MODELLING RIVER WATER QUALITY FROM DIFFUSE SOURCES AT THE CATCHMENT SCALE

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Abstract

River pollution from non-point sources, such as agricultural activities and surface runoff is actually one of the major threats to surface and groundwater quality at the catchment scale. In this paper the first results on river water quality simulation, obtained by a European funded research project called RIVERTWIN are presented. The main objective of the project is the development and application in different river basins of an integrated water resources management model, including the surface water quality simulation component. Two different mathematical models were used, i.e. the MONERIS and QUAL2K models. Results of numerical simulation together with comparison with available data are reported for the case of the Neckar River Basin, Germany.

Keywords: River water pollution; mathematical modelling; numerical simulation; Germany; Neckar river basin

1. INTRODUCTION

Until the early 1980s, the efforts to protect water quality and beneficial uses were directed primarily towards controlling point source discharges of waste from sewage treatment plants and industrial facilities. Pollution from such point source discharges has largely been controlled through stringent pollution control laws. Ground water contamination, nonpoint sources of pollution (such as urban and agricultural runoff), and physical modifications to water bodies are now considered the greatest remaining threats to water quality and beneficial uses and will increasingly be the focus of efforts in the coming years.

Agriculture has changed dramatically, especially since the end of World War II. Food and fibre productivity soared due to new technologies, mechanisation, increased chemical use, specialisation and government policies that favoured maximising production. These changes meant that most of the food and fibre produced was done so by fewer farmers with reduced labour needs.

Although these changes have had many positive effects and reduced many risks in farming, there have also been significant costs. Prominent among these are topsoil depletion, groundwater contamination, the decline of family farms, continued neglect of the living and working conditions of farm labourers, increasing costs of production, and the deterioration of economic and social conditions in rural communities.

Agriculture water pollution is becoming a major concern not only in developed regions such as the European Union (EU) but also in many developing countries. The intensification of agricultural practices, in particular the growing use of fertilisers and pesticides, and the specialisation and concentration of crop and livestock production, has had an increasing impact on water quality. The main agricultural water pollutants are nitrates, phosphorus, and pesticides. Rising nitrate concentrations threaten the quality of drinking water, while high pesticide use contributes substantially to indirect emissions of toxic substances. Increasing levels of nitrates and phosphorus in surface waters reduce their ability to support plant and animal life and make them less attractive for recreation.

Controlling water pollution from agriculture is made difficult by its particular nature. In most circumstances, agricultural pollution occurs over a wide area, and its sources are diffuse and difficult to identify. It also varies unpredictably over time and space, and depends not only on rainfall patterns and the land--slopes and soil characteristics, but also on farmers' land use and crop choices, production techniques, and fertiliser and pesticide use. Farmers' decisions, in turn, are affected by market prices for inputs and outputs, as well as by governments' agricultural support policies. In contrast to many industrial and municipal situations, few pollution treatment alternatives are readily available for installation on farms. Pollution control measures must rely heavily on approaches that affect farmers' land use and production decisions. Thus, agricultural policy, which directly influences these decisions, and environmental policy to control agricultural water pollution need to be coordinated and pursued with the same goals in mind.

In the present EU funded research project called RIVERTWIN, the research team at the Aristotle University of Thessaloniki is responsible for modelling surface water quality from diffuse sources at the basin scale. As shown in Fig. 1, two river basins having different climatic conditions have been studied.

The Neckar Basin is located in the South-West of Germany and bordered by low mountain ranges in the west and South East part (Black Forest, Swabian Alb). Being the third largest tributary of the Rhine River, the Neckar, 367km long, drains a catchment of more than 13.000 km^2. Climate in the Neckar catchment is semi humid and temperate. Average annual precipitation is 950 mm and average daily temperature in the catchment is 8.7°C.

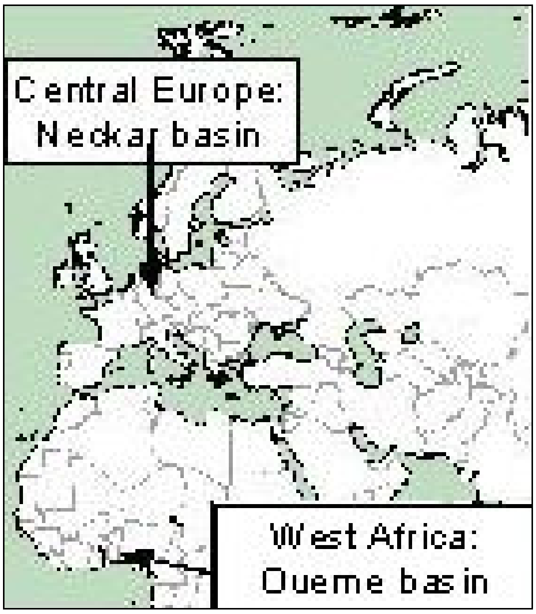

Fig. 1 Location of two river basins under investigation.

Anthropogenic impacts have led to major changes and water management problems during the last decades. Critical water management problems are floods, which frequently extend into the Rhine River during spring time, and loss of habitat for aquatic organisms. Especially changes of the riverbed morphology, implemented to facilitate navigation, have caused deterioration of river habitats. Main problems for drinking water quality can be attributed to nitrate and phosphate leaching from agriculture as well as to emissions of heavy metals, biocides and substances affecting the endocrine system.

The second river basin is the Oueme basin is located in the Republic of Benin. It has an extension of about 50.000 km^2 and its major part is located within the country borders. The climate is of the monsoon type, which is characteristic for the large sub-humid Savannah zones of the world. In third world countries such as Benin, the disposal of the urban wastes is a major problem. The streams serve as natural sewerage lines for domestic and industrial wastes. In the cities there are septic tanks, open dumps and surface impoundments. The majorities of private septic tanks are characterised by open bottoms or peculiar channels, which facilitate the seepage in depth or with direct connection to the nearby streams. Large and small-scale factories are clustered within the city and have unregulated waste disposal systems. The major solid waste disposal sites of the cities are located within the city limits, thus polluting the urban environment. These waste disposal sites are open systems, with no impermeable layer and with continuous low temperature burning. As a result of the above, the surface waters and the aquifers near urban areas area highly polluted.

The project “RIVERTWIN” aims to develop, adjust, test and implement an integrated regional model for the strategic planning of water resources management in twinned river basins under contrasting ecological, social and economic conditions. The regional model will take into account the impacts of demographic trends, economic and technological development, the effects of global climate and land use changes on the availability and quality of water bodies in humid temperate, sub-humid, tropical and semi-arid regions. Through its holistic basin wide approach, the project contributes to the EU water directive, the Millennium Goals defined by the WSSD and the EU water initiative for Africa and Newly Independent States.

RIVERTWIN intends to apply two innovative methodologies to integrate scientific knowledge from both natural and social sciences: Integrated modelling and integrated scenario development. RIVERTWIN builds upon the experiences gained in the development of the GIS based Model for Sustainable Development of Water and Land Use (MOSDEL) in the semiarid Northeast of Brazil. The project is connected through the respective project participants to ongoing projects on model integration like GLOWA-Danube (http://www.glowa-danube.de) and DEKLIM-KLIMEX (http://www.mpimet.mpg.de/de/projects/klimex/klimex_project.php). Interfaces exist with other EU Twinning projects as well as the coordinated action "Harmonised modelling tools for integrated basin management" (HARMONICA 2002) in the development and testing of practical evaluation tools and the proposal of methodologies for the evaluation of river basins.

2. DATA COLLECTION

The principle of effectiveness gives rise to the implementation of a series of economic instruments and rules for the distribution of costs, rehabilitation, protection and preservation of common water deposits.

Right at the beginning of the project a list of data requirements was compiled for the two surface water quality models (Tables 1 and 2). Data collection in the Neckar basin is far advanced. The major part of the data that are necessary for model development and testing are available, except for additional soil data (chemical and physical), highly resoluted water quality measurements and time series on water extraction from ground water aquifers and pollutant release from waste water treatments.

In the Oueme basin, data collection is ongoing. There also, soil data collection is most time-consuming as well as water quality monitoring and water demand assessment in rural areas. However, considerable efforts have been made to sample data on river discharge rates, terrain properties (digital elevation model), land use (satellite images classification has started in Benin) and statistical data on population and production in the different sectors.

Table 1. Required data and data availability for the model MONERIS.

Required data for MONERIS	**Available data for the Neckar basin**	**Available data for the Oueme basin/ status**
Mean slope (%)	Available	DEM
Tile drained area (%)	Available	0 %
Landuse area (km^2)	Available	Will be obtained
Statistics of communes: Inhabitants, arable area (km^2)	Available	Will be obtained
Urban systems: Inhabitants connected to WWTP or/and sewer (% of open septic	Available	none

tanks?). Sewer flow length, total discharge of P, N from WWTP per catchment		
Hydrogeological type areas (km^2) defined by soil, porosity, permeability, depth of groundwater	Available	Will be obtained
Mean soil loss (t*(ha*a)), proportions of soil type on total area (km^2), Nitrogen content in topsoil (%), clay content (%)	Available	Will be obtained
Precipitation (mm/m^2)	Available	*76 national stations with daily precipitation data from 1980 to 2003.*
Mean evaporation (mm/a)	Available	*3-5 national stations with daily data from 1980 to 2003.*
Atmospheric deposition (gN/m^2)	Available	Will be obtained
Nitrogen surplus (kg/(ha*a))	Available	From SLISYS

Table 2. Required data and data availability for the model QUAL2K

Required data for water quality (in hourly basis)	**Available data for the Neckar basin**	**Available data for the Oueme basin/status**
Temperature	14 water quality stations (LFU 1972-2002)	2 measurements/year
Conductivity	14 water quality stations (LFU 1972-2002)	2 measurements/year
Inorganic Solids	14 water quality stations (LFU 1972-2002)	2 measurements/year of turbidity
Dissolved Oxygen	14 water quality stations (LFU 1972-2002)	New measurements
BOD	14 water quality stations (LFU 1972-2002)	New measurements
Dissolved Organic Nitrogen	Estimated from Total N – NH_4-NO_3	N/A
NH_4-Nitrogen	14 water quality stations (LFU 1972-2002)	2 measurements/year
NO_3-Nitrogen	14 water quality stations (LFU 1972-2002)	2 measurements/year
Dissolved Organic Phosphorous	Estimated from Total P - Inorganic P	N/A
InorganicPhosphorus	14 water quality stations (LFU 1972-2002)	2 measurements/year

Phytoplankton	From literature	N/A
Detritus	14 water quality stations (LFU 1972-2002)	Estimated from Carbon in organic matters
Pathogen	N/A	New measurements
Alkalinity	From literature	2 measurements/year
pH	14 water quality stations (LFU 1972-2002)	2 measurements/year
Hydraulics data		
Cross section profiles	Available cross section profiles at each km of River Neckar	4 cross section profiles along the River Oueme (discharge,velocity,slope, water level, width)
Elevation	DEM	DEM
Station coordinates	Longitude/latitude	Longitude/latitude
Meteorological data		*3-5 national stations with daily data from 1980 to 2003*
Temperature	LFU 1988-2003	Max. & min. values
Dew-point temperature	LFU 1988-2003	Max. & min. values of humidity
Wind speed	LFU 1988-2003	Mean value
Cloud cover shade	Estimated from solar radiation data	N/A
Effective shade	N/A	Estimated from sun duration data
Point sources data	Available	Water quality at Oueme tributaries
Point abstraction data	Available from statistics	Will be obtained
Diffuse sources data	From Moneris	From Moneris

3. MODELLING ALTERNATIVE SCENARIOS
4.

Two different models were applied for modelling the surface water quality:

3.1 THE MONERIS MODEL

The MONERIS (MOdelling Nutrient Emissions in RIver Systems) model is a conceptual, quasi-static model developed to estimate annual emissions of nitrogen and phosphorus from various sources on a subcatchment scale and the resulting loads at the subcatchment outlet (Behrendt et al. 2000a, b; Behrendt, 1993). As shown in Fig. 2, the model estimates annual loads from seven different pathways, which derive from point (direct and WWTPs) and diffuse sources (atmosphere, agriculture and urban areas). Each pathway has its own Excel file where the calculations are made and these files are further linked to an input data file and an output data file.

The model is dependent on statistical data (i.e. inhabitants, nutrient surplus, information on sewer systems) and geographical data stored and analysed in a Geographical Information System (GIS).

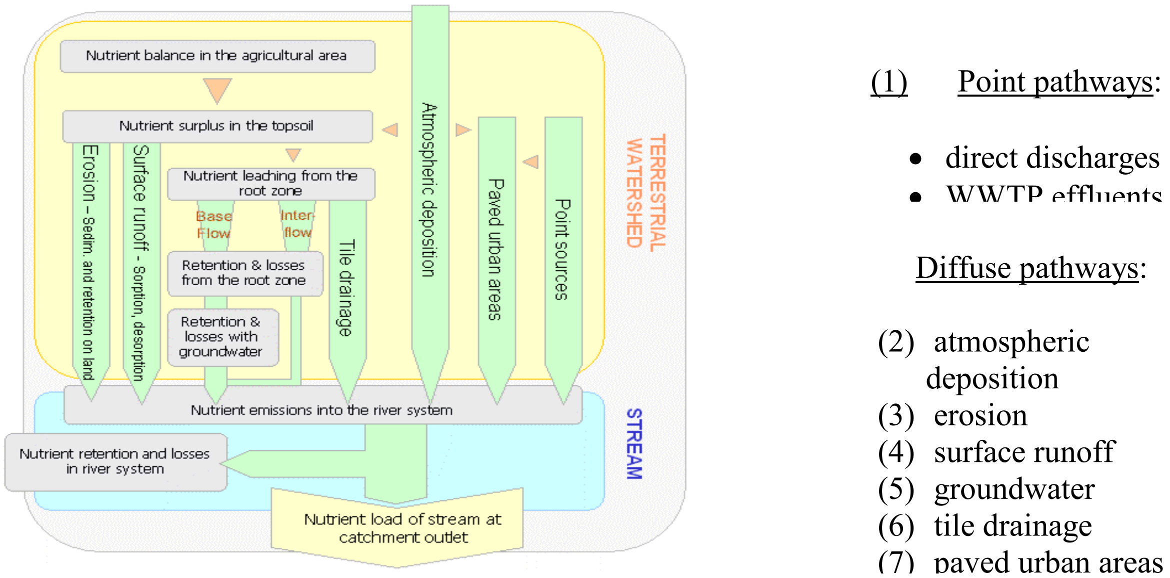

Fig. 2 Point and diffuse pollutant pathways in the MONERIS model (Behrendt et al. 2000).

3.2 THE QUAL2K MODEL

The conceptual representation of a stream used in the QUAL2K model (Brown et al., 1987) is that of an element that has been divided into a number of unequally spaced reaches or computational steps equivalent to finite difference elements (Fig. 3).

For each computational element, a hydrologic balance in terms of flow, a heat balance in terms of temperature, and a mass balance in terms of constituents' concentration are formulated. The model presently simulates the main stem of a river. In addition, multiple loadings and abstractions can be introduced for any reach. Tributaries are not modelled explicitly, but can be represented as point sources.

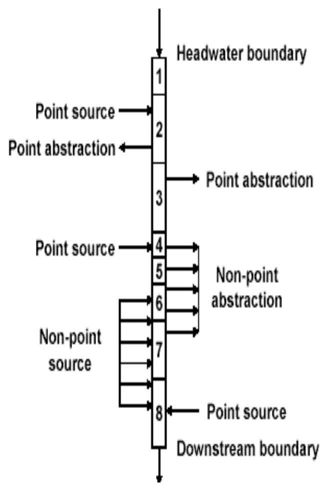

Fig. 3 The QUAL2K scheme

4. RESULTS & DISCUSSION

The model MONERIS (MOdelling Nutrient Emissions in RIver Systems) was developed and applied to estimate the nutrient inputs into river basins of Germany by point sources and various diffuse pathways. The reference year for the first application of the model is the year 2000. The model was run for the whole Neckar basin. The basin was divided in 42 subcatchments from 134 Km^2 to 505 Km^2. Some of the model outputs for the Neckar basin are shown in Figs 4 and 5 below.

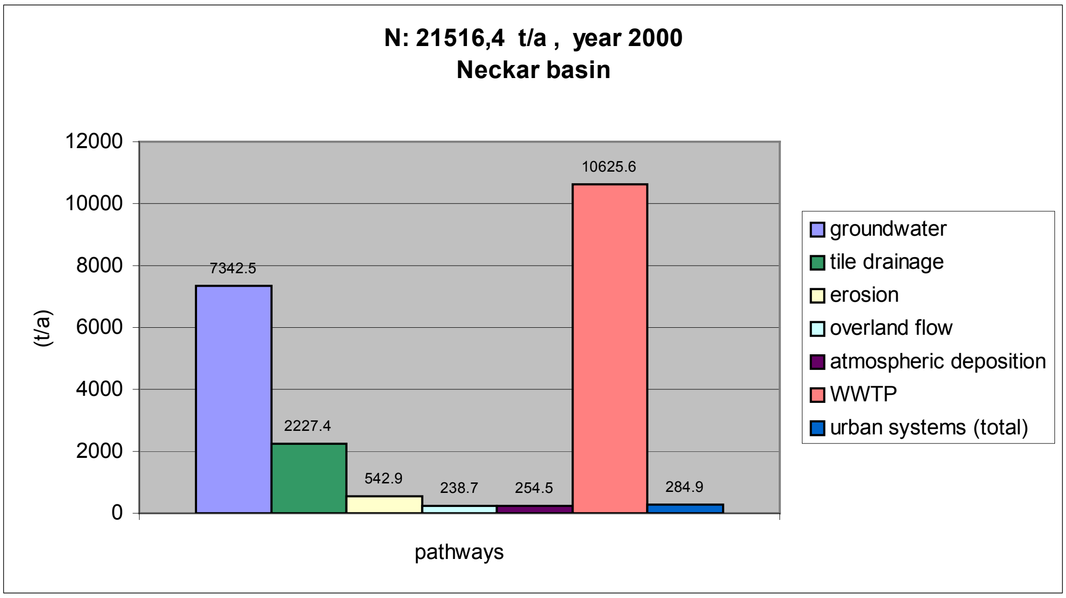

Fig. 4 Nitrogen emissions at the outlet of the Neckar basin for the reference year 2000.

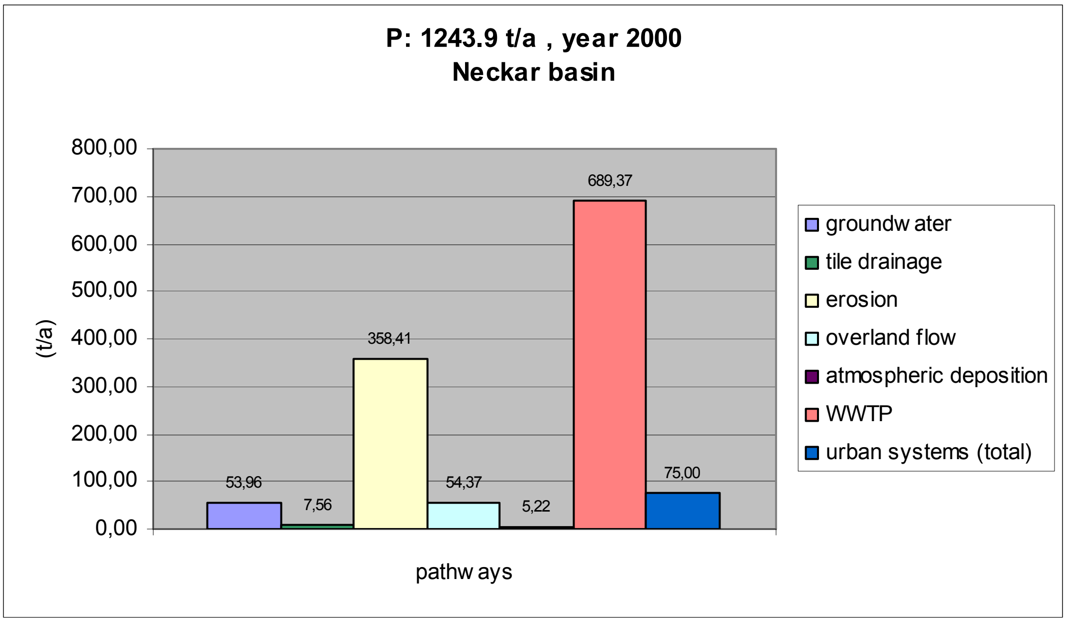

Fig. 5 Phosphorous emissions at the outlet of the Neckar basin for the reference year 2000

QUAL2K: (Chapra, 1997 ; Chapra et al. 1993 ; Cestii et al. 2003, Tomann, 1987)

The lower part of the River Neckar from Hofen to Mannheim was selected for model calibration and validation, since there is better data coverage for this lower part of the river. The reference year for the first run of the model was 2000. Some of the model outputs and comparison with available data are plotted in the graphs below (Fig. 6).

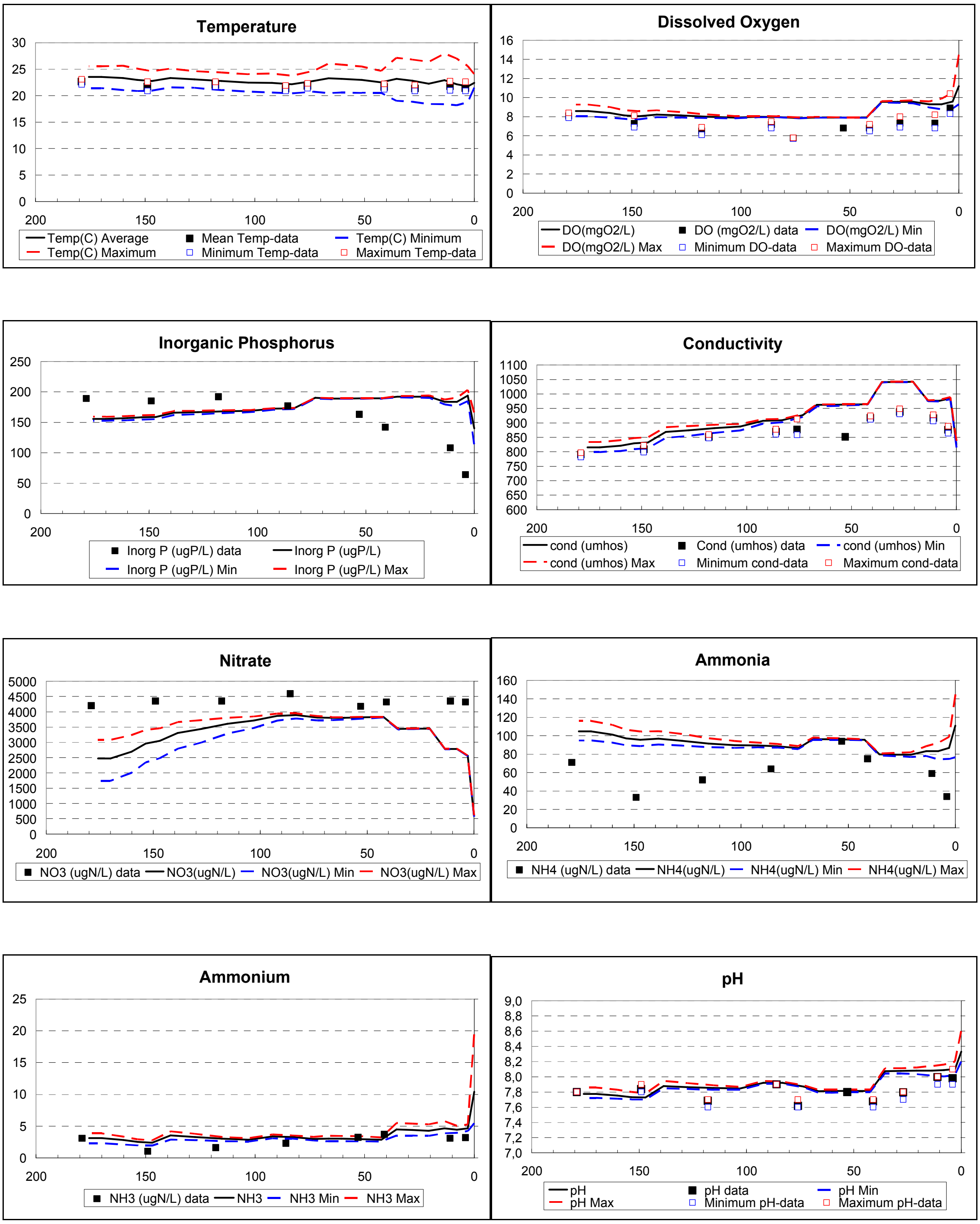

Fig. 6 Comparison between QUAL2K simulation and available data.

For better spatial differentiation of the reference scenarios, four reference regions were defined. It was accepted that economic development will be more concentrated in regions where infrastructure already is present. The subdivision, which was made by the state government, includes 4 region types differentiated according to their degree of agglomeration (1. urban agglomerations, 2. peripherals of urban agglomerations, 3. agglomerations in rural areas and 4. rural areas).

The Neckar scenario group defined two reference scenarios A (globalisation) and B (more environmentally concerned) and their driving forces in the different agglomeration areas. The two scenarios constitute two alternative socio-economic developments as a baseline to test the effects on water management measures and their robustness against contrasting socio-economic developments.

Confidence in the model results may be compromised, because QUAL2K uses over a hundred parameters, the values of which are not precisely known. In addition, uncertainties are due to incomplete knowledge about the magnitude of various inputs and abstractions as well as about their precise location along the river. All these uncertainties may influence up to 15 state variables used in the model.

Further developments will focus on the most important input variables to be modified, and on locations along the river where uncertainty analysis could be applied. Uncertainty analysis techniques that can be employed are: sensitivity analysis, first order error analysis, Monte Carlo and fuzzy logic-based simulation. For the Neckar Basin a balance between existing data and local expertise will be used in order to minimise complexity for model uncertainty analysis.

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