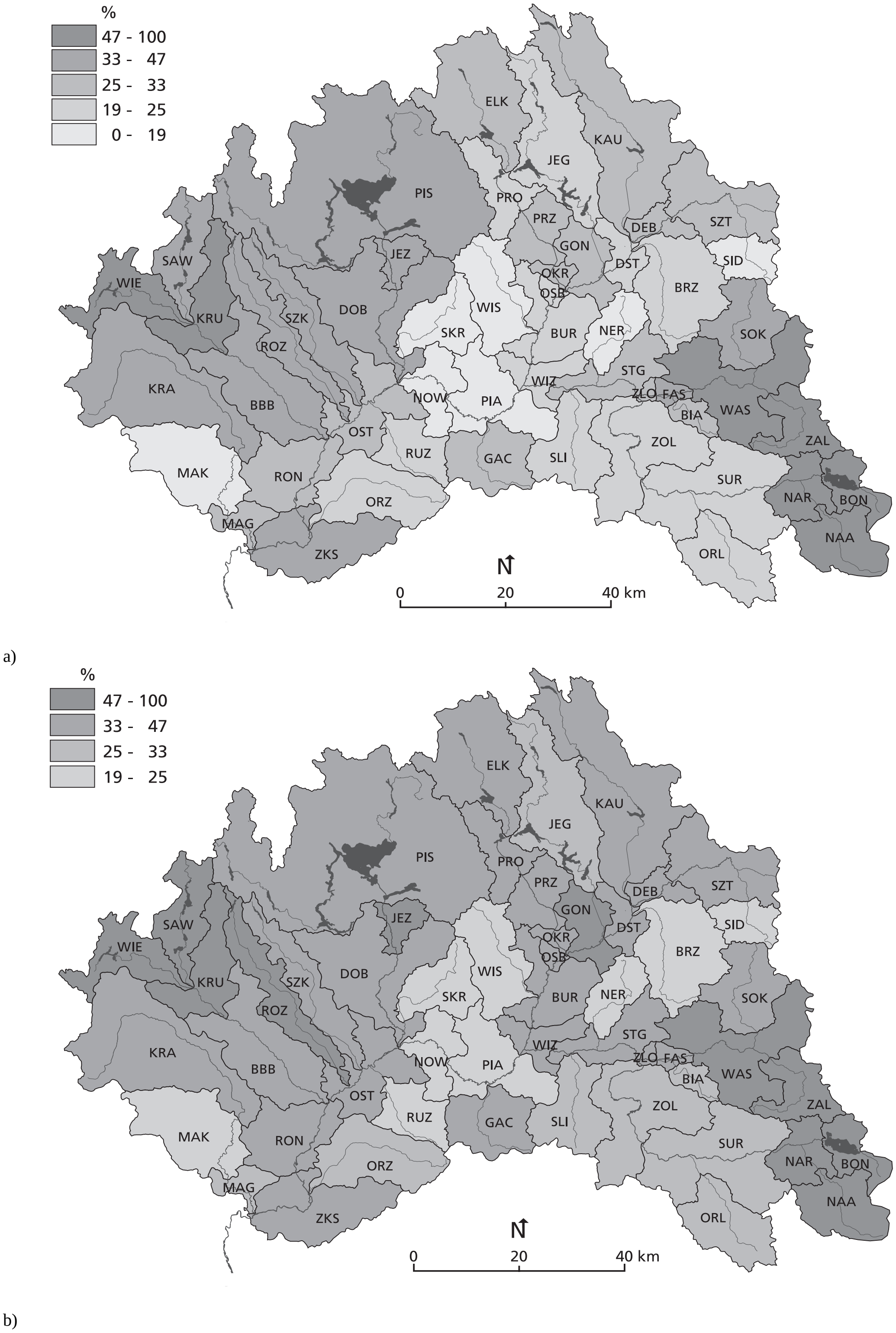


Figure 7.3 Forest acreage in the sub-catchments of the Narew River Basin: a) situation in 1997 (scenario ‘present’), b) future situation (scenario ‘achieving the Ist class water quality’)

Phosphorus

Compared to the present situation the ‘joining the European Union’ scenario resulted in the total emitted load of phosphorus increasing from just over 100 % for the Middle & Lower Narew and Upper Narew sub-catchments to almost 230 % for the Pisa river sub-catchment area (figure 7.4).

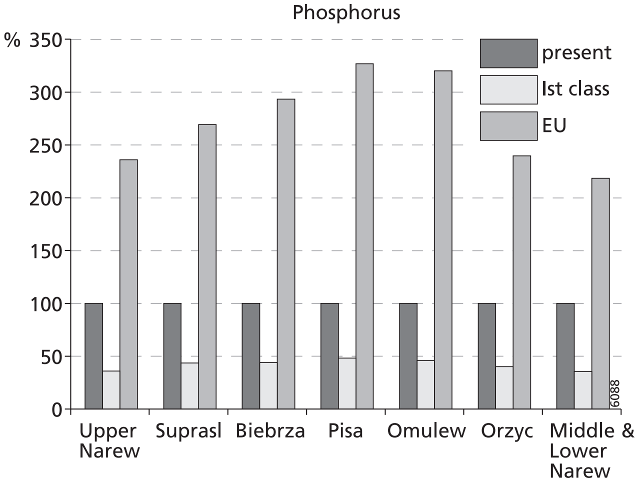


Figure 7.4 Changes in the total emitted phosphorus load for different scenarios for the main sub-catchments of the Narew River Basin

Relatively larger increases of the total emitted P-load were observed in the tributaries, especially those located in the middle and north parts of the basin (the Biebrza, Pisa and Omulew rivers) than in the sub-catchments of the main river. The scenario in which all non-productive land turned into forest (scenario ‘achieving the Ist class water quality’) reduced the total emitted phosphorus load from at least 52 % in the Pisa river sub-catchment to 65 % at most in the Middle & Lower Narew sub-catchment. The decrease was larger in the Narew river sub-catchments than in the tributaries sub-catchments. For the entire basin the reduction of the total phosphorus load was equivalent to 60% ($18.6 \cdot 10^6$ kg $P \cdot y^{-1}$) of the present load, while implementing the ‘joining the European Union’ scenario would increase the total emitted load by 163% ($50.7 \cdot 10^6$ kg $P \cdot y^{-1}$).

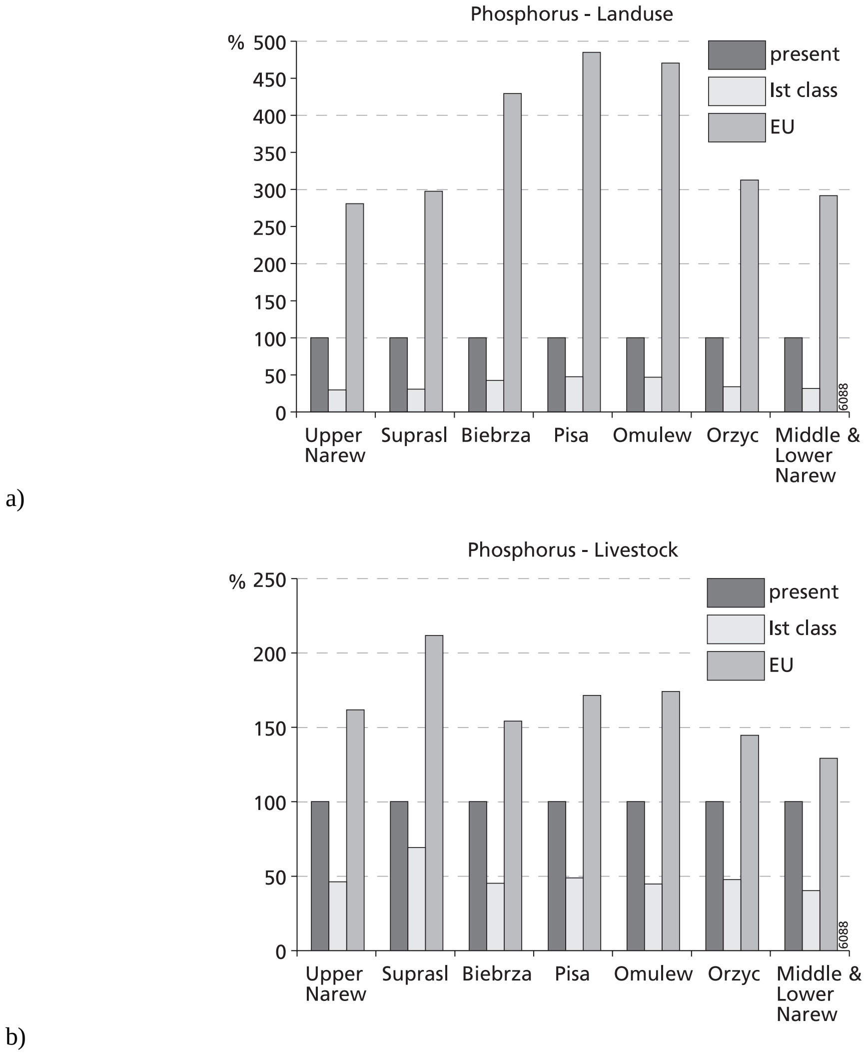


Figure 7.5 Changes in the component loads of the total emitted phosphorus load for different scenarios for the main sub-catchments of the Narew River Basin: a) land use originating load; b) livestock originating load

For the components of the total emitted load, the load originating from land use was reduced more than the changes in livestock giving loads for the 'achieving the Ist class water quality' scenario (figure 7.5a). For the entire basin the reduction in land use load was estimated at 54%, with variations from 60% (Middle & Lower Narew sub-catchment) to 31% (the Suprasl river sub-catchment). The livestock load was on average reduced in the basin by 64% and the reduction varied from 70% in the Upper Narew sub-catchment to 53% in the sub-catchments of the Pisa and Omulew rivers.

Loads coming from land use also increased more than loads originating from livestock in the 'joining the European Union' scenario (figure 7.5b). These loads increased in the entire basin respectively by 250%, with changes ranging from 180%

(Upper Narew sub-catchment) to 385% (the Pisa river sub-catchment) for land use loads and by 54%, with variation from 29% (Middle & Lower Narew sub-catchment) to 112% (the Suprasl river sub-catchment) for livestock loads.

Nitrogen

For nitrogen (figure 7.6) the reduction of the total emitted load for the scenario aiming at achieving the Ist water quality class was smaller than for phosphorus and varied from 33% (the Suprasl river sub-catchment) to 51% (Middle & Lower Narew sub-catchment). Also the increase of the total emitted load for the 'joining the European Union' scenario was lower for nitrogen than for phosphorus and ranged from 117% in the Middle & Lower Narew sub-catchment to 181% for the Pisa river sub-catchment. Relatively larger changes (increase and reduction) in the total emitted loads were observed in the upper and middle parts of the basin, especially in the sub-catchments of the tributaries (the Suprasl, Biebrza, Pisa and Omulew rivers), than in the lower part of the basin (the sub-catchments of Middle & Lower Narew and the Orzyc river). For the entire basin the decrease of the total nitrogen load was estimated at 151% ($224 \cdot 10^{6}$ kg $N \cdot y^{-1}$) of the present load. Introduction of the 'achieving the Ist class water quality' scenario could result in the reduction of the total emitted load by 45% ($66.9 \cdot 10^{6}$ kg $N \cdot y^{-1}$).

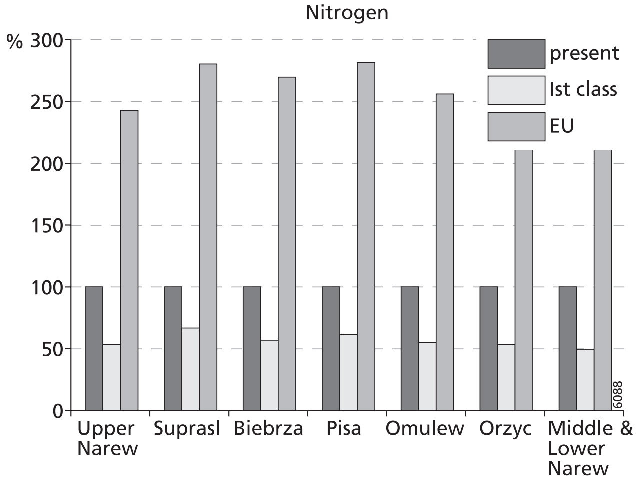


Figure 7.6 Changes in the total emitted nitrogen load for different scenarios for the main sub-catchments of the Narew River Basin

In contrast to phosphorus, for the components of the total emitted load, land use originating loads were reduced less than livestock originating loads within the 'achieving the Ist class water quality' scenario (figure 7.7a). The reduction in land use load for the entire basin was estimated at just 31%, with the range of changes varying from 37% (Upper Narew, Middle & Lower Narew and the Orzyc river sub-catchments) to 21% in the Pisa river sub-catchment. The variation in the reduction rates of the loads originating from livestock was somewhat larger and ranged from 61% in the Middle & Lower Narew sub-catchment to 33% in the Suprasl river sub-catchment, with average reduction for the entire basin accounted for 56%. The land use loads increased, as for phosphorus, more than livestock originating loads in the ‘joining the European Union’ scenario (figure 7.7b).

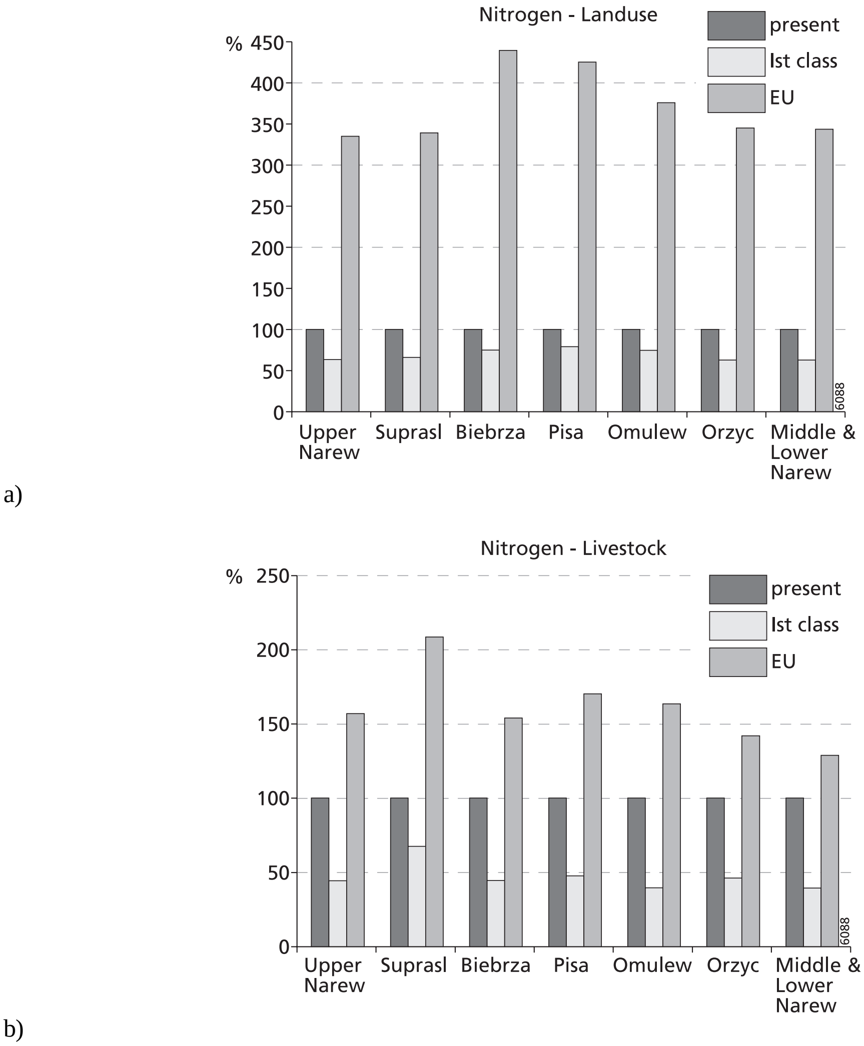


Figure 7.7 Changes in the component loads of the total emitted nitrogen load for different scenarios for the main sub-catchments of the Narew River Basin: a) land use originating load; b) livestock originating load

These loads increased in the entire basin respectively for land use loads by 277%, with the changes range from 235% (Upper Narew sub-catchment) to 339% (the Biebrza river sub-catchment) and for livestock loads by 52%, with variation from 29% (Middle & Lower Narew sub-catchment) to 108% (the Suprasl river sub-catchment).

7.3.2 STREAMPLAN

The STREAMPLAN model results were analysed at two levels: (i) a general overview for the entire river network (34 stretches) with water quality class indications for the model reaches according to a particular scenario plotted on the maps (figures 7.8 to 7.10 and 7.12 to 7.14) and (ii) with particular focus paid to the Narew river (12 stretches) where not only water quality class indications but concentration values were also studied. These results are presented in graphs (figures 7.11, 7.15 and 7.16) representing a longitudinal profile of the Narew river. The achieved results for all scenarios are plotted against limit values for the Polish official water quality classes (Water Classification, 1991). The changes in the volume of emitted loads in the sub-catchments, ensuing from an implementation of different scenarios (see section 7.3.1) had significant impact on the surface water quality in rivers of the basin. They imply that the quality status of waters will be changed, whether the quality class of most of the reaches would improve or deteriorate, depends on the scenario.

Phosphate

The most extreme impact of the different scenarios on changing the quality classes of the river stretches was observed for phosphate. At present, for this constituent only one stretch (Sztabin of the Biebrza river) is classified into the first quality class, while most of the rivers fall into the second class (20 stretches). There are still many stretches that are classified as the third quality class or beyond, respectively 9 and 4 stretches (figure 7.8). The Rudzki Canal, the entire Omulew river, lower courses of the Suprasl and Orzyc rivers and the middle course of the Narew all carrying water of the third class or worse.

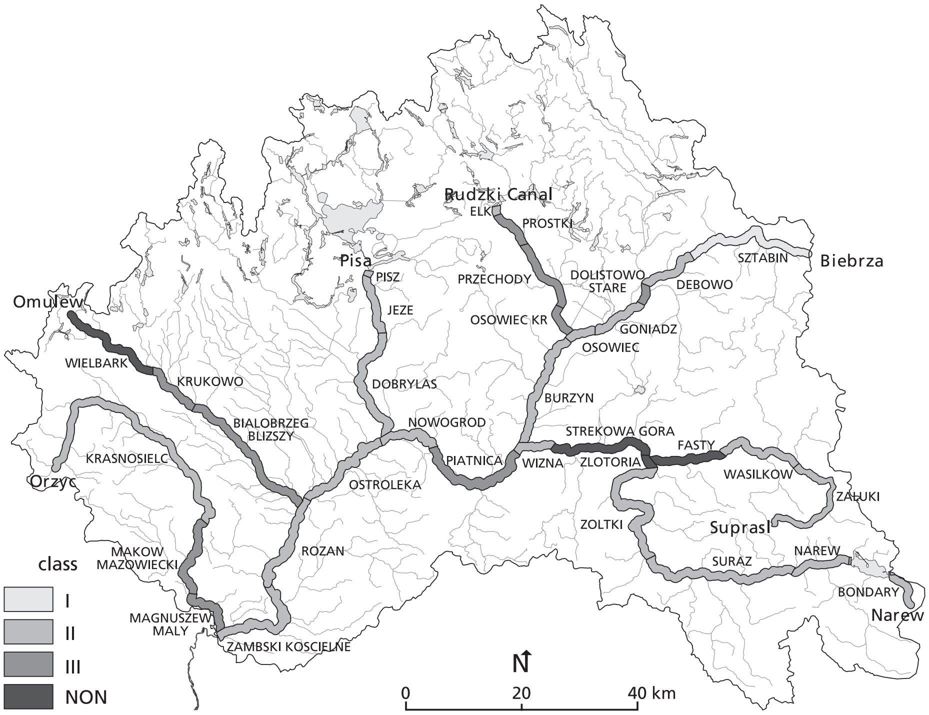


Figure 7.8 Water quality classification in the Narew network according to phosphate concentrations for scenario ‘present’. NON means concentrations higher than these of the third class.

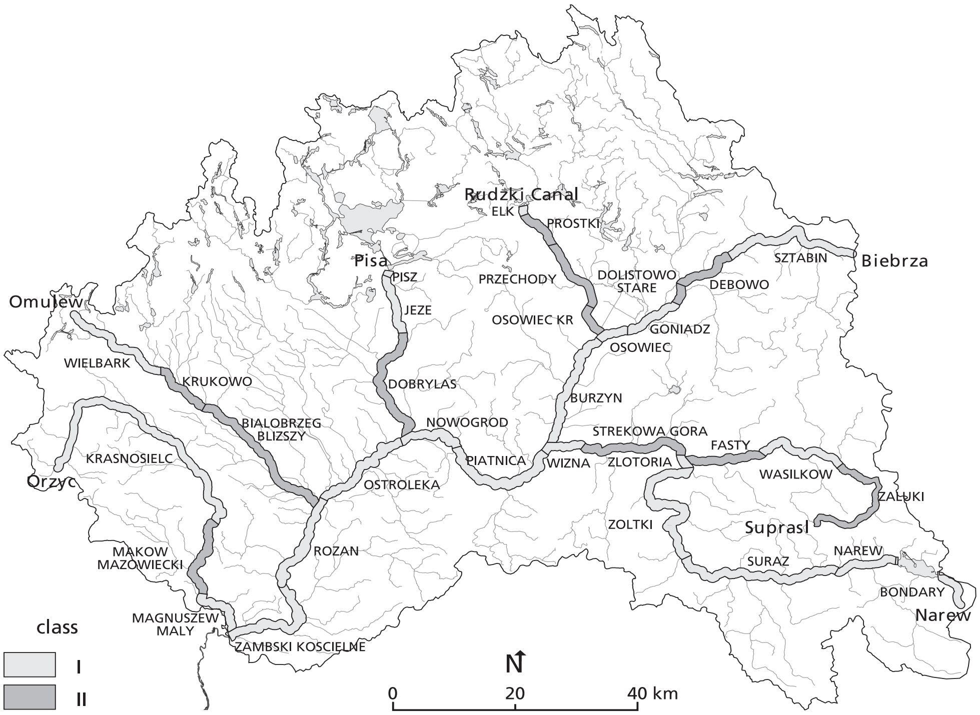


Figure 7.9 Water quality classification in the Narew river network according to phosphate concentrations for scenario ‘achieving the Ist class water quality’

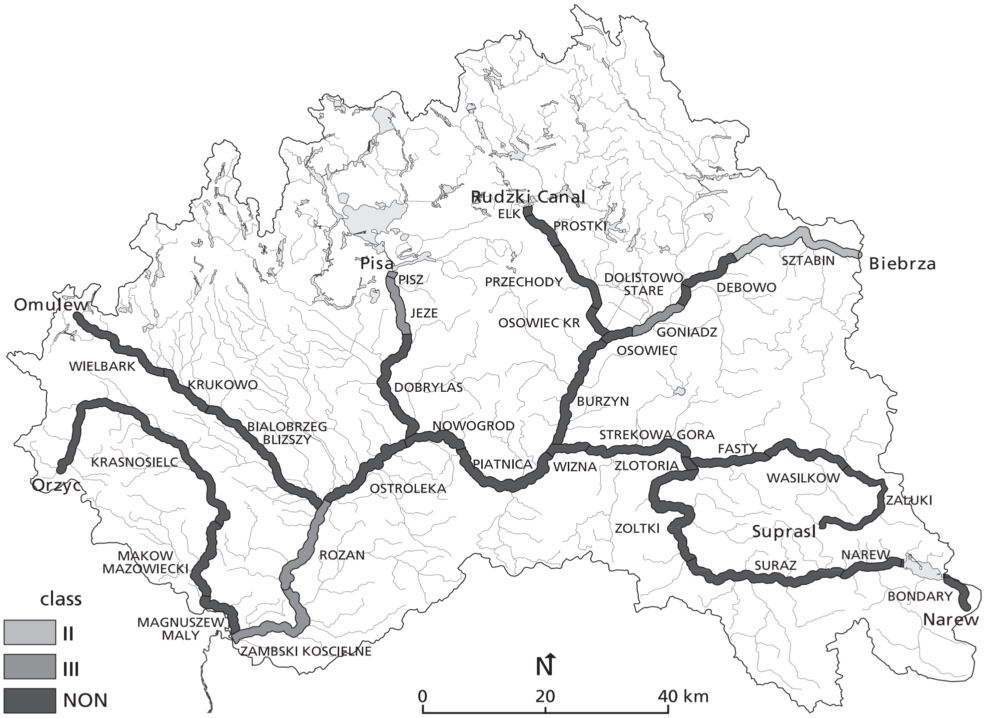


Figure 7.10 Water quality classification in the Narew river network according to phosphate concentrations for scenario 'joining the European Union'. NON means concentrations higher than these of the third class.

The implementation of the 'achieving the Ist class water quality' would improve water quality in all stretches by at least one class (figure 7.9). Most of the watercourses (22 stretches) in the basin would carry waters of the first quality class. No single stretch would be classified in the third class and only 12 stretches would fall into the second class (the lower courses of the Rudzki Canal, Suprasl, Pisa and Omulew rivers, Debowo – Dolistowo Stare stretch of the Biebrza river, Strekowa Gora stretch of the Narew river and Makow Mazowiecki stretch of the Orzyc river).

Severe deterioration in the quality of surface waters of the Narew river network would follow the introduction of changes as proposed in the 'joining the European Union' scenario (figure 7.10). All the stretches would be classified in at least one class lower compared to the present situation with only one stretch maintaining water of the second class (Sztabin of the Biebrza river); six would maintain the third class (the lower course of the Narew river, the upper course of the Pisa river and Goniadz stretch of the Biebrza river). All the other rivers (27 stretches) would carry non-classified waters (worse than the third class).

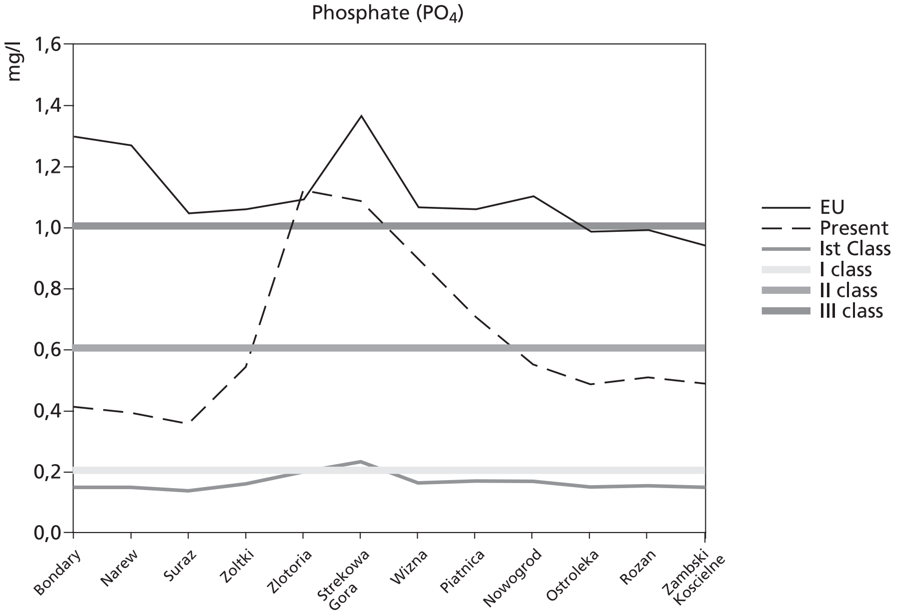


Figure 7.11 Changes in phosphate levels in surface water along the main course of the Narew river for different scenarios and their relation to the water quality classes

For phosphate, water along most of the Narew river is presently classified in the second quality class (figure 7.11). This is the case in the upper (Bondary – Zotki stretch, concentration range 0.36-0.54 mg·l^{-1}) and lower (Nowogrod – Zambski Koscielne stretch, concentration range 0.49-0.55 mg·l^{-1}) courses. In the middle course (Zlotoria – Piatnica stretch) water is characterised by higher phosphate concentrations, with maximum concentration of 1.12 mg·l^{-1} for the Zlotoria stretch, and it falls into the third quality class or even beyond it.

Implementation of the scenario ‘achieving the Ist class water quality’ would indeed improve water quality to the first class along the entire river course (concentration range 0.14-0.2 mg·l^{-1}) except for one stretch in the middle course (Strekowa Gora) where the first class limit would be slightly exceeded with a value of 0.23 mg·l^{-1}.

On the other hand the ‘joining the European Union’ scenario would cause water quality degradation along almost the entire river to values below the third quality class, with maximum concentration of 1.37 mg·l^{-1} for the Strekowa Gora stretch. Only the most lower stretch (Zambski Koscielne) would still maintain water of the third quality class, however with a concentration (0.94 mg·l^{-1}) just below the non-classified limit. This is the river stretch of particular importance because here the drinking water may be exploited.

Nitrate

For nitrate, implementation of the scenarios would also result in a shift of water quality between classes. However, the impact of different scenarios on changes in water quality classification shows less variation compared to phosphate and fewer stretches are moved to other classes. This is especially the case for 'achieving the Ist class water quality' scenario. The limited impact of this scenario is due to the present situation when already 11 stretches are classified within the first quality class (figure 7.12). The stretches in the upper course of the three rivers Narew, Biebrza and Omulew, and the entire Pisa river carry water of the highest quality. Most of the rest of the river network (17 stretches) is classified in the third quality class, while the remaining 6 stretches are classified either as the second class (5 stretches, the lower course of the Biebrza river, and individual stretches of the Narew and Omulew rivers) or beyond any class (Fasty stretch of the Suprasl river).

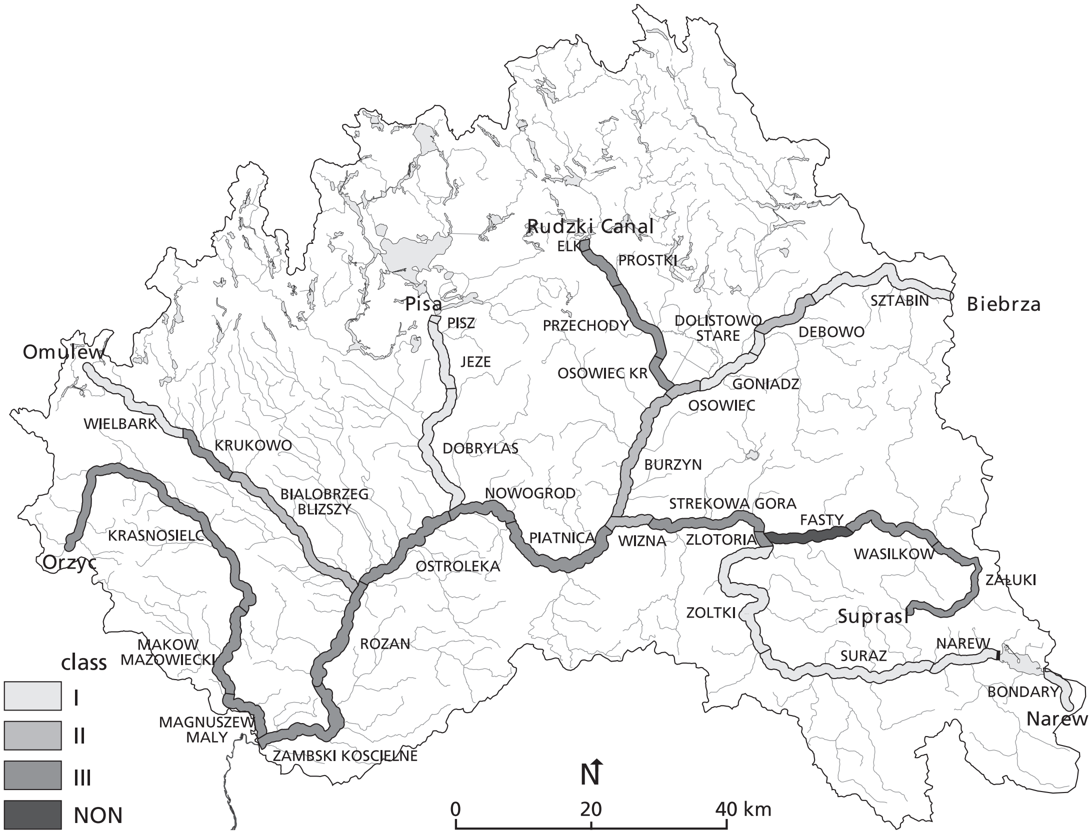


Figure 7.12 Water quality classification in the Narew river network according to nitrate concentrations for scenario 'present'. NON means concentrations higher than these of the third class.

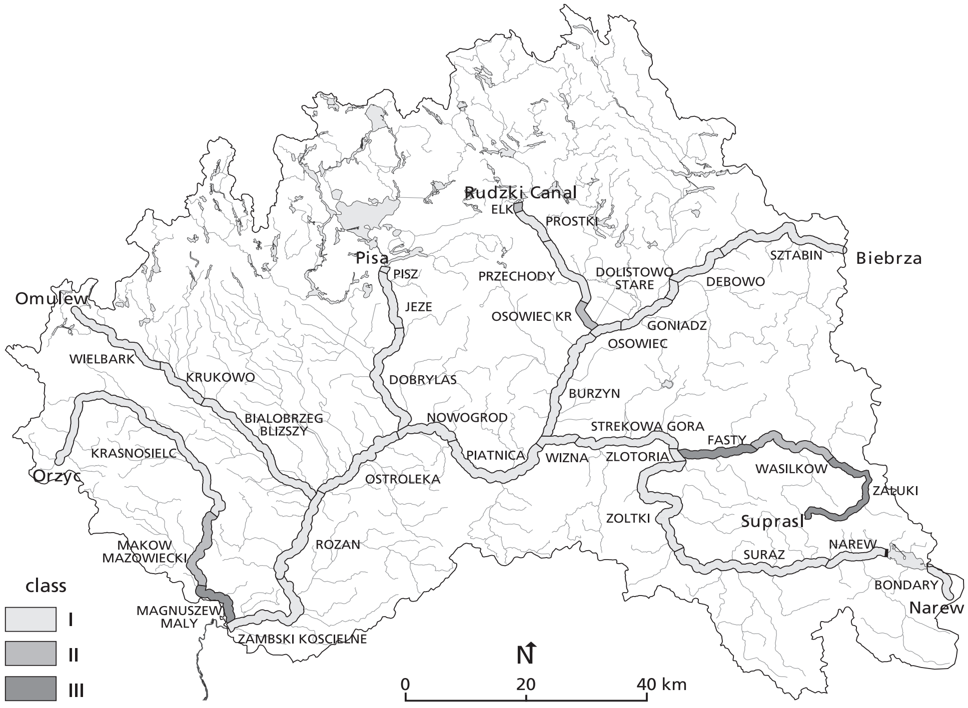


Figure 7.13 Water quality classification in the Narew river network according to nitrate concentrations for scenario 'achieving the Ist class water quality'

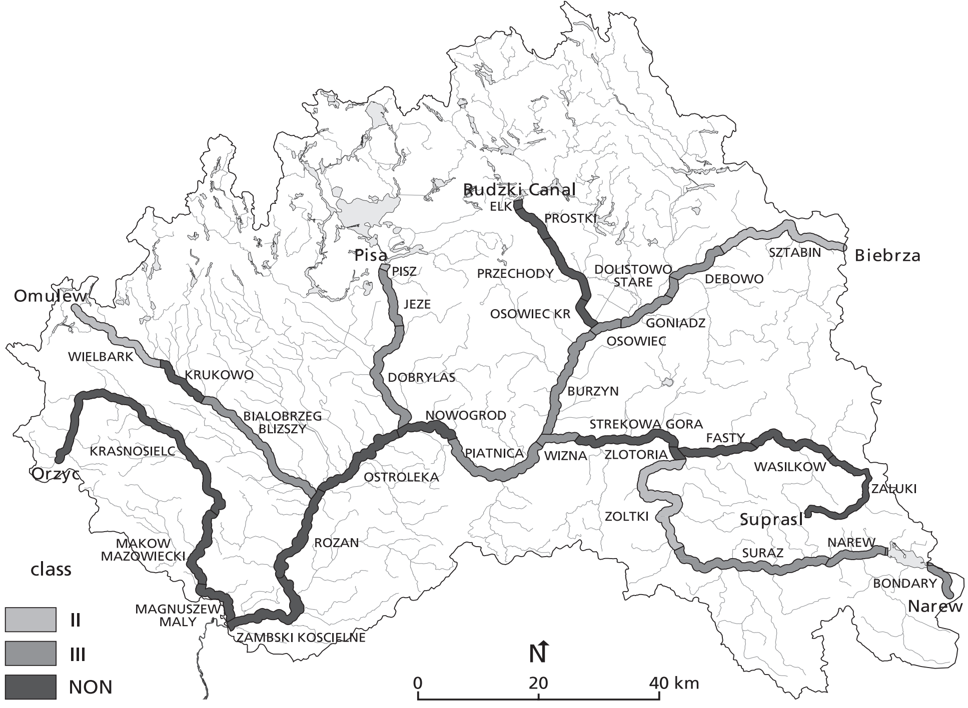


Figure 7.14 Water quality classification in the Narew river network according to nitrate concentrations for scenario 'joining the European Union'. NON means concentrations higher than these of the third class.

Implementing the 'achieving the Ist class water quality' scenario would improve the quality classification in all stretches except for those already carrying the first quality waters and two other (Zaluki of the Suprasl river and Magnuszew Maly of the Orzyc river) stretches, which maintain the same, third, quality class (figure 7.13). As a result, the number of watercourses (27 stretches) in the basin that would carry water of the first quality class is even larger than it is for phosphate. However, three stretches would be classified as low as the third class, the two mentioned above and the Fasty stretch of the Suprasl river. The four remaining stretches (individual ones in the Suprasl and Orzyc rivers and the Rudzki Canal) would be classified in the second quality class.

The introduction of the 'joining the European Union' scenario would significantly degrade the quality of surface waters in the Narew river network but this would be less than the situation for phosphate (figure 7.14). All the stretches but one (Piatnica of the Narew river) would be classified in at least one class lower compare to the present situation. However, the four stretches (head course of the Biebrza, Pisa and Omulew rivers and Zoltki stretch of the Narew river) would maintain the second quality class. The rest of the watercourses would be split between the third class stretches (13, the upper course of the Narew river, and the Biebrza and Pisa rivers) and non-classified ones (17, the lower course of the Narew river, the Rudzki Canal, and the Suprasl and Orzyc rivers).

With regard to nitrate, at present, the upper course of the Narew river (stretch from the source up to Zoltki, concentration range 2.34-4 $mg \cdot l^{-1}$) carries first quality class water (figure 7.15). Along the rest of the river water is of only the third quality class (concentration range 7.81-14 $mg \cdot l^{-1}$), except for the Wizna stretch where concentration (6.69 $mg \cdot l^{-1}$) was just below the third class limit.

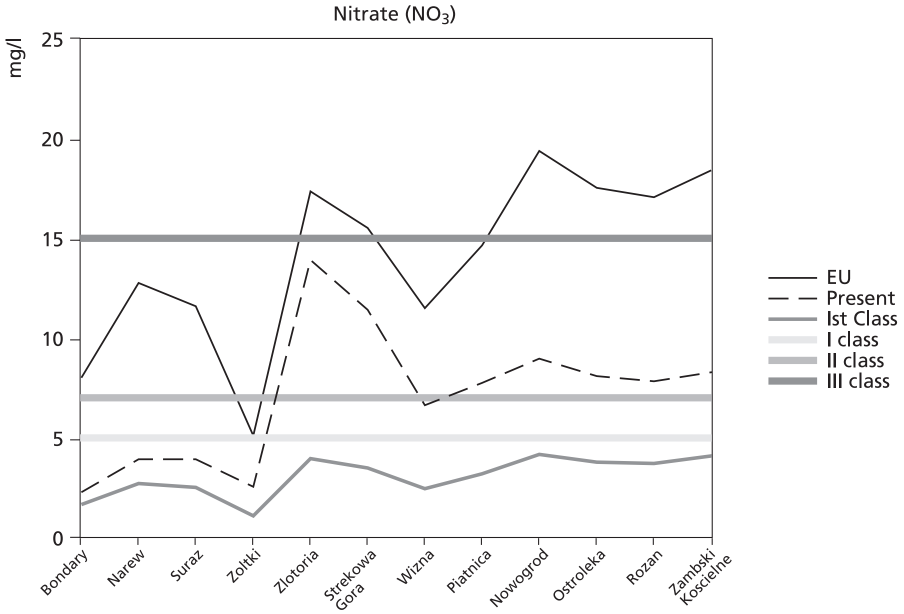


Figure 7.15 Changes in nitrate levels in surface water along the main course of the Narew river for different scenarios and their relation to the water quality classes

Reduction of nitrogen emission, assumed in ‘achieving the Ist class water quality’ scenario, would lower nitrate concentrations (range 1.14-4.24 mg$\cdot$l^{-1}) along the entire river. As a result water would be of the first quality class not only in the upper course but along the entire river.

Higher nitrogen emissions within the sub-catchments, expected from introduction of the ‘joining the European Union’ scenario, would result in higher concentrations of nitrate in surface waters and in turn in worsening of water quality. The deterioration of water quality would shift the upper course stretches from the first class into the second and third classes (concentration range 5.17-12.8 mg$\cdot$l^{-1}). The downstream stretches would maintain the third quality class but with higher concentrations (11.6-14.7 mg$\cdot$l^{-1}, Wizna – Piatnica stretch) or fall beyond any class with a maximum concentration of 19.4 mg$\cdot$l^{-1} in the Nowogrod stretch.

At Zambski Koscielne, the river stretch relevant for drinking water production, only ‘achieving the Ist class water quality’ scenario results in nitrate concentration falling in the Ist class water quality. The ‘joining the European Union’ scenarios leads to concentrations exceeding the third class limit.

Ammonium

Only for ammonium would the changes in the nutrient emissions within the sub-catchments have limited impact on the water quality in the Narew basin river network. For this constituent the water is currently of the first quality class along the entire Narew river (figure 7.16) as well as in all the other watercourses in the basin. Notwithstanding changes in ammonium concentrations with implementing different scenarios the water quality of all stretches would remain within the first quality class even for the ‘joining the European Union’ scenario.

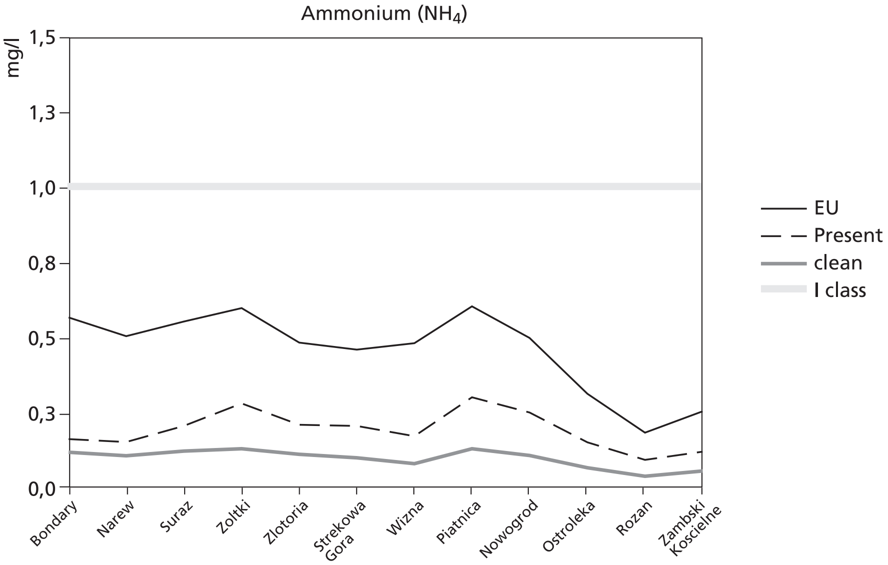


Figure 7.16 Changes in ammonium levels in surface water along the main course of the Narew river for different scenarios and their relation to the water quality classes

Certainly, depending on the scenario, ammonium concentration will increase or decrease compared to the present situation. However, even the maximum concentrations (0.95 $mg \cdot l^{-1}$ for Krasnosielc stretch of the Omulew river) estimated for any of the stretches would be better than the first quality class limit. The causes are the low present level of ammonium concentrations and the nitrification process in the river stretches.

7.3.3 INCORS

The INCORS module is used to model aquatic vegetation – water quality relationships. The ecological modelling with INCORS requires information about the abiotic conditions in the aquatic system, available from the combined NULAM and STREAMPLAN modelling. These data have been used for the locations with complete information spread over the basin, separated in 11 locations in smaller up-stream parts of the rivers and 41 locations at the wider down-stream parts of the river. At each location the probabilities to encounter 32 species have been calculated for three different scenarios. This results in about 1000 probabilities for smaller rivers and 4000 probabilities for wider rivers. The question is how to evaluate these data to a review of the ecological development with the three scenarios.

Evaluation methods

Information about the possibilities of ecological response to changes in nutrient concentrations are available from the vegetation description (see chapter 5), where the types of vegetation and their conditions are formulated. Since, very good conditions are represented in the dataset, as well as deteriorated ones, the possibilities for ecosystem development are represented. The question how to evaluate the results was answered by selection of the characteristic species of the vegetation clusters and by comparing the probabilities of encountering these species derived by three methods.

The data for the smaller rivers are summarised in table 7.2 and those of the wider rivers in table 7.3. The species groups from the clustering are first repeated in the tables, to illustrate the groups of species and their types of vegetation. This is followed by three different ways to summarise the differences between the scenarios.

The first way is to calculate the mean probability of each species for each scenario, which gives at least an indication about the level of prediction of each species. However, an extreme value at one spot will have a distinct influence on the average values; since the general tendency is requested, other methods were also used.

The second way to illustrate the differences is to calculate the mean differences in prediction of the species by an index of the first scenario results divided by the probabilities from the second scenario. When the index is almost 1, the species is equally represented in both scenarios. High values, represent that the first scenario scores definitely higher than the second; low values indicate that the second scenario leads to higher probabilities.

These values from the index are scored as follows:

index > 2.0	species indicated with	+++
2.0 < index < 1.5	species indicated with	++
1.5 < index < 1.2	species indicated with	+
1.2 < index < 0.9	species indicated with	.
0.9 < index < 0.75	species indicated with	-
0.75 < index < 0.5	species indicated with	--
index < 0.5	species indicated with	---

A third way to show the differences is simply to compare the real probabilities of each species for two scenarios at each location. For the smaller rivers (n=11) the light arrow ⇦ is used to indicate that one scenario returns higher probability values more than 6 times and the dark arrow ➡ is used to indicate that one scenario gives higher probabilities in more than 9 out of 11 cases, with the arrow head pointing in the direction of the highest values. For the wider river locations (n=41) the values are more than 25 times those for the light arrow and more than 35 times the dark one. Species giving less clear differences in response on the scenarios are denoted by a dot.

Ecological evaluation

Smaller rivers

The group of species characteristic for cluster 2 (*Ranunculus circinatus* etc.) and clusters 2 and 4 (*Elodea canadensis* etc.) seem likely to disappear in the 'joining the European Union' scenario, compared to the present conditions. These species will be stimulated by the 'achieving the Ist class water quality' scenario, compared to the present conditions. In general the species characteristic for cluster 6 (*Carex riparia* etc.) show the reverse trend: mostly stimulated by the 'joining the European Union' scenario and having the lowest probabilities in the 'achieving the Ist class water quality' scenario. The species from cluster 4 (*Glyceria fluitans* etc.) show quite different responses, however, in most cases the present conditions lead to higher probabilities. Finally, there is a tendency that species common to all clusters (2+4+6; *Potamogeton natans* etc.) will be stimulated by the 'joining the European Union' scenario, although the differences are very limited.

The interpretation of these results is that the vegetation type of cluster 2 will be maintained in the present conditions, but will be stimulated by the 'achieving the Ist class water quality' scenario. The conditions occurred from the 'joining the European Union' scenario will result in the disappearance of this type of vegetation. Since, the type of vegetation characteristic for cluster 6 is stimulated by the 'joining the European Union' scenario, it can be expected that this vegetation will replace the clean water vegetation of cluster 2. The vegetation type of cluster 4 is in an intermediate position and will in most cases be present.

Wider rivers

The types of vegetation in wider rivers (clusters 1, 3 and 5) have many species in common (*Butomus umbellatus* etc.). It appeared that most of these species have higher probabilities in the present conditions, compared with those from the 'joining the European Union' scenario as well as from the 'achieving the Ist class water quality' scenario. Most species characteristic for the vegetation types of cluster 1 and 3 (and in common for these clusters) show lower responses in the conditions of the 'joining the European Union' scenario, compared with the present conditions. Most of the same species will obtain higher responses if the 'achieving the Ist class water quality' scenario were to be implemented. Finally, there is the group of species with weak preference of cluster 1, and in general indicators for eutrophication (*Flab* etc.), which will be stimulated by the 'joining the European Union' scenario conditions, whereas the conditions from the 'achieving the Ist class water quality' scenario will result in lower probabilities.

The interpretation in terms of ecosystem development in the three scenarios is obvious for the wider rivers. The group of species common to all clusters will be maintained best by the present conditions. The only species that will be stimulated by 'joining the European Union' scenario is a group of six species, characteristic for eutrophication. The vegetation from cluster 1 as well as from cluster 3 is stimulated by the 'achieving the Ist class water quality' scenario. These two types prefer both high water quality conditions (see also chapter 5) and will obtain lower responses in the 'joining the European Union' scenario.

Table 7.2 Scenario study results for the smaller river locations

Cluster groups	Species	Cluster			Scenario[a]									
		Vegetation abundance			Mean probability			Index		Directions				
		2	4	6	EU	zero	first	EU\0	first\0	EU		zero		first
2	Ranunculus circinatus	1.08	-	-	0.07	0.13	0.13	--	+++		⇨		⇨	
	Carex acutiformis	1.85	0.42	0.33	0.27	0.47	0.48	--	.		⇨		⇨	
	Equisetum fluviatile	0.84	0.05	-	0.02	0.14	0.34	--	+++		➡		➡	
	Fontinalis antipyretica	0.46	0.16	0.33	0.25	0.68	0.63	---	+++		⇨		⇨	
	Iris pseudoacorus	0.31	-	-	0.08	0.18	0.30	--	+++		⇨		⇨	
	Potamogeton lucens	0.31	0.06	-	0.09	0.18	0.33	--	+++		➡		➡	
	Scutellaria galericulata	0.38	0.11	-	0.17	0.37	0.44	++	+++		⇨		.	
	Sium latifolium	1.31	0.21	-	0.16	0.29	0.29	--	+		⇨		.	
	Sagittaria sagittifolia	2.46	0.47	-	0.69	0.87	0.93	-	.		➡		➡	
2+4	Elodea canadensis	2.38	2.84	0.33	0.49	0.63	0.66	-	.		➡		⇨	
	Lemna trisulca	1.15	1.79	-	0.08	0.17	0.13	--	+++		⇨		⇦	
	Cicuta virosa	0.23	0.11	-	0.41	0.49	0.40	-	-		➡		➡	
	Nuphar lutea	0.85	0.68	-	0.06	0.10	0.15	--	++		⇨		⇦	
4	Glyceria fluitans	0.69	2.21	0.17	0.18	0.14	0.10	++	--		⇦		⬅	
	Berula erecta	0.15	1.68	-	0.01	0.03	0.01	.	.		⇨		⇦	
	Mentha aquatica	0.62	1.11	-	0.17	0.32	0.33	-	++		⇨		.	
	Myosotis palustris	0.69	1.00	-	0.11	0.16	0.16	+++	-		.		⇦	
	Rumex hydrolapathum	0.15	0.79	0.17	0.04	0.06	0.07	++	-		.		⇦	
	Scirpus sylvaticus	0.15	0.42	-	0.00	0.00	0.00	.	.		➡		⇨	
	Sparganium emersum	0.69	1.74	-	0.13	0.20	0.17	-	+		⇨		⇦	
	Sparganium erectum	0.62	1.63	0.17	0.05	0.16	0.26	--	++		➡		➡	
6	Carex riparia	0.08	0.26	0.50	0.00	0.00	0.00	.	.		⇦		⬅	
	Typha latifolia	-	0.16	0.50	0.09	0.04	0.02	+++	--		⇦		⇦	
	Flab (= algae)	0.23	0.95	3.50	0.63	0.43	0.33	++	--		⬅		⬅	
	Acorus calamus	0.08	0.21	0.50	0.08	0.12	0.19	-	+++		➡		➡	
	Potamogeton pectinatus	0.46	0.37	1.83	0.63	0.45	0.35	++	--		⬅		⬅	
	Potamogeton perfoliatus	-	-	0.33	0.81	0.61	0.55	++	.		⬅		⇦	
2+6	Callitriche species	0.92	-	0.83	0.24	0.20	0.11	++	--		⬅		⬅	
2+4+6	Potamogeton natans	0.54	0.68	1.17	0.74	0.75	0.84	.	.		⇦		⇦	
	Lemna minor	1.77	2.11	1.17	0.54	0.49	0.30	+	--		⇦		⬅	
	Phalaris arundinacea	2.85	1.37	2.83	0.86	0.78	0.66	.	-		⬅		⬅	
	Butomus umbellatus	0.08	0.63	0.67	0.82	0.78	0.78	.	.		⬅		.	

[a] ‘EU’ denotes ‘joining European Union’ scenario; ‘zero’ & ‘0’ denote ‘present’ scenario; ‘first’ denotes ‘achieving Ist class of water quality’

Table 7.3 Scenario study results for the wider river locations

Cluster	Species	Cluster			Scenario[a]									
groups		Vegetation abundance			Mean probability			Index		Directions				
		2	4	6	EU	zero	first	EU\0	first\0	EU		zero		first
5+1+3	Butomus umbellatus	1.50	1.93	1.47	0.90	0.88	0.88	.	.		⬅		.	
	Nuphar lutea	1.55	1.46	3.03	0.62	0.69	0.52	.	-		⇨		⬅	
	Sagittaria sagittifolia	2.90	1.93	2.43	0.81	0.93	0.97	-	.		➡		➡	
	Mentha aquatica	0.30	0.71	0.77	0.18	0.43	0.30	--	--		➡		⇦	
	Spirodela polyrhiza	1.40	2.43	1.47	0.07	0.29	0.51	---	++		➡		➡	
	Sparganium emersum	1.00	1.04	0.63	0.17	0.25	0.20	--	-		➡		⇦	
	Sparganium erectum	1.00	0.75	1.23	0.01	0.13	0.33	---	-		➡		➡	
	Myosotis palustris	0.80	0.82	0.70	0.14	0.20	0.13	.	--		⇨		⬅	
	Rumex hydrolapathum	0.20	0.18	0.47	0.06	0.09	0.02	+	---		.		⬅	
1+3	Potamogeton perfoliatus	0.15	1.36	1.73	0.91	0.77	0.69	+	.		⬅		⇦	
	Potamogeton natans	-	0.71	1.03	0.70	0.70	0.70	.	.		⇦		.	
	Myriophylum verticillatum	-	0.36	0.23	0.00	0.04	0.38	--	+++		➡		➡	
	Ranunculus aquatilis	-	0.29	0.13	0.18	0.33	0.54	--	++		➡		➡	
	Hydrocharis morsus-ranae	-	0.46	0.33	0.00	0.00	0.00	.	+		➡		➡	
1	Potamogeton nodosus	0.15	0.71	-	0.08	0.08	0.07	.	-		.		⇦	
	Potamogeton trichoides	-	0.32	-	0.00	0.06	0.14	-	+++		➡		⇦	
	Ranunculus fluitans	0.05	0.57	-	0.01	0.11	0.51	---	+++		➡		➡	
	Myriophyllum spicatum	0.15	0.39	0.03	0.25	0.29	0.37	-	+		➡		➡	
3	Acorus calamus	-	0.61	1.20	0.14	0.20	0.30	--	++		➡		➡	
	Potamogeton lucens	0.05	0.89	1.93	0.16	0.30	0.49	--	++		➡		➡	
	Phragmites australis	0.35	0.29	1.53	0.08	0.11	0.15	--	+		➡		➡	
	Cicuta virosa	-	0.11	0.43	0.07	0.12	0.17	--	++		➡		➡	
	Nymphaea alba	-	-	0.40	0.00	0.00	0.00	.	+		➡		➡	
	Scirpus lacustris	0.05	0.25	0.67	0.06	0.11	0.17	--	++		➡		➡	
	Stratiotes aloides	-	0.04	0.27	0.28	0.09	0.02	+++	--		⬅		⬅	
	Typha angustifolia	-	0.14	1.13	0.09	0.11	0.16	-	++		⇨		➡	
1+eutro	Flab (= algae)	0.35	1.71	0.97	0.71	0.53	0.37	+	--		⬅		⬅	
	Potamogeton pectinatus	0.10	2.39	0.30	0.77	0.62	0.48	+	--		⬅		⬅	
	Lemna minor	1.60	2.25	1.63	0.70	0.61	0.30	+	---		⇦		⬅	
	Phalaris arundinacea	3.00	1.57	1.53	0.85	0.76	0.63	+	-		⬅		⬅	
	Ceratophyllum demersum	0.05	0.57	0.63	0.11	0.07	0.02	++	--		⬅		⬅	
	Glyceria fluitans	0.10	0.54	0.37	0.15	0.11	0.06	+	---		⇦		⬅	

[a] ‘EU’ denotes ‘joining European Union’ scenario; ‘zero’ & ‘0’ denote ‘present’ scenario; ‘first’ denotes ‘achieving Ist class of water quality scenario

7.4 Discussion and conclusions

The impacts of nutrient emission, surface water quality and status of aquatic vegetation were modelled and analysed by means of the Integrated Management Tool. This tool proved to be efficient for scenario analysis and allowed a relatively simple and effective assessment of the impact of one element on the others in the environmental cause-and-effect chain.

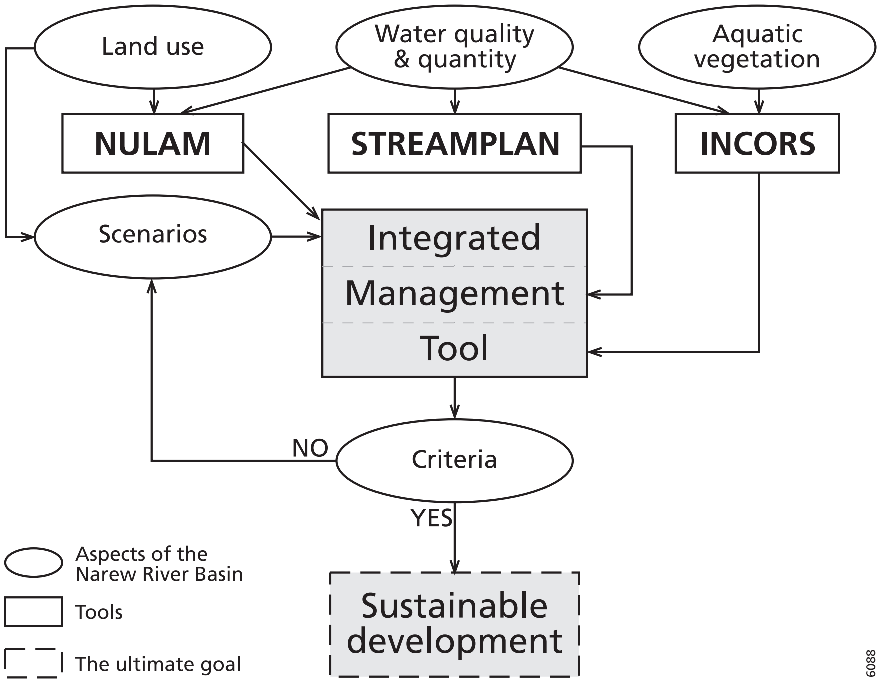
The two proposed scenarios for future development of the Narew River Basin were based on present knowledge about expected directions of such development. They were designed to analyse effects of political and for the natural environment benign development of the basin. However, they rather indicate the frames within which the possible management strategies for the basin are plausible to evolve than present the ultimate targets to be reached, if any of the scenarios would be implemented as a management policy (especially in case of the 'joining the European Union' scenario). Even when the environmental aspects are determined in an objective, scientific sound way, it is still not possible to deduce unequivocal norms and prerequisites for human behaviour (van de Klundert, 1995).

The absolute implementation of 'joining the European Union' scenario would result in approximately 2.5 times higher nutrient emissions in the basin. In turn this would cause the degradation of water quality in watercourses to the third quality class and beyond, and would restrain development of mesothropic plant species while at the same time stimulating growth of eutrophic species. Also for the suitability of the river water at Zambski Koscielne for drinking water production, implementation of the 'joining the European Union' scenario has negative consequences: for both nitrate and phosphate concentrations would be around the upper limit of the IIIrd water quality class. Thus it is shown that rapid intensification of agriculture in the basin which might take place after Poland joins the European Union might significantly reduce surface water quality leading to lower suitability for drinking water preparation and endanger highly valuable aquatic ecosystems that are characteristic for the region.

On the other end the execution of measures proposed in the 'achieving the Ist class water quality' scenario would reduce nutrient emissions for both nitrogen and phosphorus, by 45 % and 60% respectively. This reduction would cause an upgrading of surface water quality in the river network to, predominantly, the Ist quality class and enhance the conditions for growth of characteristic mesotrophic plant species at the cost of indicators of eutrophication. Therefore, only very restricted agricultural practices, especially limited use of fertilisers, might lead to the preservation of the aquatic ecosystems at the desired level and to improvement of the surface water quality and thus increasing its potential for drinking water production. And ultimately, reaching the first water quality class in the main rivers might be the crucial target for securing sustainable development of the basin (Gielczewski et al., 1998a).

The procedure of setting up changes to different scenarios concentrated on two aspects: changes related to land use characteristics and those related to livestock. The impact of the changes applied to these two parts on the total emitted nutrient loads and then subsequently on surface water quality and condition of aquatic ecosystems had a different extent within the same scenario. A major increase of the total emitted load of nitrogen and phosphorus, by 80% and 85% respectively, resulted from the changes applied to land use in the ‘joining the European Union’ scenario. For phosphorus also in case of ‘achieving the I^{st} class water quality’ scenario the major reduction in the total emitted load (60%) resulted from reduction of the load originating from land use changes. Only in the case of the reduction of nitrogen load from livestock did changes account for a larger reduction (70%) of the total emitted load. Thus, the measures taken in the land use would supposedly have a larger influence than those applied on livestock, on the improvement or deterioration of the present situation in the basin.

The results of the study confirm that, in general, agricultural borne pollution is a key issue in reaching a good status of surface waters and water ecosystems in Polish lowland rivers.


Land use
Water quality & quantity
Aquatic vegetation
NULAM
STREAMPLAN
INCORS
Scenarios
Integrated Management Tool
NO
Criteria
YES
Sustainable development
Aspects of the Narew River Basin
Tools
The ultimate goal
6088

8 APPLICABILITY OF THE INTEGRATED MANAGEMENT TOOL IN THE DECISION MAKING PROCESS

8.1 The dilemma of choosing a specialised approach or covering a wider multidisciplinary field

Today, anybody attempting to investigate environmental issues at the river basin scale faces a well known dilemma from the sport stadiums ‘who is the bigger master - a decathlon man or a 100 metre runner’. The question is “shall I focus on a single element of the environment and then study it very thoroughly or is it better to investigate a broader cause-and-effect chain of environmental issues but on a more general level?” The public loves 100 metre runners because they are the fastest of all but they also admire decathlon champions for their strength and overall skills. Individual discipline masters develop the most advanced training methods and push their own discipline towards the limits while decathlon men use and combine the experiences of many others and show how far one may reach if the elements are integrated in one. River basin research needs ‘100 metre runners’ to understand better the functioning of elements in the basin and to develop more precise and efficient methods for analysing these elements. On the other hand an integrated, ‘decathlon man’, approach is essential to understand relations between and functioning of the cause-and-effect chains consisting of inevitably related elements and to study effects of changes in one element on the other elements of the chain.

In the mid-90ties when the project that created a basis and framework for this thesis was formulated an integrated basin approach was not well recognised and rarely addressed. This holds especially for inclusion of ecosystems in river basin studies. The idea, in the project description, of connecting drinking water production and conservation of nature for mutual benefits started more from searching for solutions to these problems than from systematised concepts of basin wide management, which were yet to be formulated at this time. The necessity of an integrated approach to river basin issues, which has been stressed and foreseen among other topics also by this project, was ultimately confirmed by the formulation of the European Water Framework Directive for River Basins issued in October 2000 (EU, 2000).

The problem addressed in this thesis required detailed investigation and combination of several aspects of physical environment. Therefore, a ‘decathlon man’ approach was required. Such an integrated approach was applied to investigate relations and changes in the physical environment cause-and-effect chain consisting of land use, surface water and aquatic ecosystems on the river basin level. The aim of this thesis was to investigate the scientific basis for linking the functions of a large city and unspoiled nature in search for sustainable development of the Narew River Basin by responding to a need to support decision makers who must make a management plan that meets such development. A way to achieve that aim was to develop an integrated tool that allows policy makers to analyse management strategies in the Narew River Basin and to separate sustainable strategies from non-sustainable ones. The intended tool should quantify the impact of land use changes on nutrient emissions, water quality and aquatic vegetation and allow for scenario studies. This was realised in chapter 7, where the separate calculation modules for nutrient emissions, surface water quality and presence of aquatic species were assembled into an Integrated Management Tool (IMT). The IMT was then in turn used for a simple scenario study.

8.2 The IMT as the adequate answer

After completing the three sub-modules, they were linked as three hierarchically interlinked modules in the IMT (see figure 1.1 chapter 1). The component modules of the IMT were described in respectively chapter 2 (emitted nutrient load assessment module, NULAM), chapter 4 (in-stream water quality module, STREAMPLAN) and chapter 6 (aquatic species response module, INCORS).

As explained in chapter 2 the NULAM module is a lumped model based on an export coefficient approach. It assesses nutrient emission from different sources in the sub-catchments of the basin based on land use characteristics (land use types, livestock, fertilisation), excretion coefficients and atmospheric deposition. Subsequently, it calculates the fate of the emitted load that reaches the surface water and converts load data into concentration values. Statistics, literature and monitoring datasets considering respectively land use characteristics, excretion coefficients and water quality and quantity were used for model calculations. The NULAM model was calibrated based on land use data for administrative units (communities and voivodeships) for 1995-1996 and water quality and quantity data collected in September 1997.

The output results of the NULAM module were fed to an in-stream water quality model (STREAMPLAN). This is a one-dimensional, linear, steady state model. The physical processes are described based on the principles of mass balance along the river reach. The model was calibrated and validated for the nodal points representing the end points of the main stretches of the river network in the basin. These were the same points as the closing points of sub-catchments for which the load assessment module was applied. For calibration and validation water quality and quantity data were used, collected in the monitoring network in September 1997 and September 1996 respectively. For any given river stretch the data include nutrient inflow from up-stream, from a sub-catchment, from a tributary(ies) and from a point source(s), and outflow to the downstream stretch. Calibrated and validated parameters (nutrient decay coefficients) are representative for a vegetation period characterised by low discharge. The results of in-stream water quality modelling are nutrient concentrations at the nodal points located along the river network of the basin.

These concentrations are input data for the aquatic vegetation model (INCORS), which was based on vegetation composition data collected during field work at over 100 relevees including the water quality model nodal points. This empirical statistical approach is based on the concept of Generalized Linear Models. Multiple logistic regression modelling was used to specify the functional relationship between aquatic plant species on the one hand and nutrient concentrations and river morphology on the other hand. The applied procedure resulted in regression formulations for 47 plant species present at least five times in the entire dataset. The results of the model performance are probability values that certain plant species are present at a given location in the basin with given certain environmental conditions.

As the final step the IMT was used for a simple scenario simulation. From this exercise it was concluded that the IMT is suitable for decision makers and managers and may support them in their working towards sustainable development of the Narew River Basin since:

- it may provide answers to questions concerning the achievement of sustainable development of the basin and to some of their questions, which are recently being formulated, concerning water management in the basin, such as the improvement of the quality of water resources, reduction of urban, industrial and agricultural pollution of surface water, (RZGW, 2001b,c).
- it is suitable for scenario studies that yield various predictions for different management strategies; in particular, it was shown that aquatic ecosystems are sensitive to changes in land use. So, different land use scenarios may be assessed to separate sustainable ones from non-sustainable ones. Sustainability here is defined as the permanent availability of good quality of drinking water in sufficient quantity for the population of Warsaw and north-east Poland and the conservation of the widespread and well developed wetland ecosystems in the river basin;
- it is operational because the sub-modules are sufficiently simple to be run on standard computer hardware and software. The IMT is run in the environments of commonly used programs (EXCEL and MAPINFO). These are also used by the decision makers and managers in Poland;
- it is based on the main elements of the land use - surface water – aquatic ecosystem cause-and–effect chain, including nutrient emissions and inputs into surface water, in-stream changes in nutrient concentration and the response of aquatic plant species to changes in water composition, the latter being one of the main concerns of decision makers when planning sustainable development;
- finally, the data requirements are modest and the necessary datasets are for a major part based on: available data (hydrological and administrative units), data collected within standard monitoring programs and networks (water quality and quantity) or census data (land use, livestock, population), which are accessible and commonly used by decision makers.

8.3 Further verification of the models

Following the definition of model credibility formulated by Rykiel (1996) as ‘a sufficient degree of belief in the validity of the model to justify its use for research and decision making’ I consider the IMT to be a suitable tool for the decision making process at the basin scale.

However, there is a need for further verification of the models and the assessment of the uncertainty in the models structure, in the parameters of the models and the accuracy of the predictions, which was not currently possible due to the available time and data.

The STREAMPLAN module was calibrated and validated for low flow period conditions and the sensitivity of its parameters was analysed. Although, to cover all water regimes characteristic for Polish lowland rivers two additional parameter sets would preferably had to have been used for validation: for winter conditions and for snow-melt high water conditions. These conditions were not sufficiently represented in the available datasets to perform validation of the model and eventually if necessary an extra calibration. Thus, an incorporation of these periods would require additional collection of water quality and quantity data.

The NULAM module was calibrated for low flow conditions and its sensitivity to parameters describing load sources was analysed. A true validation of the model was not possible due to lack of an independent dataset of land use characteristics. Model validation could be approached by comparing the riverine observed load of another month with the calculated emissions. Such an approach is no more than a check on how the simulated loads computed with calculated export coefficients fit to observed loads at another moment in time. Thorough validation of the model would require independent data on land use, agricultural production, population and additional data on water quality and quantity. Also due to limited data availability the model was calibrated on only a single month's data whereas the use of seasonal (vegetation period) average over the years might have improved model estimations.

The INCORS model was built using all available vegetation recordings. The model was not validated due to sparse data and it was decided to use the entire dataset for efficient model identification instead of keeping a part of the data apart for validation. This approach has been often used in modelling of species response (e.g. Barendregt, 1993; Ertsen et al., 1998), however, it disallows validation of a model without collecting additional vegetation and explanatory variables data.

8.4 Improvement of the IMT, bottom up and top down

Each model can be subject to improvement. However, making improvements is only relevant where there is a good reason to do so. In this case, the separate components of the IMT are not ideal models and several modifications and improvements are possible. However, it seems to be not the most efficient to improve them one by one since an improvement of one has consequences for the others. Moreover, attempts for improvement may be time consuming and may not bring significant improvement whether a model performance is considered (De Wit, 1999) or a tool acceptability (van der Molen, 1999). Therefore, it is better to focus on the IMT as a whole and in such a chain of modules it is the weakest link that counts and which governs overall assessment. But what is then the weakest link? How is this decided? There are two possible approaches for sorting this out: 'bottom up' and 'top down'. They are both still possible in the Narew River Basin since the regional policy development in the area has not stood still. This also gives the 'good reason' for improvements: if policy development lead to new needs, indicators, aspects or questions that have to be taken into consideration.

A 'bottom up' approach may be related to the European Union Water Framework Directive, which will ultimately be obligatory for the basin when Poland joins the European Union. Moreover, the basin was selected in the bilateral Polish-French governmental project on implementing the directive in the candidate states as a pilot basin (RZGW, 2001a). This directive assumes that the condition of an ecosystem is the best and main indicator of the basin status. It focuses on 4 biological indicators: helophytes, benthos, fish and algae. So, the improvement of the IMT could focus on adding the three others indicators (except for the present helophytes) into the species response model (INCORS) or alternatively further focus on the helophytes by for instance incorporating other characteristic species, including population dynamics and dynamics in surface water chemistry or pay more attention to morphological differences in the rivers. Any of these improvements would have different consequences for the two other modules so they would have be modified and improved too.

The other way of thinking is to apply a 'top down' approach and take as a starting point a socio-economic point of view of the basin development. The basin area is located within three voivodeships of the present administrative division of the country. Voivodeship authorities are obliged to prepare a Regional Development Plan in which the targets, assumptions and directions of the regional development are presented and elaborated. These plans are not yet ready for all the voivodeships in the basin but when ready they may presumably give cause for certain changes in the load assessment module (NULAM) such as aggregation or disaggregation of sub-catchments, a need for a fine spatial resolution of land use data or the incorporation of other quality components. Such changes in NULAM also have consequences for the two other component modules. Thus, the further testing and improvement of the IMT is probably necessary but it may be done in close relation to existing or coming concepts and ideas for developing the area. For instance, the Polish Committee of Scientific Research selected the IMT concept for testing and improvement of existing tools for integrated modelling at the basin scale for using in an implementation of European Water Framework Directive in the Polish river basins (KBN, 2001).

The conceivable changes imposed on the IMT resulting from its possible improvement may also require a formulation of different and/or additional sustainability criteria. The scenarios designed in the thesis were assessed against proposed sustainability criteria (see chapter 1). Notwithstanding, the accomplishment of the proposed criteria may lead to sustainable development of the basin when the physical environment is taken into account. There may be other criteria defining sustainable development from for instance social or economical points of view and the sustainable development will then reflect all aspects of the basin development.

8.5 Towards spatially distributed scenarios

The Regional Development Plans (on a voivodeship level) are also an interesting starting point for designing feasible scenarios for the Narew River Basin management. In this thesis the IMT was applied to two theoretically possible scenarios, and as a reference, the present situation. The so-called 'achieving the Ist water quality class' scenario and 'joining the European Union' scenario are in fact 'corner' scenarios, assuming quite different developments in land use but uniform per scenario for the entire basin.

The ‘joining the European Union’ scenario merely illustrates what the environmental consequences might be if the expected European Union agriculture compensation subsidies were to be predominantly invested in the intensification of the agricultural production in the region. If mitigation measures are undertaken to stimulate nutrient take-up and diminish leaching and outwash after the nutrients are being applied on the fields then the predicted situation may be avoided. The awareness of this problem is already reflected in recent developments of the European Union policy concerning agricultural subsidies. The European Union moves towards supporting farmers per surface area of land instead of a quantity of agricultural product, and what is more important, the farmers may get subsidies for keeping water clean, preserving biodiversity and saving the landscape and cultural heritage. Moreover, the available funds may be utilized in such a way as to enhance the development of ecological farming and to stimulate diversification of the activities on farms (van Os et al., 1995) in the form of i.e. semi-agricultural activities, namely sales of agricultural products at the farm and farm-based recreation and tourism. The other important issue that needs investments is to improve farmers’ knowledge concerning environmental friendly agricultural practices (e.g. Code of Good Agricultural Practice elaborated by Polish Ministries of Environment, and Agriculture and Rural Development, 2002), which is not sufficient at the moment (Dzikiewicz, 2000).

The ‘achieving the Ist water quality class’ scenario is based on the situation that resulted from economical recession and major structural changes, especially in agriculture, which took place during political transition of the country after the 1989 collapse of the communist economic systems (Dzikiewicz, 2000). Although this low production situation was current until recently, it is unrealistic to expect that agricultural production will remain at this level, especially at the basin scale.

Therefore, it may be expected that some intermediate scenario(s) in a sense of both characteristic values and spatial differences will have greater feasibility. As one may assume there will be a spatial differentiation in the basin development plan resulting from different characteristics and predispositions of the different areas in the basin. The more feasible spatially differentiated scenarios may be proposed and elaborated when the Regional Development Plans will be prepared in the near future. Based on the available knowledge and information about geomorphology, nature condition, economical development and soil pattern one may already foresee expected dominant but general directions of the Narew River Basin development.

Figure 8.1 presents a schematic sketch of possibly dominant functions of particular areas of the basin. These functions are assigned to parts of the basin, based on an analysis of the main patterns in nature reserves, vulnerability of aquifers for pollution, intensity of agricultural production and recreation and tourism intensiveness and potential.

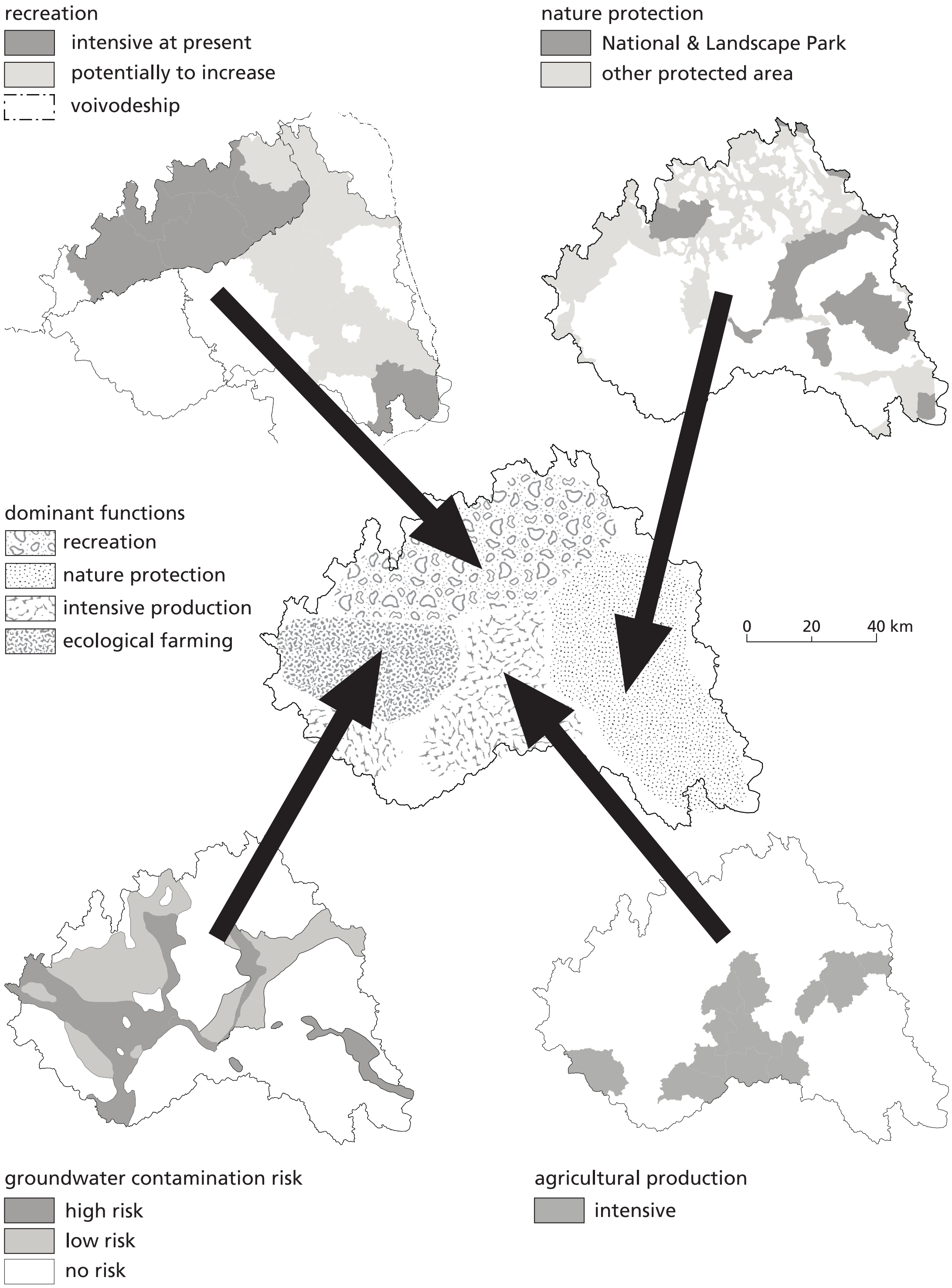


Figure 8.1 Anticipated dominant functions of the regions in the Narew River Basin

For the eastern part of the basin, the Upper Narew basin and the Biebrza and Suprasl river sub-catchments, characterised by the most valuable nature areas, as reflected by the presence of three National Parks and a number of other protected areas, the nature protection function may be expected to dominate, with related recreational and tourist functions following. These three functions may also dominate the north of the basin, characterised by the abundance of lakes (i.e. Great Masurian Lake District) suitable for water recreation, the presence of extended tourist facilities and a number of protected nature areas, however with recreational and tourist functions being the main focus. The outwash plains in the west of the basin, characterised by sandy soils sensitive for leaching and a major contribution of meadows and pastures to land use patterns, may be used for strictly fertiliser limited ecological farming based on extensive dairy production. Finally, in the south and central parts of the basin, where nature and recreational potentials are limited and clayey soils dominate, more intensive farming practices may be applied, however with the exception of the river valleys. Thus, the sketch of figure 8.1 shows that the spatial scale and distribution of administrative regions as well as a subdivision in regions differing in physical and biological features allow for dividing the basin in zones where certain developments may be expected and/or may be desirable. More important, these coarse-scale patterns can also be evaluated by the IMT (see figure 8.2) since the spatial grain of the IMT (sub-catchments and river reaches) is smaller than these patterns.

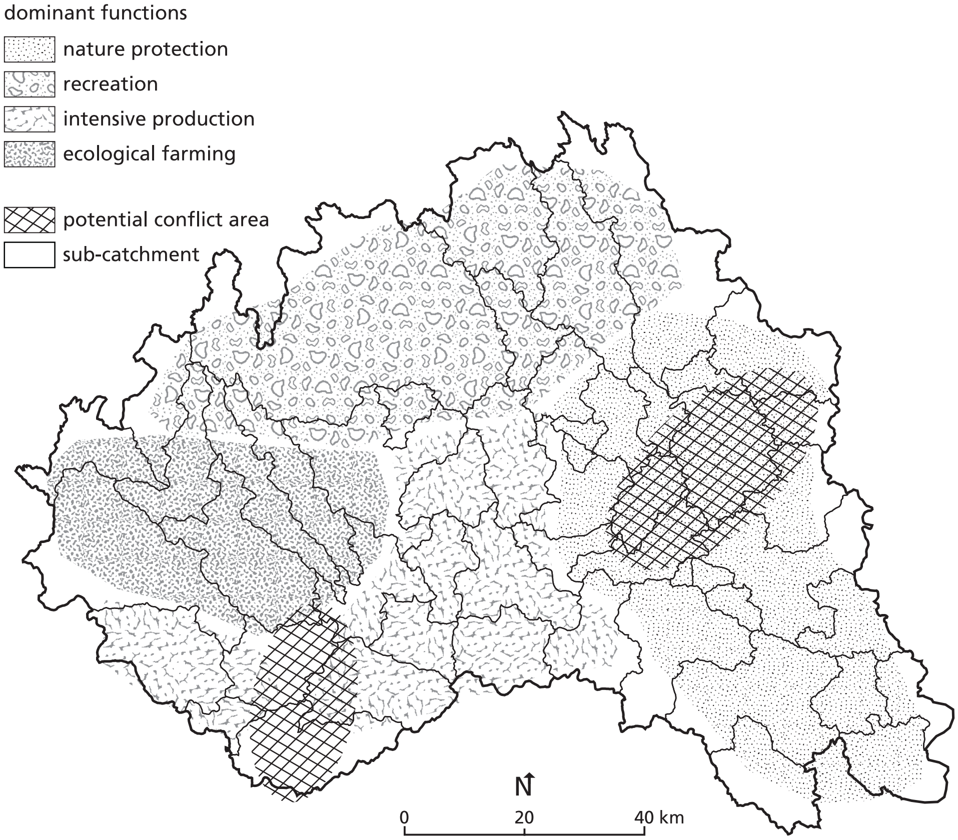


Figure 8.2 The IMT spatial structure and anticipated dominant functions of the regions in the Narew River Basin

Such spatially distributed scenarios may well be evaluated with the IMT since it has been designed for studying spatially explicit scenarios at the basin scale. Moreover, the IMT may be useful for assessing ‘potential conflict zones’ between different functions and for defining limits for agricultural intensification and tourist development. The distributed model approach allows for incorporation of the variable ‘distance to the downstream end of the Narew river’ (i.e. the potential in-take location for drinking water production) as an important parameter in new policies or land use patterns. In general this distance parameter may describe the level of changes in land and water management through a decreasing effect with larger distance. Some ‘potential conflict zones’ may be already anticipated (see figure 8.2). For instance an area in the east of the basin, comprising the sub-catchments of the Sidra, Brzozowka and Neresl rivers, is suitable for agricultural intensification due to limited nature and recreational potentials and non leaching sensitive soils. This area is surrounded by and located upstream of nature protection areas. Similarly, in the most downstream part of the basin where possible intensification of agricultural production in the sub-catchments of Orz and Orzyc rivers may conflict with drinking water production potential. Additional potential conflict areas may arise when applying the proposed distance parameter. This holds especially when intensification of land use practice is at stake. For instance, the distance between an area of intensive agriculture and an envisaged site for drinking water abstraction or a vulnerable nature area. Here, the IMT is indeed a strong tool for the evaluation of land use planning.

This thesis has demonstrated that there is considerable potential for the application of the IMT for planning at different decision making levels as well as that there is room for improvement at the various fundamental stages of the assembling of the IMT. The acceptability of a tool is not only related to its functionality and scientific credibility. It is also affected by motivations to undertake a project and by the constraints in time and money imposed by managers and/or through informal and personal relationships as well as accidental factors such as how well does it fit in with their urgent questions (van der Molen, 1999). Therefore, testing by real users in real world cases will prove its acceptability for the decision-making process, even though a modeller delivers a useful tool.

APPENDIX A1: Sub-catchments characteristics

Table A1.1 Land use types (ha) in the sub-catchments of the Narew River Basin

No	Code	Sub-catchment	Total	Arable land	Grass land	Forest	Waste land	Bulit-up area	Water
1	BON	BONDARY	109500	18312	15662	53973	1362	779	19413
2	NAA	Narewka	59000	5605	5348	43763	3914	371	0
3	NAR	NAREW	28795	6114	5765	13799	2593	524	0
4	ORL	Orlanka	47748	20409	11570	11367	1961	2425	17
5	SUR	SURAZ	94912	40275	24826	21816	5307	2689	0
6	ZOL	ZOLTKI	78128	33147	17518	16012	7619	3667	166
7	ZAL	ZALUKI	35189	7727	5890	17860	2929	717	66
8	SOK	Sokolda	46319	17993	8056	16449	2642	1161	18
9	WAS	WASILKOW	83580	21779	11117	42867	5628	2154	35
10	BIA	Biala	10802	1876	1241	3008	233	4303	141
11	FAS	FASTY	6412	1718	1423	2349	643	279	0
12	ZLO	ZLOTORIA	3005	983	778	801	313	130	0
13	NER	Neresl	27867	12040	7706	4584	2135	1007	395
14	SLI	Slina	46778	23143	8836	10702	2260	1836	0
15	STG	STREKOWA GORA	38233	13405	10423	10184	2812	1027	383
16	SID	Sidra	22617	11217	5745	3922	1240	482	10
17	SZT	SZTABIN	60953	23462	14687	15545	5805	1426	27
18	KAU	K. Augustowski	134774	51067	23376	41101	12843	2073	4313
19	DEB	DEBOWO	14016	4026	4030	3998	1444	518	0
20	BRZ	Brzozowka	69445	31294	18803	13574	3599	2163	11
21	DST	DOLISTOWO STARE	17851	5841	4378	3942	3415	275	0
22	JEG	Jegrznia	85763	39295	16825	16951	6355	1801	4536
23	GON	GONIADZ	29959	7029	6366	8733	7400	432	0
24	ELK	ELK	85170	30303	16540	23031	7655	1813	5827
25	PRO	PROSTKI	30912	11503	6236	7120	4172	775	1105
26	PRZ	PRZECHODY	30078	9912	8533	8183	2087	1227	135
27	OKR	OSOWIEC KANAL	6752	1913	1832	2027	905	77	0
28	OSB	OSOWIEC BIEBRZA	4676	1492	1311	1004	837	32	0
29	WIS	Wissa	51666	26050	11038	9423	3284	1870	0
30	BUR	BURZYN	44380	14702	10162	8737	9800	980	0
31	WIZ	WIZNA	22693	8275	4978	4751	4057	592	40
32	GAC	Gac	44275	19931	7411	11661	3365	1753	153
33	PIA	PIATNICA	54469	27553	12656	8840	3191	2229	0
34	PIS	PISZ	299801	75522	48809	111323	24687	4707	34753
35	JEZ	JEZE	15883	2348	2426	7113	3702	289	5
36	SKR	Skroda	38077	21488	6707	7186	1280	1409	8
37	DOB	DOBRYLAS	91839	24924	24296	31712	8891	1108	908
38	NOW	NOWOGROD	29464	15010	5790	4975	1432	2251	6
39	RUZ	Ruz	30574	15712	6462	5979	1663	758	0
40	SZK	Szkwa	48706	10272	15550	19896	2250	479	258
41	ROZ	Rozoga	49148	10944	14487	19486	3616	458	158
42	OST	OSTROLEKA	48440	16510	12363	14762	3374	1431	0
43	WIE	WIELBARK	40816	7907	3942	23213	3715	705	1335
44	SAW	Sawica	40394	10346	5971	16768	3922	1051	2336
45	KRU	KRUKOWO	45839	8382	9715	23197	3305	645	594
46	BBB	BIALOBRZEG BLIZSZY	80193	18348	26884	29860	4058	879	163
47	RON	ROZAN	50903	21180	10584	14861	3034	1234	10
48	KRA	KRASNOSIELC	126607	42669	28042	45365	8081	2352	98
49	MAK	MAKOW MAZOWIECKI	67038	40812	9867	12133	2481	1728	17
50	MAG	MAGNUSZEW MALY	14351	7847	1670	3674	899	261	0
51	ORZ	Orz	61681	30279	13051	14064	2484	1733	70
52	ZKS	ZAMBSKI KOSCIELNE	66191	26321	12710	22045	3788	1318	9

Table A.1.2 Fertilisation ($\mathrm{kg{\cdot}ha^{-2}{\cdot}y^{-1}}$), livestock ($\mathrm{head{\cdot}km^{-2}}$) and population (person) in sub-catchments of the Narew River Basin

			N	P	Cattle	Pigs	Horses	Sheep	Poultry	Population
1	BON	BONDARY	45.9	17.9	2015	1460	245	313	5753	3148
2	NAA	Narewka	45.9	17.9	1747	1617	244	464	7975	4770
3	NAR	NAREW	45.9	17.9	4227	4935	468	834	34460	5130
4	ORL	Orlanka	45.9	17.9	14836	16161	1301	3589	43971	34471
5	SUR	SURAZ	45.9	17.9	29506	28382	2132	4131	133404	29604
6	ZOL	ZOLTKI	46.4	18.1	27618	40492	1797	1139	102276	83851
7	ZAL	ZALUKI	45.9	17.9	3798	2472	397	370	13040	5936
8	SOK	Sokolda	45.9	17.9	11260	19117	682	1741	29955	31417
9	WAS	WASILKOW	45.9	17.9	9266	13173	955	1500	39122	53215
10	BIA	Biala	45.9	17.9	898	1831	146	113	5151	221260
11	FAS	FASTY	45.9	17.9	1374	987	113	69	4474	24644
12	ZLO	ZLOTORIA	45.9	17.9	817	881	76	41	2733	1441
13	NER	Neresl	46.5	18.2	11382	28428	529	204	22050	19937
14	SLI	Slina	50.1	20.1	25798	30783	836	927	37468	16578
15	STG	STREKOWA GORA	46.3	18.1	14967	17119	908	651	26784	16519
16	SID	Sidra	45.9	17.9	8107	10567	540	745	17531	6577
17	SZT	SZTABIN	35.0	12.1	18564	30464	1307	991	40967	22168
18	KAU	K. Augustowski	25.5	7.0	47658	65807	3139	1405	112954	66178
19	DEB	DEBOWO	34.8	12.0	4364	5770	296	143	12641	2779
20	BRZ	Brzozowka	45.8	17.9	26726	42951	1020	2260	71269	20656
21	DST	DOLISTOWO STARE	46.3	18.1	5517	9218	233	137	10504	3759
22	JEG	Jegrznia	27.3	8.0	23310	48426	1589	1348	56544	38991
23	GON	GONIADZ	50.5	20.3	7612	10849	419	173	12750	6295
24	ELK	ELK	25.2	6.9	15815	23479	1013	620	54781	56222
25	PRO	PROSTKI	26.2	7.4	5932	11568	459	129	15631	26349
26	PRZ	PRZECHODY	47.0	18.4	10336	12095	612	297	17974	29798
27	OKR	OSOWIEC KANAL	50.8	20.4	2036	2667	94	46	2738	1270
28	OSB	OSOWIEC BIEBRZA	50.8	20.4	1486	1960	76	29	2198	1020
29	WIS	Wissa	48.5	19.2	22313	33264	1210	264	39137	19564
30	BUR	BURZYN	50.3	20.2	12615	23417	698	193	22206	9636
31	WIZ	WIZNA	50.7	20.3	7378	11343	368	115	12756	5486
32	GAC	Gac	50.8	20.4	19776	33640	713	317	41584	37884
33	PIA	PIATNICA	50.8	20.4	21407	40078	1078	313	51426	30976
34	PIS	PISZ	28.1	7.4	48788	66012	2719	1335	141694	116540
35	JEZ	JEZE	50.8	20.4	1878	1526	110	17	3163	11225
36	SKR	Skroda	50.8	20.4	15800	39134	640	153	62540	23916
37	DOB	DOBRYLAS	40.3	14.8	29232	33257	1829	319	47756	22407
38	NOW	NOWOGROD	50.8	20.4	10876	26342	623	102	36867	66411
39	RUZ	Ruz	48.2	18.8	14447	24472	557	147	37569	10577
40	SZK	Szkwa	41.5	14.2	16726	6311	1505	67	22924	14616
41	ROZ	Rozoga	40.5	13.2	15843	5523	1535	75	23987	18465
42	OST	OSTROLEKA	47.0	18.1	15107	18704	1387	125	34224	43556
43	WIE	WIELBARK	37.3	8.8	3097	7598	247	45	8550	6377
44	SAW	Sawica	37.3	8.8	6123	4967	494	91	13080	32054
45	KRU	KRUKOWO	37.9	9.3	9186	10392	862	97	12834	14651
46	BBB	BIALOBRZEG BLIZSZY	41.8	14.9	29943	12334	3233	123	47884	32137
47	RON	ROZAN	41.9	15.1	17058	25807	1321	192	45095	45439
48	KRA	KRASNOSIELC	43.7	14.5	40569	37214	2794	752	89258	33741
49	MAK	MAKOW MAZOWIECKI	47.1	17.3	26823	51626	1526	223	80584	46054
50	MAG	MAGNUSZEW MALY	44.3	16.1	4546	10211	255	105	40130	12249
51	ORZ	Orz	42.4	15.4	26715	50607	1734	269	59045	24301
52	ZKS	ZAMBSKI KOSCIELNE	41.9	15.1	18567	37289	2310	307	64216	28856

Table A1.3 Observed riverine nutrient load in sub-catchments of the Narew River Basin

			Area	Nitrogen		Phosphorus	
			km^2	kg·y^{-1}	kg·km^{-2}·y^{-1}	kg·y^{-1}	kg·km^{-2}·y^{-1}
1	BON	BONDARY	1095.00	82233	75	16765	15
2	NAA	Narewka	590.00	31001	53	3368	6
3	NAR	NAREW	287.95	64702	225	3320	12
4	ORL	Orlanka	477.48	33462	70	5195	11
5	SUR	SURAZ	949.12	61061	64	2514	3
6	ZOL	ZOLTKI	781.28	65449	84	20759	27
7	ZAL	ZALUKI	351.89	71927	204	4167	12
8	SOK	Sokolda	463.19	88393	191	5747	12
9	WAS	WASILKOW	835.80	42782	51	3729	4
10	BIA	Biala	108.02	33998	315	1793	17
11	FAS	FASTY	64.12	264701	4128	4932	77
12	ZLO	ZLOTORIA	30.05	82287	2739	5101	170
13	NER	Neresl	278.67	10345	37	2199	8
14	SLI	Slina	467.78	5612	12	1249	3
15	STG	STREKOWA GORA	382.33	149372	391	32022	84
16	SID	Sidra	226.17	3922	17	532	2
17	SZT	SZTABIN	609.53	18892	31	2028	3
18	KAU	K. Augustowski	1347.74	166337	123	16718	12
19	DEB	DEBOWO	140.16	27601	197	4927	35
20	BRZ	Brzozowka	694.45	24041	35	3220	5
21	DST	DOLISTOWO STARE	178.51	3170	18	14173	79
22	JEG	Jegrznia	857.63	20822	24	1897	2
23	GON	GONIADZ	299.59	35087	117	1420	5
24	ELK	ELK	851.70	109796	129	4653	5
25	PRO	PROSTKI	309.12	9604	31	14183	46
26	PRZ	PRZECHODY	300.78	91697	305	5050	17
27	OKR	OSOWIEC KANAL	67.52	35418	525	2911	43
28	OSB	OSOWIEC BIEBRZA	46.76	57498	1230	934	20
29	WIS	Wissa	516.66	64432	125	3410	7
30	BUR	BURZYN	443.80	100245	226	15859	36
31	WIZ	WIZNA	226.93	21933	97	1672	7
32	GAC	Gac	442.75	51737	117	9080	21
33	PIA	PIATNICA	544.69	796808	1463	40585	75
34	PIS	PISZ	2998.01	224235	75	30314	10
35	JEZ	JEZE	158.83	157128	989	1053	7
36	SKR	Skroda	380.77	153466	403	8933	23
37	DOB	DOBRYLAS	918.39	180557	197	46715	51
38	NOW	NOWOGROD	294.64	1169433	3969	4576	16
39	RUZ	Ruz	305.74	33246	109	1873	6
40	SZK	Szkwa	487.06	51134	105	4400	9
41	ROZ	Rozoga	491.48	21571	44	4369	9
42	OST	OSTROLEKA	484.40	291015	601	2530	5
43	WIE	WIELBARK	408.16	16642	41	3153	8
44	SAW	Sawica	403.94	57877	143	30016	74
45	KRU	KRUKOWO	458.39	100831	220	5268	11
46	BBB	BIALOBRZEG BLIZSZY	801.93	27281	34	17632	22
47	RON	ROZAN	509.03	617076	1212	11886	23
48	KRA	KRASNOSIELC	1266.07	83937	66	5701	5
49	MAK	MAKOW MAZOWIECKI	670.38	222633	332	17574	26
50	MAG	MAGNUSZEW MALY	143.51	93002	648	588	4
51	ORZ	Orz	616.81	33186	54	4304	7
52	ZKS	ZAMBSKI KOSCIELNE	661.91	751506	1135	14509	22

Table A1.4 Generated nutrient load for sub-catchments of the Narew River Basin

a) nitrogen

			Land use		Livestock		Total		Land use	Live-stock
			kg·y^{-1}	kg·km^{-2}·y^{-1}	kg·y^{-1}	kg·km^{-2}·y^{-1}	kg·y^{-1}	kg·km^{-2}·y^{-1}	%	%
1	BON	BONDARY	1814963	1658	204426	187	2019389	1845	89.9	10.1
2	NAA	Narewka	736408	1248	196950	334	933358	1582	78.9	21.1
3	NAR	NAREW	557448	1936	462930	1608	1020378	3544	54.6	45.4
4	ORL	Orlanka	1415480	2964	1624575	3402	3040055	6366	46.6	53.4
5	SUR	SURAZ	2826661	2978	2959184	3118	5785845	6096	48.8	51.2
6	ZOL	ZOLTKI	2308305	2955	3066195	3925	5374500	6880	43.0	57.0
7	ZAL	ZALUKI	680416	1934	373966	1063	1054382	2997	64.5	35.5
8	SOK	Sokolda	1257573	2715	1348551	2911	2606124	5626	48.2	51.8
9	WAS	WASILKOW	1716775	2054	1159666	1387	2876441	3441	59.7	40.3
10	BIA	Biala	175687	1626	216079	2000	391766	3626	44.8	55.2
11	FAS	FASTY	142041	2215	222668	3473	364709	5688	39.0	61.0
12	ZLO	ZLOTORIA	75742	2521	86482	2878	162224	5399	46.7	53.3
13	NER	Neresl	857180	3076	1458238	5233	2315418	8309	37.0	63.0
14	SLI	Slina	1606633	3435	2535662	5421	4142295	8856	38.8	61.2
15	STG	STREKOWA GORA	1028896	2691	1519457	3974	2548353	6665	40.4	59.6
16	SID	Sidra	741081	3277	845960	3740	1587041	7017	46.7	53.3
17	SZT	SZTABIN	1402650	2301	2081745	3415	3484395	5716	40.3	59.7
18	KAU	K. Augustowski	2372708	1761	5124408	3802	7497116	5563	31.6	68.4
19	DEB	DEBOWO	281557	2009	452995	3232	734552	5241	38.3	61.7
20	BRZ	Brzozowka	2166766	3120	2880526	4148	5047292	7268	42.9	57.1
21	DST	DOLISTOWO STARE	450541	2524	596783	3343	1047324	5867	43.0	57.0
22	JEG	Jegrznia	1757124	2049	2846427	3319	4603551	5368	38.2	61.8
23	GON	GONIADZ	661688	2209	799541	2669	1461229	4878	45.3	54.7
24	ELK	ELK	1413158	1659	1723286	2023	3136444	3682	45.1	54.9
25	PRO	PROSTKI	546063	1767	708230	2291	1254293	4058	43.5	56.5
26	PRZ	PRZECHODY	797828	2653	1052862	3500	1850690	6153	43.1	56.9
27	OKR	OSOWIEC KANAL	173448	2569	206252	3055	379700	5624	45.7	54.3
28	OSB	OSOWIEC BIEBRZA	128216	2742	151692	3244	279908	5986	45.8	54.2
29	WIS	Wissa	1747423	3382	2372441	4592	4119864	7974	42.4	57.6
30	BUR	BURZYN	1202532	2710	1423459	3207	2625991	5917	45.8	54.2
31	WIZ	WIZNA	656008	2891	784832	3458	1440840	6349	45.5	54.5
32	GAC	Gac	1433286	3237	2236683	5052	3669969	8289	39.0	61.0
33	PIA	PIATNICA	1991437	3656	2439987	4480	4431424	8136	44.9	55.1
34	PIS	PISZ	4451349	1485	5348421	1784	9799770	3269	45.4	54.6
35	JEZ	JEZE	266679	1679	184415	1161	451094	2840	59.1	40.9
36	SKR	Skroda	1435594	3770	2004482	5264	3440076	9034	41.7	58.3
37	DOB	DOBRYLAS	1934656	2107	2919910	3179	4854566	5286	39.8	60.2
38	NOW	NOWOGROD	1045948	3550	1370603	4652	2416551	8202	43.3	56.7
39	RUZ	Ruz	1052404	3442	1568833	5131	2621237	8573	40.2	59.8
40	SZK	Szkwa	944504	1939	1472759	3024	2417263	4963	39.1	60.9
41	ROZ	Rozoga	941680	1916	1413940	2877	2355620	4793	40.0	60.0
42	OST	OSTROLEKA	1271295	2624	1607209	3318	2878504	5942	44.2	55.8
43	WIE	WIELBARK	607783	1489	412925	1012	1020708	2501	59.6	40.4
44	SAW	Sawica	713510	1766	691683	1712	1405193	3478	50.8	49.2
45	KRU	KRUKOWO	735293	1604	967809	2111	1703102	3715	43.2	56.8
46	BBB	BIALOBRZEG	1639369	2044	2709933	3379	4349302	5423	37.7	62.3
47	RON	ROZAN	1366813	2685	1882577	3698	3249390	6383	42.1	57.9
48	KRA	KRASNOSIELC	3082139	2434	392487	3100	7006986	5534	44.0	56.0
49	MAK	MAKOW	2500350	3730	3162423	4717	5662773	8447	44.2	55.8
50	MAG	MAGNUSZEW MALY	466838	3253	562302	3918	1029140	7171	45.4	54.6
51	ORZ	Orz	1866454	3026	3070811	4979	4937265	8005	37.8	62.2
52	ZKS	ZAMBSKI KOSCIELNE	1725818	2607	2313867	3496	4039685	6103	42.7	57.3

b) phosphorus

			Land use		Livestock		Total		Land use	Live-stock
			kg·y^{-1}	kg·km^{-2}·y^{-1}	kg·y^{-1}	kg·km^{-2}·y^{-1}	kg·y^{-1}	kg·km^{-2}·y^{-1}	%	%
1	BON	BONDARY	436471	399	31062	28	467533	427	93.4	6.6
2	NAA	Narewka	140990	239	30993	53	171983	292	82.0	18.0
3	NAR	NAREW	146044	507	75423	262	221467	769	65.9	34.1
4	ORL	Orlanka	433693	908	260491	546	694184	1454	62.5	37.5
5	SUR	SURAZ	867158	914	467861	493	1335019	1407	65.0	35.0
6	ZOL	ZOLTKI	706792	905	515818	660	1222610	1565	57.8	42.2
7	ZAL	ZALUKI	178155	506	56525	161	234680	667	75.9	24.1
8	SOK	Sokolda	375654	811	231411	500	607065	1311	61.9	38.1
9	WAS	WASILKOW	462405	553	194686	233	657091	786	70.4	29.6
10	BIA	Biala	41749	386	38785	359	80534	745	51.8	48.2
11	FAS	FASTY	39506	616	22969	358	62475	974	63.2	36.8
12	ZLO	ZLOTORIA	22092	735	13878	462	35970	1198	61.4	38.6
13	NER	Neresl	266183	955	266831	958	533014	1913	49.9	50.1
14	SLI	Slina	525152	1123	411232	879	936384	2002	56.1	43.9
15	STG	STREKOWA GORA	307245	804	244766	640	552011	1444	55.7	44.3
16	SID	Sidra	232965	1030	138493	612	371458	1642	62.7	37.3
17	SZT	SZTABIN	351961	577	353743	580	705704	1157	49.9	50.1
18	KAU	K. Augustowski	421648	313	850361	631	1272009	944	33.2	66.8
19	DEB	DEBOWO	66598	475	74522	532	141120	1007	47.2	52.8
20	BRZ	Brzozowka	674366	971	489949	706	1164315	1677	57.9	42.1
21	DST	DOLISTOWO STARE	131784	738	102010	571	233794	1309	56.4	43.6
22	JEG	Jegrznia	358102	418	503255	587	861357	1005	41.6	58.4
23	GON	GONIADZ	189341	632	132982	444	322323	1076	58.7	41.3
24	ELK	ELK	242188	284	289718	340	531906	624	45.5	54.5
25	PRO	PROSTKI	99908	323	123886	401	223794	724	44.6	55.4
26	PRZ	PRZECHODY	237508	790	170250	566	407758	1356	58.2	41.8
27	OKR	OSOWIEC KANAL	52397	776	33845	501	86242	1277	60.8	39.2
28	OSB	OSOWIEC BIEBRZA	39539	846	24920	533	64459	1379	61.3	38.7
29	WIS	Wissa	561701	1087	397686	770	959387	1857	58.6	41.4
30	BUR	BURZYN	369505	833	247053	557	616558	1390	59.9	40.1
31	WIZ	WIZNA	204848	903	132200	583	337048	1486	60.8	39.2
32	GAC	Gac	462425	1044	385448	871	847873	1915	54.5	45.5
33	PIA	PIATNICA	660512	1213	425360	781	1085872	1994	60.8	39.2
34	PIS	PISZ	683742	228	890750	297	1574492	525	43.4	56.6
35	JEZ	JEZE	66502	419	28650	180	95152	599	69.9	30.1
36	SKR	Skroda	479189	1258	368137	967	847326	2225	56.6	43.4
37	DOB	DOBRYLAS	496918	541	469116	511	966034	1052	51.4	48.6
38	NOW	NOWOGROD	344730	1170	249745	848	594475	2018	58.0	42.0
39	RUZ	Ruz	334712	1095	269577	882	604289	1977	55.4	44.6
40	SZK	Szkwa	218095	448	210159	431	428254	879	50.9	49.1
41	ROZ	Rozoga	206229	420	201502	410	407731	830	50.6	49.4
42	OST	OSTROLEKA	371138	766	261546	540	632684	1306	58.7	41.3
43	WIE	WIELBARK	84383	207	74910	184	159293	391	53.0	47.0
44	SAW	Sawica	109938	272	109680	272	219618	544	50.1	49.9
45	KRU	KRUKOWO	111254	243	155327	339	266581	582	41.7	58.3
46	BBB	BIALOBRZEG	403672	503	389436	486	793108	989	50.9	49.1
47	RON	ROZAN	376539	740	316369	622	692908	1362	54.3	45.7
48	KRA	KRASNOSIELC	758308	599	613441	485	1371749	1084	55.3	44.7
49	MAK	MAKOW	762462	1137	554702	827	1317164	1964	57.9	42.1
50	MAG	MAGNUSZEW MALY	136658	952	102280	713	238938	1665	57.2	42.8
51	ORZ	Orz	536138	869	534728	867	1070866	1736	50.1	49.9
52	ZKS	ZAMBSKI KOSCIELNE	471068	712	404451	611	875519	1323	53.8	46.2

Table A1.5 Nutrient load export in sub-catchments of the Narew River Basin

			Nitrogen		Phosphorus	
			kg$\cdot$km$^{-2}\cdot$y^{-1}	%	kg$\cdot$km$^{-2}\cdot$y^{-1}	%
1	BON	BONDARY	1769	4.07	412	3.59
2	NAA	Narewka	1529	3.32	286	1.96
3	NAR	NAREW	3319	6.34	758	1.50
4	ORL	Orlanka	6297	1.10	1443	0.75
5	SUR	SURAZ	6032	1.06	1404	0.19
6	ZOL	ZOLTKI	6795	1.22	1538	1.70
7	ZAL	ZALUKI	2792	6.82	655	1.78
8	SOK	Sokolda	5436	3.39	1298	0.95
9	WAS	WASILKOW	3390	1.49	782	0.57
10	BIA	Biala	3312	8.68	729	2.23
11	FAS	FASTY	1560	72.58	897	7.90
12	ZLO	ZLOTORIA	2660	50.72	1027	14.18
13	NER	Neresl	8272	0.45	1905	0.41
14	SLI	Slina	8843	0.14	1999	0.13
15	STG	STREKOWA GORA	6275	5.86	1360	5.80
16	SID	Sidra	7000	0.25	1640	0.14
17	SZT	SZTABIN	5686	0.54	1154	0.29
18	KAU	K. Augustowski	5439	2.22	931	1.31
19	DEB	DEBOWO	5044	3.76	972	3.49
20	BRZ	Brzozowka	7233	0.48	1672	0.28
21	DST	DOLISTOWO STARE	5849	0.30	1230	6.06
22	JEG	Jegrznia	5343	0.45	1002	0.22
23	GON	GONIADZ	4760	2.40	1071	0.44
24	ELK	ELK	3554	3.50	619	0.87
25	PRO	PROSTKI	4027	0.77	678	6.34
26	PRZ	PRZECHODY	5848	4.95	1339	1.24
27	OKR	OSOWIEC KANAL	5099	9.33	1234	3.38
28	OSB	OSOWIEC BIEBRZA	4757	20.54	1359	1.45
29	WIS	Wissa	7849	1.56	1850	0.36
30	BUR	BURZYN	5691	3.82	1354	2.57
31	WIZ	WIZNA	6253	1.52	1478	0.50
32	GAC	Gac	8172	1.41	1895	1.07
33	PIA	PIATNICA	6673	17.98	1919	3.74
34	PIS	PISZ	3194	2.29	515	1.93
35	JEZ	JEZE	1851	34.83	592	1.11
36	SKR	Skroda	8631	4.46	2202	1.05
37	DOB	DOBRYLAS	5089	3.72	1001	4.84
38	NOW	NOWOGROD	4233	48.39	2002	0.77
39	RUZ	Ruz	8465	1.27	1970	0.31
40	SZK	Szkwa	4858	2.12	870	1.03
41	ROZ	Rozoga	4749	0.92	821	1.07
42	OST	OSTROLEKA	5342	10.11	1301	0.40
43	WIE	WIELBARK	2460	1.63	383	1.98
44	SAW	Sawica	3335	4.12	469	13.67
45	KRU	KRUKOWO	3495	5.92	570	1.98
46	BBB	BIALOBRZEG BLIZSZY	5390	0.63	967	2.22
47	RON	ROZAN	5171	18.99	1338	1.72
48	KRA	KRASNOSIELC	5468	1.20	1079	0.42
49	MAK	MAKOW MAZOWIECKI	8115	3.93	1939	1.33
50	MAG	MAGNUSZEW MALY	6523	9.04	1661	0.25
51	ORZ	Orz	7951	0.67	1729	0.40
52	ZKS	ZAMBSKI KOSCIELNE	4968	18.60	1301	1.66

APPENDIX A.2: STREAMPLAN characteristics

Table A.2.1 Characteristics (water temperature, length, and longitudinal slope, closing cross-sectional profile data) of the Narew river network reaches used for the STREAMPLAN model identification.

	Temperature IX’97	Temperature IX’96	Reach length	Reach slope	Base length	Side slope
	°C	°C	km	%	m	deg
Bondary	20.8	22.3	0	-	11.50	12°48’
Narew	19.7	20.4	21.7	0.028	18.80	6°58’
Suraz	19.5	20.4	45.3	0.03	10.80	9°37’
Zoltki	19.8	20.7	53.1	0.016	24.40	25°47’
Zaluki	17.0	16.2	0	-	5.00	30°
Wasilkow	16.8	17.4	32.9	0.035	32.50	25°39’
Fasty	20.8	19.2	14	0.04	7.41	7°22’
Zlotoria	19.9	20.0	5	0.01	24.40	25°47’
Strekowa Gora	19.8	20.6	25.8	0.14	15.46	6°12’
Sztabin	21.3	22.3	0	-	13.83	19°1’
Debowo	20.4	21.2	18.3	0.03	29.66	25°53’
Dolistowo Stare	21.0	21.8	7.5	0.02	29.66	25°53’
Goniadz	21.4	21.2	16	0.005	16.64	5°13’
Elk	21.4	21.0	0	-	10.53	11°12’
Prostki	20.6	19.5	22.8	0.02	6.93	4°36’
Przechody	20.7	18.6	22.8	0.02	10.26	7°32’
Osowiec Kanal Rudzki	20.6	18.3	8.6	0.024	10.25	33°31’
Osowiec Biebrza	21.8	19.0	11.4	0.008	23.09	24°25’
Burzyn	21.6	18.6	51.9	0.013	16.52	17°12’
Wizna	21.3	18.6	25.8	0.005	79.99	20°07’
Piatnica	21.6	19.4	42.3	0.006	58.62	7°19’
Pisz	21.6	22.3	0	-	11.67	14°09’
Jeze	20.6	21.2	40.4	0.026	12.76	25°27’
Dobrylas	19.2	20.0	38.2	0.02	20.33	6°31’
Nowogrod	19.6	19.8	23.3	0.008	84.70	15°53’
Ostroleka	22.7	22.3	33.5	0.013	54.47	12°52’
Wielbark	18.0	19.0	0	-	5.29	30°42’
Krukowo	18.6	19.9	17.4	0.042	23.09	20°52’
Bialobrzeg Blizszy	20.2	20.3	49.9	0.032	16.30	8°2’
Rozan	22.4	21.6	30	0.015	57.90	8°14’
Krasnosielc	18.9	19.2	0	-	12.90	15°28’
Makow Mazowiecki	20.0	17.8	31.7	0.036	14.79	59°21’
Magnuszew Maly	20.2	17.6	20	0.039	11.62	20°33’
Zambski Koscielne	22.2	19.0	35.6	0.015	61.86	4°15’

Table A.2.2 Results of the STREAMPLAN model identification

a) calibration

	NO_3				PO_4				NH_4			
	meas.	cal.	error	coeff.	meas.	cal.	error	coeff.	meas.	cal.	error	coeff.
	mg/l	mg/l	%		mg/l	mg/l	%		mg/l	mg/l	%	
Krasnosielc[a]	7.39				0.415				0.406			
Makow Mazowiecki	12.30	12.23	-0.6	0.25	0.647	0.645	-0.3	0.13	0.119	0.116	-2.9	0.95
Magnuszew Maly	13.23	12.93	-2.3	0.25	0.715	0.769	+7.6	0.13	0.139	0.144	+3.8	1.85
Wielbark[a]	4.97				2.326				0.832			
Krukowo	7.03	7.09	+0.9	0.25	0.854	0.849	-0.6	0.13	0.139	0.144	+3.5	0.95
Bialobrzeg Blizszy	5.50	5.21	-5.3	0.25	0.935	0.924	-1.2	0.13	0.137	0.136	-0.9	0.95
Pisz[a]	1.86				0.212				0.115			
Jeze	3.01	3.01	+0.1	0.25	0.216	0.216	-0.1	0.13	0.188	0.215	+14.4	1.85
Dobrylas	4.80	4.85	+1.0	0.25	0.474	0.475	+0.2	0.13	0.104	0.114	+9.7	0.95
Elk[a]	8.54				0.271				0.187			
Prostki	7.70	7.44	+0.6	0.25	0.653	0.657	+0.6	0.13	0.103	0.103	+0.3	0.95
Przechody	11.37	11.25	-1.0	0.25	0.944	0.975	+3.3	0.13	0.132	0.129	-2.4	1.85
Osowiec Kanal Rudzki	12.09	11.85	-2.0	0.25	0.961	0.984	+2.4	0.13	0.128	0.124	-3.4	0.95
Sztabin[a]	2.03				0.172				0.100			
Debowo	5.62	5.66	+0.7	0.25	0.467	0.465	-0.5	0.13	0.141	0.140	-0.4	0.95
Dolistowo Stare	4.01	4.40	+9.8	0.6	0.610	0.607	-0.6	0.13	0.105	0.104	-1.1	0.95
Goniadz	3.63	3.76	+3.6	0.3	0.315	0.299	-5.0	0.7	0.140	0.140	0.0	1.1
Osowiec Biebrza	5.16	5.65	+9.5	0.3	0.403	0.425	+5.4	0.7	0.254	0.282	+10.9	1.1
Burzyn	4.92	5.02	+2.0	0.3	0.435	0.456	+4.9	0.225	0.305	0.299	-2.1	1.1
Zaluki[a]	13.79				0.572				0.111			
Wasilkow	8.95	9.34	+4.4	0.25	0.365	0.381	+4.4	0.13	0.100	0.118	+18.4	0.95
Fasty	35.41	35.24	-0.5	0.25	2.210	2.330	+5.4	0.13	0.129	0.138	+7.3	1.85
Bondary[a]	2.34				0.412				0.165			
Narew	3.92	3.98	+1.7	0.25	0.383	0.392	+2.4	0.13	0.146	0.156	+6.5	0.95
Suraz	3.99	4.00	+0.1	0.25	0.345	0.356	+3.2	0.13	0.205	0.209	+1.7	0.95
Zoltki	2.41	2.61	+8.3	0.6	0.557	0.542	-2.6	0.225	0.273	0.283	+3.8	1.1
Zlotoria	12.37	13.97	+12.9	0.6	0.950	1.121	+18.0	0.7	0.176	0.212	+20.6	3.9
Strekowa Gora	10.65	11.47	+7.7	0.3	0.978	1.085	+11.0	0.225	0.190	0.209	+10.1	1.1
Wizna	5.95	6.69	+12.5	0.3	0.538	0.594	+10.4	0.225	0.140	0.175	+25.1	3.9
Piatnica	7.80	7.81	+0.2	0.3	0.715	0.707	-1.1	0.225	0.303	0.304	+0.4	1.1
Nowogrod	9.02	9.03	+0.1	0.3	0.556	0.550	+1.0	0.225	0.244	0.254	+4.0	1.1
Ostroleka	8.49	8.15	-4.0	0.3	0.497	0.486	-2.3	0.225	0.161	0.154	-4.4	1.1
Rozan	8.42	7.89	-6.3	0.3	0.525	0.508	-3.3	0.225	0.100	0.096	-3.8	1.1
Zambski Koscielne	9.02	8.35	-7.4	0.3	0.512	0.488	-4.7	0.225	0.125	0.123	-1.5	1.1

[a] head reach

b) validation

	NO_3				PO_4				NH_4			
	meas.	cal.	error	coeff.	meas.	cal.	error	coeff.	meas.	cal.	error	coeff.
	mg/l	mg/l	%		mg/l	mg/l	%		mg/l	mg/l	%	
Krasnosielc[a]	6.35				0.316				0.211			
Makow Mazowiecki	7.93	7.79	-1.8	0.25	0.686	0.684	-0.3	0.13	0.208	0.205	-1.4	0.95
Magnuszew Maly	11.20	10.97	-2.0	0.25	0.702	0.743	+5.9	0.13	0.213	0.103	-51.4	1.85
Wielbark[a]	4.21				1.788				0.892			
Krukowo	5.89	6.13	+4.1	0.25	0.834	0.875	+4.9	0.13	0.461	0.485	+5.3	0.95
Bialobrzeg Blizszy	4.87	4.95	+1.6	0.25	1.062	1.076	+1.3	0.13	0.220	0.218	-0.8	0.95
Pisz[a]	4.62				0.136				0.174			
Jeze	5.13	5.05	-1.7	0.25	0.270	0.271	+0.3	0.13	0.150	0.078	-48.2	1.85
Dobrylas	5.92	5.75	-2.9	0.25	0.323	0.323	+0.1	0.13	0.118	0.084	-28.4	0.95
Elk[a]	5.74				0.213				0.214			
Prostki	12.30	12.39	+0.7	0.25	1.590	1.591	+0.0	0.13	0.124	0.112	-10.0	0.95
Przechody	10.83	10.59	-2.2	0.25	0.915	0.895	-2.1	0.13	0.128	0.054	-57.4	1.85
Osowiec Kanal Rudzki	12.24	11.90	-2.8	0.25	1.000	0.981	-1.9	0.13	0.131	0.069	-47.0	0.95
Sztabin[a]	6.21				0.141				0.133			
Debowo	5.86	5.96	+1.6	0.25	0.408	0.407	-0.3	0.13	0.203	0.205	+0.9	0.95
Dolistowo Stare	7.47	7.95	+6.4	0.6	0.392	0.390	-0.4	0.13	0.169	0.170	+0.5	0.95
Goniadz	6.45	6.51	+0.9	0.3	0.296	0.179	-39.4	0.7	0.157	0.162	+3.2	1.1
Osowiec Biebrza	7.67	8.24	+7.2	0.3	0.461	0.446	-3.3	0.7	0.183	0.194	+6.0	1.1
Burzyn	8.30	8.15	-1.8	0.3	0.344	0.341	-1.0	.225	0.100	0.094	-5.7	1.1
Zaluki[a]	8.11				0.403				0.148			
Wasilkow	7.79	8.36	+7.3	0.25	0.379	0.384	+1.4	0.13	0.180	0.207	+15.0	0.95
Fasty	24.90	25.33	+1.7	0.25	2.851	2.941	+3.1	0.13	0.316	0.297	-6.0	1.85
Bondary[a]	4.26				0.520				0.330			
Narew	4.68	4.74	+1.3	0.25	0.487	0.493	+1.2	0.13	0.417	0.433	+3.7	0.95
Suraz	4.36	4.50	+3.3	0.25	0.539	0.558	+3.4	0.13	0.272	0.274	+0.8	0.95
Zoltki	4.29	4.62	+7.7	0.6	0.575	0.540	-6.1	.225	0.336	0.306	-8.8	1.1
Zlotoria	11.20	13.03	16.6	0.6	1.296	1.535	+18.4	0.7	0.275	0.332	+20.8	3.9
Strekowa Gora	9.56	10.78	12.8	0.3	1.005	1.178	+17.3	.225	0.167	0.203	+21.6	1.1
Wizna	9.26	10.25	10.6	0.3	0.639	0.698	+9.2	.225	0.355	0.344	-3.1	3.9
Piatnica	8.82	8.76	-0.6	0.3	0.679	0.666	-2.0	.225	0.141	0.090	-36.3	1.1
Nowogrod	8.09	7.87	-2.7	0.3	0.527	0.505	-4.2	.225	0.156	0.140	-10.4	1.1
Ostroleka	8.74	8.21	-6.1	0.3	0.480	0.454	-5.3	.225	0.114	0.100	-11.9	1.1
Rozan	7.52	6.84	-9.1	0.3	0.556	0.529	-4.8	.225	0.204	0.191	-6.3	1.1
Zambski Koscielne	6.95	6.21	10.7	0.3	0.587	0.553	-5.7	.225	0.180	0.163	-9.6	1.1

[a] head reach

APPENDIX A.3: INCORS characteristics

Table A.3.1 INCORS model terms, parameters and characteristics (sig. = significance, %D = percentage of explained deviance) for the final response models for selected species

	Intercept	PO_4	NH_4	NO_3	width	(PO4)^2	(NH4)^2	(NO3)^2	(width)^2	df	sig.	%D
Acorus calamus	-2.05	-2.306	1.819	-0.5729	1.342					5	0.00810	9.9
Berula erecta	-4.53	-6.761	-6.086	-2.097	4.21	-8.025	-7.078		-2.287	8	0.00016	22.6
Butomus umbellatus	-2.73	-1.679	0.9066	1.608	3.182					5	0.00000	23.0
Callitriche spec	-1.369	3.098	-2.071	-0.1714	-1.233					5	0.02911	12.2
Carex acutiformis	-4.074	-0.6309	-9.274	0.4275	-0.5506		-4.772			6	0.03876	7.9
Carex riparia	-0.4066	2.347	-2.628	-3.338	-1.593		-5.516	-0.9318		7	0.04296	24.7
Ceratophyllum demersum	-4.371	0.508	1.676	-1.306	3.058	-2.969				6	0.00013	24.5
Cicuta virosa	-8.944	-0.8942	0.1347	-0.6421	11.66				-4.482	6	0.05720	10.8
Elodea canadensis	0.9616	0.7422	-2.069	-0.1181	-1.905					5	0.00154	11.1
Equisetum fluviatile	-4.402	-3.377	-3.047	-1.268	-1.277					5	0.00575	18.0
Flab	-0.5797	0.0368	1.853	0.4603	1.417					5	0.00996	8.5
Fontinalis antipyretica	-35.21	-0.4616	-37.34	3.008	28.05		-16.58		-12.62	7	0.00003	39.5
Glyceria fluitans	0.7886	0.7166	-1.891	-0.9282	-1.396		-2.433			6	0.01075	10.7
Hydrocharis morsus-ranae	-3.093	-0.5603	0.9984	-5.825	0.8963			-4.681		6	0.00655	15.7
Iris pseudacorus	-25.18	-3.59	-50.24	-0.1262	-2.728		-23.85			6	0.00041	33.3
Lemna minor	1.217	0.8562	0.7459	-1.217	1.103	-3.002				6	0.00372	14.5
Lemna trisulca	0.5485	-2.899	0.1547	-1.157	-1.21	-4.494				6	0.01243	9.8
Mentha aquatica	-5.878	-3.922	-6.103	0.0331	5.503	-3.939	-4.332		-2.297	8	0.00832	12.5
Myosotis palustris	-3.678	-0.7657	-7.622	-1.208	3.217		-6.926		-1.478	7	0.00095	14.4
Myrophyllum spicatum	-30.71	-2.617	0.3242	1.718	34.44				-10.1	6	0.00868	26.6
Myrophyllum verticillatum	-13.54	-7.792	-2.289	-1.941	4.006					5	0.00005	36.7
Nuphar lutea	-0.8183	-1.89	0.6356	-0.1829	1.683	-3.587				6	0.00034	15.4
Nymphaea alba	-44.09	-3.099	-0.3213	-5.439	46.04				-13.43	6	0.00570	40.0
Phalaris arundinacea	0.7151	2.348	-1.195	0.1457	0.0569					5	0.08787	5.9
Phragmites australis	-6.79	-0.36	0.3833	-1.047	10.01				-4.114	6	0.02312	10.6
Potamogeton lucens	-3.503	-1.969	-0.0626	-0.2008	1.553					5	0.00260	12.0
Potamogeton natans	-6.285	-0.0044	-1.467	1.476	8.374				-3.327	6	0.00733	11.1
Potamogeton nodosus	-9.688	2.766	-2.329	-0.7347	4.271					5	0.00000	39.5
Potamogeton pectinatus	-7.187	0.0636	1.189	1.097	9.856				-2.779	6	0.00012	17.3
Potamogeton perfoliatus	-5.441	-3.28	2.191	1.113	4.092			2.77		6	0.00000	32.1
Potamogeton trichoides	-2703	-29.54	-6397	3.836	1.433		-3803			6	0.00001	78.2
Ranunculus aquatilis	-19.88	-3.318	-1.364	2.278	18.8				-5.439	6	0.05303	23.2
Ranunculus fluitans	-9.935	-6.132	-1.576	-0.0699	2.862					5	0.00134	26.3
Rumex hydrolapathum	-4.993	-1.405	-21.15	-1.369	-1.062		-19.2			6	0.00001	22.4
Sagittaria sagittifolia	-2.207	-2.247	-1.689	1.051	1.552					5	0.00000	22.8
Scirpus lacustris	-5.37	-0.1744	-0.8875	-0.7365	2.093					5	0.00661	14.8
Scirpus sylvaticus	-12.4	-20.43	0.105	-12.5	17.92	-25.37		-19.16	-10.49	8	0.00002	44.6
Scutellaria galericulata	-41.95	-2.895	-47.2	2.852	41.87		-25.71		-22.76	7	0.00433	40.2
Sparganium emersum	-0.1726	-1.547	0.5037	-1.097	0.1856	-2.821				6	0.06941	6.5
Sparganium erectum	0.1241	0.1976	-0.8623	-0.9024	-0.1941			-3.814		6	0.04900	7.0
Spirodela polyrhiza	-2.36	0.8054	-0.7907	-1.111	2.455			-2.613		6	0.00001	20.3
Stratiotes aloides	-61.38	0.4225	5.458	0.354	77.07				-22.99	6	0.00235	39.4
Typha angustifolia	-7.871	-2.857	2.528	-0.0393	9.177				-2.895	6	0.03402	14.9
Typha latifolia	-0.4661	0.465	2.423	-0.3231	-0.2248	-2.802				6	0.07275	16.0
Veronica catenata	-15.6	-0.2971	-17.67	2.327	4.426		-11.14			6	0.00092	35.8
Ranunculus circinatus	-11.22		-22.51	-0.5234	-1.059		-11.42			5	0.08293	10.8
Sium latifolium	-0.6288	-2.057	-0.9975		-1.271	-2.83				5	0.07695	6.9

SUMMARY

This thesis is a search for a method of environmental management that may lead to sustainable development in North-eastern Poland and the Warsaw region. The methods studied in this thesis provide the components of a decision support system for managing the water quality of the Narew River Basin. The tools that have been created enable competent authorities and other stakeholders to evaluate the impacts of different choices that are intended to preserve and develop nature, to improve human health, to improve land use planning and to implement optimal technical measures for water quality improvement.

Sustainability is an area-specific concept, which of necessity focuses on specific characteristics of the region being considered. In the present case the study area includes the city of Warsaw and the nearby catchment of the Narew River. The Narew River Basin is located in North-eastern Poland in an area known as 'the Green Lungs of Poland'. This remarkable name reflects perfectly the character of the region, which is characterised on the one hand by the abundance of forests, lakes, fens and marshes and clean rivers and streams and scarcity of industry and extensive agriculture on the other. The mix of well preserved cultural and agricultural landscapes and nature areas makes the area very attractive for recreation. Moreover, the region is not only characterised by high quality environmental, biological and cultural conditions but it has also the potential to solve the present problems concerning the drinking water supply for the capital city Warsaw. Currently Warsaw abstracts its drinking water mainly from the river River Vistula, which is polluted. The Narew River, however, carries sufficient amounts of relatively good quality water and therefore has the potential to solve the drinking water problems of Warsaw. Sustainability in this case, is thus defined as maintaining a high quality source for drinking water preparation and preservation of the present nature and landscape. Water quality in the rivers is the crucial aspect connecting land use, nature and drinking water.

The longer term prospects for the water quality from the Narew very much depend on the future policies for land development of the region. Possible futures vary from preserving the current rural nature of the catchment to implementing intensive agricultural land use that resembles that found in countries of north west Europe. Given the possibility that Poland will join the European Union in several months implies a considerable impact on the social, economical and environmental aspects of the future development of the Narew River Basin. This "European" perspective as well as specific regional and national developments, has underlined the need for the present study to enable policy makers to evaluate the effects of future land use scenarios.

The decision support system created by this study consists of an integrated model that incorporates the relevant elements of the land use – surface water – aquatic ecosystem cause-and-effect chain. The building of such a model and its evaluation required the formulation of a sequence of steps.

The first step was the collection of sufficient data, both for investigating the present situation as well as for modelling and studying different scenarios. The database contains information on land use, water quality and quantity, and vegetation characteristics. The investigation of the present situation revealed some problematic aspects and areas in the basin. These are: (i) surface waters were generally of relatively good quality, but had some problems mainly consisting of high concentrations of nutrients (phosphate and nitrate); (ii) nutrient emissions were relatively low and agricultural non-point (diffuse) sources were the main source of nutrient input to surface waters and (iii) aquatic vegetation was well developed, with characteristic differences between upper and lower river courses and high biodiversity, with few problem sites downstream of point source effluent discharges.

Second, the so-called integrated management tool (IMT) was built. The proposed tool consists of three hierarchically linked modules that compute, respectively the emission of nutrient loads to surface waters (NULAM), the modelling of in-stream water nutrients (STREAMPLAN) and the assessment of aquatic species response to changes in nutrient concentrations (INCORS).

NULAM models nutrient emissions from the catchment to the surface water using the export coefficients approach. This is a lumped model, which calculates nutrient losses for each land use type and each type of livestock found in the catchment. The output results from the nutrient emission model were input to an in-stream water quality model. STREAMPLAN, an existing water quality model was used for this. STREAMPLAN uses a one-dimensional, linear and steady state approach in which the physical processes are described based on the principles of mass balance along a river reach. Subsequently, the nutrient concentrations generated as output of the in-stream water quality model were used an input for an empirical statistical model that describes the response of plant species to changes in nutrient concentrations (INCORS). This is a logistic regression model based on the framework of Generalized Linear Models. All three modules were calibrated for the Narew River Basin for low flow periods during the growing season and linked together in the GIS-based integrated management tool (IMT).

In the third step the IMT was used to study different scenarios for possible developments for the basin. The scenario study considered future developments based on present ideas, premises and perspectives. In the Narew River Basin two very different development schemes may be expected when looking at the present political situation. The first considers Poland joining the European Union, which may lead to a rapid intensification of agricultural production and a situation comparable to high Western European levels of production and associated eutrophication. The second scenario explores the idea of sustainable development following current ideas for transition towards ecological farming in areas with high quality nature.

The most important conclusion to be drawn from the scenario study is that straightforward implementation of the European Union standards and limits in agriculture may result in more than double the current nutrient emissions, which as a consequence may cause severe deterioration of surface water quality and river ecosystems. Such a development will also disqualify water of the Narew River as a suitable source for drinking water production for Warsaw. In this scenario, it will be essential to implement a careful and wise use of the European Union subsidies, focusing on stimulation of good agricultural practices, ecological farming and enhancing farmers' knowledge will be necessary to avoid dramatic consequences for the physical environment. The second scenario showed that extensive, fertiliser-limited agriculture may lead to ca. 50% reduction in nutrient emissions, which improves quality of surface water and will be a guarantee for maintaining biodiversity of aquatic vegetation. According to the latter scenario water of the Narew River will be the best source of raw material for drinking water production for Warsaw among all available sources.

The thesis illustrates the value of the IMT by demonstrating the results of two quite extreme development strategies for the basin. Therefore, the tool gives policy makers, local authorities as well as society an idea of the range within which the basin may develop and what the consequences of particular strategies might be. Moreover, the GIS-based approach permitted the development and illustration of spatially distributed scenarios and their dependence on present and expected spatial settings of dominant land use functions.

The study presented in this thesis is but one of a few for which a large catchment a decision support system has been developed. It also demonstrates that sustainability can be defined in operational variables for water managers and land use planners. The IMT complies with an important standard of the European Water Framework Directive which requires all EU-member states to develop methods enabling them to quantify the effects of changes in land use and water management on ecosystems.

HET STROOMGEBIED VAN DE NAREW: EEN MODEL VOOR DUURZAAM BEHEER VAN LANDBOUW, NATUUR EN DRINKWATERVOORZIENING

SAMENVATTING

Het doel van dit proefschrift is het vinden van een methode om het land en water gebruik van een gebied in het noordoosten van Polen en de regio rondom Warschau op een duurzame manier te kunnen beheren en verder ontwikkelen. De ontwikkelde modellen voorzien in een beslissingondersteunend systeem waarmee de waterkwaliteit van de Narew kan worden gestuurd. Dit systeen maakt het de bevoegde overheden en overige belanghebbenden mogelijk om de invloed van verschillende keuzes te evalueren. Dit betreft het beschermen en ontwikkelen van natuurwaarden, het verbeteren van volksgezondheid, het proces van ruimtelijke ordening en het nemen van technische maatregelen ter verbetering van de waterkwaliteit.

Duurzaamheid is een gebiedsgericht concept, dat vanzelfsprekend is gericht op karakteristieke aspecten van de betreffende regio. De voorliggende studie concentreert zich op de stad Warschau en het stroomgebied van de Narew. Dit stroomgebied bevindt zich in noordoost Polen, een gebied dat bekend staat als “de groene longen” van Polen. Deze naam karakteriseert de aard van het noordoostelijk deel van Polen heel treffend, enerzijds door de rijke aanwezigheid van bossen, meren, moerassen, venen en de heldere beken en rivieren en anderzijds de zeer schaars voorkomende industrie en de extensieve landbouw. De afwisseling van het agrarisch cultuur landschap met en natuurgebieden maakt dit gebied zeer aantrekkelijk voor recreatie. Naast deze intrinsieke omgevingskwaliteiten, heeft dit gebied grote potenties voor waterwinning, waarmee de huidige problemen met de drinkwatervoorziening van Warschau zouden kunnen worden opgelost.

De huidige kwaliteit van het drinkwater in Warschau is niet bijster goed, omdat daarvoor water uit de vervuilde Vistula wordt gebruikt. De Narew daarentegen voert voldoende water van relatief goede kwaliteit en zou daarom een goed alternatief kunnen vormen. In dit geval wordt het begrip duurzaamheid derhalve gedefinieerd als het beheren van een kwalitatief hoogwaardige grondstof voor de bereiding van drinkwater tezamen met de bescherming van de huidige natuur- en landschapswaarden. De waterkwaliteit van deze rivier is dus een essentieel aspect dat landgebruik, natuur en drinkwatervoorziening met elkaar verbind.

De vooruitzichten voor de waterkwaliteit van de Narew voor de langere termijn hangen sterk af van de ontwikkeling van dit gebied. Mogelijke toekomstige ontwikkelingsrichtingen variëren van bescherming van het huidige natuurlijke karakter van het stroomgebied tot implementatie van een intensief landbouwkundig gebruik vergelijkbaar met dat van landen in noordwest Europa. Het perspectief van toetreding tot de Europese Unie van Polen over enkele maanden impliceert een mogelijk grote invloed op de sociale, de economische, de ruimtelijke en de milieukundige aspecten van de toekomstige ontwikkeling van het stroomgebeid van de Narew. Zowel dit Europees perspectief als specifieke regionale en nationale ontwikkelingen onderstrepen de noodzaak en het doel van deze studie om het beleidsmakers mogelijk te maken de effecten van toekomstscenario’s voor landgebruik in te schatten.

Het beslismodel uit deze studie bestaat uit een serie van drie modellen die geïntegreerd zijn in een GIS. Deze modellen reeks beschrijven de milieueffect keten landgebruik – waterkwaliteit – aquatische ecosystemen. Voor de ontwikkeling en de evaluatie daarvan was het formuleren van de volgende stappen noodzakelijk.

De eerste stap bestond uit het verzamelen van voldoende gegevens ten behoeve van zowel het onderzoek van de huidige situatie als het modelleren en de ontwikkeling van scenario’s. Het gegevensbestand bestaat uit informatie over landgebruik, waterkwaliteit en –kwantiteit en planten soorten in de rivieren. Het onderzoek naar de huidige situatie onthulde meerdere problemen in het stroomgebied: (i) hoewel de kwaliteit van het oppervlaktewater in het algemeen relatief goed was, werden er toch enige riviertrajecten met hoge concentraties van nutriënten (fosfaat en nitraat) aangetroffen; (ii) de uitspoeling van nutriënten naar oppervlaktewater was relatief laag en werd hoofdzakelijk veroorzaakt door diffuse bronnen van agrarische oorsprong; (iii) de aquatische vegetatie was goed ontwikkeld met karakteristieke verschillen tussen boven- en benedenlopen en had een grote biodiversiteit uitgezonderd die gebieden waar puntbronnen effluent loosden op de rivier.

In de tweede stap werd het geïntegreerde model gebouwd. Het vooropgestelde model kende drie hiërarchisch gekoppelde modules waarmee achtereenvolgens de emissie van nutriënten op oppervlaktewater (NULAM), het gedrag van nutriënten in de rivier (STREAMPLAN) en de reactie van de aquatische vegatatie op veranderingen van nutriëntenconcentraties (INCORS) werden berekend.

NULAM modelleert nutriënten emissies vanuit het stroomgebied naar het oppervlaktewater en maakt daarbij gebruik van een export coëfficiënten benadering. Dit is een model, dat het nutriëntenverlies berekent van iedere vorm van landgebruik en iedere vorm van veehouderij die in het stroomgebied voorkomen. De resultaten van dit emissiemodel vormen de input voor het waterkwaliteitsmodel van de rivier zelf, STREAMPLAN, een bestaand waterkwaliteitsmodel. STREAMPLAN gebruikt een één dimensionale, lineaire, statische benadering waarin de fysische processen worden beschreven volgens de principes van een massa balans binnen het beschouwde deel van de rivier. Vervolgens zijn de nutriëntenconcentraties die dit model berekende gebruikt als input voor het empirisch statistische model dat de reacties van plantensoorten op veranderingen in nutriëntenconcentratie beschrijft, INCORS. Dit is een logistisch regressiemodel gebaseerd op “Generalised Linear Models”. Alle de drie modules zijn gekalibreerd voor het Narew stroomgebied tijdens lage debieten gedurende het groeiseizoen en aan elkaar gekoppeld in het op GIS gebaseerde geïntegreerde beslismodel.

De derde stap bestond uit het toepassen van het beslismodel voor het bestuderen van de effecten van verschillende scenario’s m.b.t. toekomstige ontwikkelingen in het stroomgebied. Deze toekomstscenario’s zijn gebaseerd op de huidige ideeën, en perspectieven voor land gebruik veranderingen Voor het Narew stroomgebied kunnen op basis van de huidige politieke setting twee ontwikkelingsscenario’s worden verwacht. Het eerste is de situatie waarin Polen toetreedt tot de Europese Unie, wat zou kunnen leiden tot een snelle intensivering van agrarische productie, vergelijkbaar met de hoge west Europese niveau’s van productie en daarmee samenhangende eutrofiëring van het milieu. Het tweede scenario gaat uit van een duurzame ontwikkeling gebaseerd op actuele ideeën over een overgang naar biologische landbouw in gebieden met hoge natuurwaarden.

De belangrijkste conclusie van de scenariostudie is dat het ongewijzigd invoeren van de in de Europese Unie gehanteerde standaarden m.b.t. agrarisch gebruik van deze regio, kunnen leiden tot een verdubbeling van de huidige nutriëntenbelasting waarmee de oppervlaktewaterkwaliteit en de biodiversiteit van de ecosystemen ernstig achteruit kan gaan. Hiermee wordt ook de geschiktheid van dit watersysteem voor de drinkwatervoorziening van Warschau in gevaar gebracht. In een dergelijk scenario is het dus essentieel zorgvuldig en verstandig gebruik te maken van Europese subsidiestromen, gericht op het stimuleren van duurzaam agrarisch gebruik, biologische landbouw en het benutten van aanwezige agrarische gebiedskennis om ernstige consequenties voor de fysieke leefomgeving te vermijden.

Het tweede scenario liet zien dat extensieve landbouw met gelimiteerde bemestingsgiften kan leiden tot een verlaging van de nutriëntenbelasting met 50% t.o.v. de huidige situatie, wat ten goede komt aan de waterkwaliteit en het behoud van de biodiversiteit van het aquatisch ecosysteem. In dit laatste scenario vormt de Narew van alle onderzochte potentiële bronnen de meest geschikte bron voor de drinkwatervoorziening van Warschau.

Dit proefschrift illustreert de waarde van het geïntegreerde beslismodel doordat het de effecten inzichtelijke maakt van twee heel verschillende ontwikkelingsstrategieën voor het stroomgebied. Het beslismodel geeft daarmee beleidsmakers, locale overheden en de maatschappij een beeld van de bandbreedte waarbinnen ontwikkelingen kunnen plaatsvinden en wat de consequenties van verschillende keuzes zijn. Bovendien toonde de op een GIS gebaseerde benadering de mogelijkheid van ruimtelijk gedifferentiëende ontwikkelingsscenario’s die gemaakt kunnen worden op basis van de verwachte ruimtelijke indeling van functies.

Deze studie is één van de weinigen waarvoor een beslismodel voor een stroomgebied van zo grote omvang (ca. 28000 km^2, tweederde van Nederland) is ontwikkeld. Tevens is in deze studie het begrip duurzaamheid uitgewerkt tot concrete gebiedsspecifieke randvoorwaarden voor landgebruik en waterkwaliteit. Het beslismodel voldoet aan een belangrijke eis van “The European Water Framework Directive”, die zegt dat van alle EU lidstaten verwacht mag worden dat zij methoden ontwikkelen waarmee zij de effecten van veranderingen in landgebruik en watermanagement op ecosystemen kunnen kwantificeren.

MODEL DLA POTRZEB ZRÓWNOWAŻONEGO ZARZĄDZANIA ZAOPATRZENIEM W WODĘ, ROLNICTWEM I OCHRONĄ ŚRODOWISKA ZLEWNI RZEKI NARWI

STRESZCZENIE

Niniejsza rozprawa doktorska poświęcona jest opracowaniu narzędzi przydatnych, w szeroko pojętym zarządzaniu środowiskiem. Metody prezentowane w pracy zawierają składowe systemu wspomagania decyzji w gospodarowaniu jakością wody w zlewni rzeki Narwi. Opracowane modele powinny być przydatne w procesie podejmowania decyzji poprzez stworzenie możliwości oceny wpływu zagospodarowania zlewni i infrastruktury technicznej cieków i systemów wodno-gospodarczych na jakość środowiska wodnego.

Stworzenie koncepcji zrównoważonego rozwoju jest związane nierozerwalnie z konkretnym obszarem, w związku z czym stworzenie takiej koncepcji wymaga wzięcia pod uwagę specyficznych charakterystyk rozważanego regionu. W obecnym przypadku rozważany obszar obejmuje zlewnię rzeki Narwi, uwzględniając również jej geograficzną bliskość w stosunku do Warszawy. Zlewnia Narwi położona jest w północno-wschodniej Polsce na obszarze znanym jako "Zielone Płuca Polski". Ta charakterystyczna nazwa doskonale oddaję specyfikę regionu, który z jednej strony charakteryzuje się obfitością lasów, jezior, mokradeł, i czystych cieków wodnych oraz ograniczoną obecnością przemysłu i ekstensywnym rolnictwem z drugiej strony. Mieszanka dobrze zachowanych walorów i krajobrazów kulturowych, rolniczych oraz naturalnych przyczynia się do wysokiej atrakcyjności regionu dla rekreacji. Co więcej, obszar ten nie tylko charakteryzuje się wysokiej jakości warunkami środowiskowymi, biologicznymi i kulturowymi ale także ma potencjał do rozwiązania obecnych problemów związanych z zaopatrzeniem Warszawy w wodę pitną. W chwili obecnej Warszawa pozyskuje wodę pitną ze źródeł (Zalew Zegrzyński, Wisła), które są niskiej jakości. Natomiast Narew prowadzi wystarczające ilości relatywnie wysokiej jakości wody i dlatego potencjalnie może stanowić alternatywę dla rozwiązania problemów jakości wody pitnej w Warszawie. W poruszanym przypadku zrównoważony rozwój oznacza stworzenie wysokiej jakości źródła dla produkcji wody pitnej przy zachowaniu obecnego krajobrazu i stanu środowiska przyrodniczego. Jakość wody w rzekach jest decydującym czynnikiem łączącym użytkowanie ziemi, środowisko naturalne i wodę pitną.

Długookresowe perspektywy dotyczące jakości wody opuszczającej zlewnie Narwi zależą w ogromnym stopniu od przyszłych strategii rozwoju użytkowania ziemi w regionie. Możliwe wizje przyszłości rozciągają się pomiędzy zachowaniem obecnego, ekstensywnego rolnictwa i bogactwa środowiskowego regionu, a wprowadzeniem intensywnego rolniczego użytkowania ziemi, o podobnej intensywnosci jak ma to miejsce obecnie w krajach północno-zachodniej Europy. Perspektywa wstąpienia Polski do Unii Europejskiej oznacza początek zmian we wszystkich znaczących społecznych, ekonomicznych i przyrodniczych aspektach rozwoju obszaru zlewni rzeki Narwi. Zarówno perspektywa „europejska" jak i obecność specyficznych lokalnych i regionalnych koncepcji rozwoju przestrzennego podkreślają potrzebę istnienia, podobnych do niniejszego, studiów zintegrowanej gospodarki zasobami wodnymi aby

umożliwić planistom i decydentom ocenę efektów przyszłych scenariuszy użytkowania ziemi.

System wspomagania decyzji stworzony w ramach niniejszego opracowania składa się ze zintegrowanego modelu, który zawiera istotne elementy łańcucha przyczynowo-skutkowego obejmującego użytkowanie ziemi, przepływ wód powierzchniowych oraz obecność zróżnicowanych ekosystemów wodnych. Stworzenie takiego modelu i ocena jego przydatności w procesie decyzyjnym zostało przeprowadzone w kilku skoordynowanych etapach.

Pierwszym krokiem było zgromadzenie odpowiednich danych, pozwalających na ocenę obecnej sytuacji jak i umozliwiajacych proces modelowania oraz stworzenia różnych scenariuszy rozwoju obszaru zlewni. Stworzona baza danych zawiera informacje o charakterystykach dotyczących użytkowania ziemi, jakości i ilości wody oraz roślinności wodnej. Ocena obecnej sytuacji w zlewni pozwoliła na sformułowanie podstawowych problemów gospodarki wodnej. Należą do nich: (i) jakość wód powierzchniowych, która ogólnie relatywnie była dobra, natomiast występowały problemy związane głównie z wysokimi koncentracjami związków biogennych (fosforany i azotany); (ii) kontrola emisji związków biogennych, będąca obecnie stosunkowo niska ale z tendencją wzrostową, ze szczególnym naciskiem położonym na rolnicze rozproszone źródła, które były głównymi źródłami biogenów w wodach powierzchniowych oraz (iii) co najmniej zachowanie obecnego stanu roślinności wodnej, która była dobrze rozwinięta, z charakterystycznymi różnicami pomiędzy górnymi i dolnymi odcinkami rzek i dużą bioróżnorodnością, ale także kilkoma problematycznymi obszarami położonymi poniżej punktowych źródeł zanieczyszczeń.

W drugim kroku stworzone zostało zintegrowane narzędzie dla potrzeb zarządzania (ang. Integrated Management Tool, IMT). IMT składa się z trzech hierarchicznie połączonych modułów, które odpowiednio, pozwalają na obliczanie wielkości emitowanego ładunku biogenów do wód powierzchniowych (NULAM), modelowanie związków biogennych w wodach płynących (STREAMPLAN) oraz ocenę reakcji roślin wodnych na zmiany w koncentracjach związków biogennych (INCORS).

NULAM pozwala na modelowanie emisji biogenów z obszaru zlewni do wód powierzchniowych przy wykorzystaniu metody współczynników eksportowych. Jest to model typu “czarnej skrzynki”, który oblicza emisje biogenów z każdego typu użytkowania ziemi i od każdego rodzaju chowu zwierząt gospodarczych. Rezultaty modelowania emisji biogenów są jednocześnie danymi wejściowymi do modelu jakości wody. Dla potrzeb pracy dokonano indentyfikacji modelu STREAMPLAN dla warunków rzeki Narwi. Jest to jednowymiarowy, liniowy model statyczny w którym procesy fizyczne opisane są na podstawie bilansu zachowania masy na danym odcinku rzeki. Koncentracje związków biogennych, będące rezultatem modelowania jakości wody, były wykorzystane jako dane wejściowe do empirycznego, statystycznego modelu opisującego reakcje roślin wodnych na zmiany koncentracji biogenów (INCORS). Jest to model logarytmiczno-regresyjny oparty na koncepcji Generalized Linear Models. Wszystkie trzy moduły zostały skalibrowane w zlewni Narwi dla niskich przepływów w okresie wegetacyjnym i połączone na platformie GIS w zintegrowane narzędzie dla potrzeb zarządzania (IMT).

Trzecim krokiem było zastosowanie IMT do oceny różnych scenariuszy możliwego rozwoju zlewni. W studium scenariuszowym rozważone zostały strategie przyszłego rozwoju bazujące na obecnych przesłankach, pomysłach i perspektywach. Dla obszaru zlewni rzeki Narwi można zakładać, analizując obecną sytuacje polityczną, dwa rożne schematy rozwoju. Pierwszy zakłada wstąpienie Polski do Unii Europejskiej, co może doprowadzić do gwałtownego wzrostu produkcji rolnej i sytuacji porównywalnej z wysokim zachodnioeuropejskim poziomem produkcji rolnej. Drugi wykorzystuje koncepcję zrównoważonego rozwoju bazującą na istniejących pomysłach zmian w kierunku rolnictwa ekologicznego na obszarach o wysokich walorach przyrodniczych.

Najważniejszym wnioskiem płynącym ze studium scenariuszowego jest możliwość ponad dwukrotnego wzrostu, w stosunku do sytuacji obecnej, emisji związków biogennych w przypadku bezpośredniego i bezwarunkowego wprowadzenia obowiązujących w Unii Europejskiej standardów i limitów. W konsekwencji może to prowadzić do znaczącego pogorszenia jakości wód powierzchniowych i ekosystemów rzecznych. Taka sytuacja dyskwalifikowała by wody Narwi jako odpowiednie źródło dla produkcji wody pitnej dla Warszawy. W przypadku tego scenariusza niezwykle istotnym było by uważne i rozsądne wykorzystanie subsydiów pochodzących z funduszy Unii Europejskiej, skupiające się na stymulowaniu stosowania dobrych praktyk rolniczych, rolnictwie ekologicznym oraz podnoszeniu wiedzy wśród rolników, koniecznych w celu uniknięcia znaczących konsekwencji dla środowiska naturalnego. Drugi scenariusz pokazuje iż ekstensywne, z ograniczonym wykorzystaniem nawozów sztucznych, rolnictwo może prowadzić do około 50% redukcji emitowanych związków biogennych, co wpłynie na poprawę jakości wód powierzchniowych i zagwarantuje zachowanie bioróżnorodności roślinności wodnej. Zgodnie z tym scenariuszem woda Narwi była by najlepszym, spośród wszystkich istniejących, źródłem surowego materiału dla produkcji wody pitnej w Warszawie.

Poniższa rozprawa pokazuje wartość IMT poprzez przedstawienie rezultatów dwóch całkowicie przeciwnych strategii rozwoju zlewni. Zatem, narzędzie to daje zarówno planistom, lokalnym władzom jak i społeczeństwu możliwość oceny ram w jakich rozwój zlewni może przebiegać i jakie mogą być konsekwencje realizacji poszczególnych strategii. Co więcej, bazująca na GIS metodologia pozwala na opracowanie i przedstawienie przestrzennie zróżnicowanych scenariuszy i ich zależności od obecnych i spodziewanych przestrzennych założeń dotyczących dominujących funkcji użytkowania ziemi.

Studium przedstawione w rozprawie jest jednym z niewielu w których został opracowany system wspomagania decyzji dla zlewni o obszarze przekraczającym 25000 km^2. Pokazuje ono również, iż zrównoważony rozwój może być zdefiniowany poprzez zmienne operacyjne dla instytucji i osób odpowiedzialnych za gospodarkę wodną oraz planowanie użytkowania ziemi. IMT odpowiada istotnemu standardowi Europejskiej Ramowej Dyrektywy Wodnej, która wymaga od wszystkich państw członkowskich opracowania metod pozwalających na ilościową ocenę efektów zmian w użytkowaniu ziemi oraz gospodarce wodnej na ekosystemy.

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CURRICULUM VITAE

Marek Giełczewski was born on 10th of July in 1967 in Warsaw, Poland. In June 1987 he obtained his graduation diploma at the Stefan Batory High School in Warsaw. From 1987 to 1994 he studied Geography at Faculty of Geography and Regional Studies at Warsaw University. In 1994 he graduated with a major in the hydrology of the mountainous river watershed (Skawa river). In 1994 he followed for five months the Tempus Program fellowship at the Faculty of Water Resources at Wageningen Agricultural University. From 1995 to 2002 he worked at the Department of Environmental Sciences at Utrecht University as a Ph.D. researcher. The research, which was funded by Utrecht University Fund for Research of Societal Relevance, aimed at the development and integration of environmental models to support and direct the development planning of the Narew River Basin towards sustainability.

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