ECOMAG: a distributed model of runoff formation and pollution transformation in river basins

YU. MOTOVILOV
Water Problems Institute, Russian Academy of Sciences, Gubkina St. 3, 119333 Moscow, Russia
motol@pochta.ru

Abstract The ECOMAG model consists of hydrological and water quality submodels, which operate at a daily time step. The hydrological submodel describes the main processes of the terrestrial hydrological cycle: snow accumulation and melting, soil freezing and thawing, water infiltration into unfrozen and frozen soil, evapotranspiration, the thermal and water regime of soil, and the lateral surface, subsurface, groundwater and channel flow. The water quality submodel describes the processes of pollutant accumulation on the surface, dissolution of pollutants by rain or snowmelt waters, penetration of soluble pollutants into soil, interaction with the soil solution and soil matrix, and biochemical degradation of pollutants. The transfer and transformation of pollutants in the river system are described, taking into account the lateral diffusive inflow of pollutants by surface, subsurface and groundwater flows, the load from point sources of pollutants discharged to the rivers, the exchange of pollutants between the river water and river bed. An application of the hydrological and water quality submodels is shown for simulating water quality dynamics in river basins of the Kola Peninsula which is exposed to intensive pollution from the Pechenganickel Industrial Complex. Simulated nickel concentrations in river water are compared with the corresponding observed data. Results of modelling experiments are presented to illustrate the impact of Pechenganickel on water quality in river channels.

Key words ECOMAG model; river basin; runoff formation; nickel; pollution transformation; water quality; Russia

INTRODUCTION

Enterprises of non-ferrous metallurgy have a considerable impact on the ecological state around their locations. The plants of the world's largest nickel producer, the Norilsk Nickel Company, which undertakes the extraction of ore and produces about 20% of the world's nickel, have a special role with regards to the high production and the considerable impact on the environment. The main plants of the Company are concentrated in two areas of environmental stress: on the Kola Peninsula and the Taimyr Peninsula. These regions are characterized by ecological vulnerability. For many years, extremely high concentrations of nickel, copper and other heavy metals have been observed in the water bodies around the location of the factories.

About one half of ore extraction and nickel production is provided by a subsidiary Kola branch of the Company, in particular, by the Pechenganickel Industrial Complex (PIC). The industrial complex accounts for about one half of emissions of pollutants from stationary pollutant sources in the Murmansk region and a considerable part of the contaminated industrial wastewater discharges into water bodies. As a result of the PIC operation, degradation of forests and severe pollution of soils and groundwaters by heavy metals are observed. According to the State reports on the status and environmental protection of the Russian Federation, the Kolos-Yoki and Luottn-Yoki rivers and their tributaries, to which PIC discharges industrial wastewaters, are the ones most polluted by heavy metals amongst Russian rivers for many years.

The negative impact of PIC on the environment is connected with transboundary pollution issues. The frontier territories of Norway and Finland suffered from the industrial impacts for many years due to atmospheric transfer of pollutants and transfer in transboundary water bodies located near the Norwegian border. Therefore, the issues of transboundary environmental pollution by the Pechenganickel Industrial Complex are addressed by international conventions and intergovernmental agreements on the environment, implying the transboundary context; they are a subject for scientific research and monitoring under various international projects and draw much attention from Russian and international (WWF, Bellona) environmental organizations.

In order to fulfill the general task on minimizing the negative impact on the environment, the Kola Mining Company takes a series of activities that help to decrease emissions and discharges of pollutants, reduce the amount of industrial wastes and thus to considerably decrease industrial impact in the areas where the main factories are located. In this regard, within the project funded by the Kola Mining Company to assess the anthropogenic contribution to river pollution over the area of influence of the PIC, the ECOMAG model of runoff formation and pollution transformation in river basins was applied. This paper presents some results of the project concerning modelling of the nickel pollution in the Kolos-Yoki and Luottn-Yoki rivers.

ECOMAG MODEL

ECOMAG is the acronym for ECOlogical Model for Applied Geophysics, a distributed physically-based model developed for description of runoff formation and pollution transformation in river basins located in the cold regions of the Earth (Motovilov & Belokurov, 1996). ECOMAG consists of hydrological and water quality submodels, which operate at a daily time step.

Hydrological submodel

The hydrological submodel for a landscape unit was developed using the following scheme, which takes into account the processes of hydrological cycle (Fig. 1, Motovilov *et al*., 1999a,b). During the summer season, rain partially infiltrates into the soil and penetrates into the deeper soil layers. The soil is divided into a top layer (horizon A), an intermediate layer (horizon B) and a bottom layer (groundwater storage). The total porosity of the soil is divided into two parts: a capillary zone (the upper limit of which is the field capacity) and a non-capillary zone (the difference between total porosity and field capacity).

After the surface depressions are filled, the excess water not absorbed by the soil runs off on the sloping land surface to the river network (surface flow). From the capillary zone of the soil the water is only lost by evapotranspiration. It is assumed that under the condition of high soil moisture content, the actual evapotranspiration equals the potential evaporation, and then linearly decreases to zero at soil moisture content equal to wilting point (Feddes *et al*., 1974). The potential evaporation is estimated by the Dalton formulae using data on air temperature and humidity. A part of water infiltrated into the soil flows over a relatively impermeable boundary along the slope as subsurface flow. Another part is transported into the groundwater zone and forms the base flow. The subsurface and groundwater flows are modelled as Darcy flow, while the surface runoff and river flow are described by the kinematic wave equation.

During cold periods of the year, the scheme is supplemented by hydrothermal processes: snow cover formation, snowmelt, freezing and thawing of the soil, and infiltration of snowmelt water into the frozen soil. The phase composition of precipitation is determined by the daily average air temperature and the threshold temperature. Snowmelt rate is calculated using the degree-day method.

The hydrological submodel of ECOMAG was tested for many river basins in Russia, Norway, Sweden and France. Since 2004 it has been applied in an operational mode for simulation of hydrological characteristics and water inflow into reservoirs of the Volga-Kama and Angara-Yenisey cascades in Russia (Gelfan & Motovilov, 2009). The total drainage area of the Volga-Kama cascade is 1 332 400 km^2 and the drainage area of the Angara-Yenisey cascade (without the basin area of Lake Baikal) is 491 600 km^2.

Water quality submodel

The water quality submodel of a river basin was developed taking into account the following processes (Fig. 2). The pollutants may arrive at the land surface from the atmosphere, and directly from the sources of contaminants located on the land surface. In some cases, pollution sources may be located inside the soil or in the groundwater zone. The atmospheric pollutants may dissolve in rain or snowmelt water, or fall on the land surface as dry deposition. Most of the atmosphere-derived pollutants result from human activities (e.g. combustion of fuels, industrial gaseous emissions). Point sources of contamination (concentrated dumping from wastewater treatment plants and industrial enterprises) refer mainly to the river network or sometimes to the groundwater zone. Non-point sources usually originate from agriculture fields or mining industries.

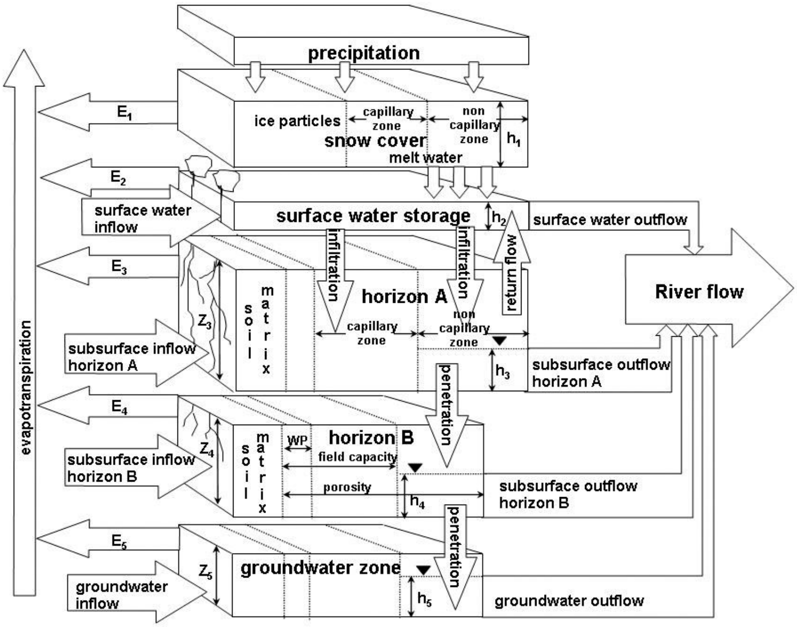

Fig. 1 The structure of the ECOMAG hydrological submodel (from Motovilov *et al*., 1999a,b).

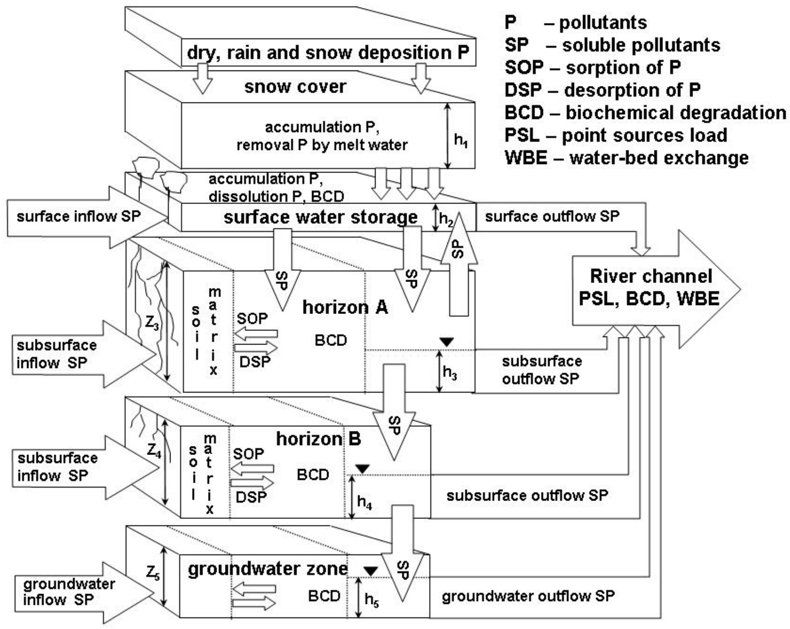

Fig. 2 The structure of the ECOMAG water quality submodel.

During rainfall pollutants partially dissolve in the rain water. One part of the dissolved pollutants is removed by surface runoff, and the second part penetrates into the soil with infiltrated water. A large number of chemical reactions may occur in the soil–water mixture. In addition, pollutants in the soil may be adsorbed by solid particles of the soil matrix or be released into the soil–water mixture from solids.

The behaviour of dissolved pollutants in the river basin depends on the intensity of hydrological processes. The contaminants are mainly carried along with water flows, i.e. by surface, subsurface and groundwater flows. Therefore, the amount of pollutants transported by river runoff from the basin is governed by the combination of these river flow components, as well as by pollutant loading to the river basin. In the spring period this pattern is supplemented by the process of pollutant release from the melting snow cover (Jones & Stein, 1990).

The following basic assumptions were made in the water quality submodel of ECOMAG. Modelling of geochemical processes for each landscape element of the river basin is performed at the same levels as in the hydrological submodel, i.e. for surface storage, three horizons of the soil, and snow cover. The process of biochemical degradation of dissolved organic pollutants is considered as a first order kinetic process. The sorption–desorption equilibrium in the soils is described by the Freundlich linear isotherm. Complete and instantaneous mixing is assumed for each water storage under consideration. It is necessary to note that this version of the water quality submodel can simulate the regime of only one constituent or pollutant at a time whose behaviour is described satisfactorily by the 1st order kinetic equations. Further considerable detail of the processes and improvement of the submodel algorithms are needed to describe the cycle of nutrients transformation (e.g. the nitrogen cycle).

Pollutants are carried by moving water from the landscape elements to the river network. Thus the lateral diffusive inflow of pollutants by surface, subsurface and groundwater flows into rivers is determined. The transfer and the transformation of pollutants in the river system are described, taking into account the lateral diffusive inflow of pollutants, the load of pollutants from point sources in the rivers, the process of pollutant degradation in river water, exchange of pollutants between the river water and river bed. Hydrological characteristics developed in the hydrological submodel are used for the water quality submodel of ECOMAG.

INDUSTRIAL COMPLEX AND STUDY AREA

Industrial complex

The industrial complex Pechenganickel was built in 1945. It is located in the northwest of the Kola Peninsula in the vicinity of Russian borders with Norway and Finland. The complex is located at two industrial sites in the Zapoljarny and Nickel settlements (Fig. 3), and includes mines, beneficiation, kiln, smelter, sulfuric acid plants and other auxiliary works. The plants consume a lot of water for technological needs. The volume of water recycled is about 80% of the total water consumption. The plants dump the mine and quarry water, water filtered from tailings and settling ponds into surface water bodies. Physico-chemical and biological water treatment plants, settling ponds, local treatment plants purifying effluents of transportation and power plants reduce the negative impact on water bodies. There are 14 point sources of wastewater release into the rivers: four of them are located in Nickel and discharge into the Kolos-Yoki River, and 10 sources are in Zapoljarny and discharge into the Luottn-Yoki River and its tributaries. Wastewaters contain a wide spectrum of polluting substances, which are controlled by the Environmental Survey of Pechenganikel (ESP). In addition, this Environmental Survey also monitors pollutants in river water at sampling points upstream and downstream from the wastewater dumping points. Concentrations of pollutants are also monitored by the Russian State Hydrological and Meteorological Survey (SHMS) in Kolos-Yoki River at sampling point 1, which is the most distant from the sources of pollution (background pollution level) and at the river mouth (points 3 and 4). Figure 3 shows only those sampling points which were used in this study to compare modelling results with observations.

Study area

The Kolos-joki River flows into Kuets'Yarv Lake. The river length is 21 km, and the drainage basin area is 140 km^2. The Luottn-Yoki flows into the Pechenga River. The river length is 28 km, and the drainage basin area is 96 km^2. The relief is a hilly plain. The average height of the drainage areas is 260 m a.m.s.l.; forest occupies about 50% of the area, lakes 4%, and wetlands 10%. The dominant soil types are podzols (illuvial-humus and illuvial-ferruginous). Soils are mainly sandy and pebbly, sometimes clay and acid metamorphic soils can be found. Taiga and forest-tundra landscapes dominate.

The total area of the drainage basins was approximated by irregular landscape elements – elementary watersheds, taking into consideration the peculiarities of topography, soil and vegetation types in a GIS framework. In total, about 150 elementary watersheds were allocated on the Kolos-Yoki and Luottn-Yoki drainage basins.

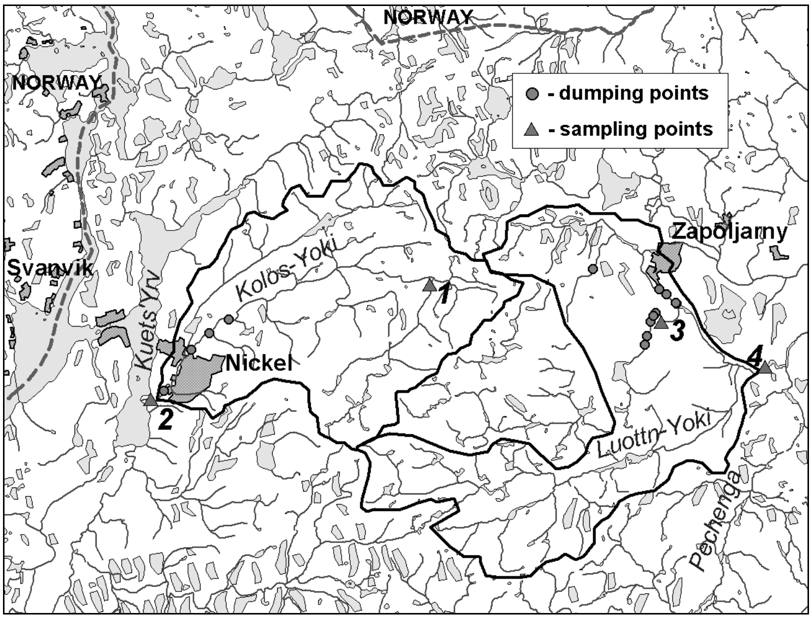

Fig. 3 Location of studied river basins, dumping and sampling points.

DATA, INITIAL AND BOUNDARY CONDITIONS

Data for the hydrological submodel

The hydrological submodel uses the following meteorological data as input: precipitation, air temperature and humidity. Data from 18 meteorological stations in the Kola Peninsula area of SHMS were used to assign boundary conditions for the hydrological submodel.

The daily runoff data for several hydrological stations of SHMS in different catchments of the Kola Peninsula area, including the Kolos-Yoki River (station Nickel), were used for calibration of the model parameters and testing the hydrological submodel. Meteorological and hydrological data were collected for the period of 2001–2004.

Data for the water quality submodel

The mean monthly discharges and Ni concentrations for 14 point sources of wastewater into the river network according to ESP were used as input to the water quality submodel. The Ni concentrations in river waters were usually measured by SHMS one or two times per month, and composite mean monthly Ni concentrations of river water according to ESP in different points of the river network were used for calibration of the model parameters and testing of the water quality submodel.

The mean monthly air emissions of Ni from two industrial sites in Nickel and Zapoljarny, as well as the mean monthly data on Ni concentrations in precipitation for EMEP station Svanvik (Norway), located 8 km from Nickel, were used to assign the spatially distributed impact on river basins (boundary conditions). This was done taking into account the relation between Ni deposition intensity and the distance from the source of emissions according to Ratkin (1999). All data on Ni emissions and Ni concentrations were collected for the period 1 August 2001–31 December 2003.

Unfortunately, available information on spatial Ni contamination of the soils based on field data is not sufficient to adequately assign initial conditions. Therefore, they were modelled using all available data on meteorology, point sources, air emissions and precipitation contamination for the period of 2.5 years by continuously repeating simulations for the whole period of the plants' operation since 1945. According to the adopted scheme (Ratkin, 1999), the maximum Ni concentrations in the soil solution are confined to the industrial sites area and decrease with the distance from the sources.

Model parameters

Most of the hydrological parameters were set up based on cartographical information (DEM, structure of river network, spatial distributions of soil and vegetation types, etc.), regional catalogues of soils properties (porosity, field capacity, wilting point) and the special database of ECOMAG vegetation and land-use parameters (degree-day factor for snowmelt, maximal surface retention storage, distribution of the root system between soil layers, Manning's roughness coefficient). Parameters such as degree-day constant for snowmelt, evaporation constant in the Dalton formulae, vertical and horizontal soil hydraulic conductivity at saturation were calibrated manually using the Nash and Sutcliffe criterion. The same values of parameters for each soil and vegetation type were assigned for different river basins of the Kola Peninsula area. The most important and sensitive parameter of the water quality submodel is the equilibrium constant of the Freundlich linear isotherm. It was calibrated visually against data on Ni concentration in river water taking into account the limits for similar soil published in Sauve *et al*. (2003). Two parameters describing the exchange of pollutants between the river water and river bed, and the dissolution intensity of dry air deposited pollutants by rain or snowmelt waters, were also calibrated.

RESULTS

Figure 4 illustrates how ECOMAG reproduces the runoff dynamics and Ni concentrations in the study area. As can be seen from Fig. 4(a), the modelled hydrograph for the mouth of the Kolos-Yoki River (point 2) is in good agreement with the measurements. The Nash and Sutcliffe efficiency is 0.80. In general, the dynamics of simulated Ni concentrations at different points of the river network is in a satisfactory agreement with the measured data. In most cases discrepancies are of the same order as for the measured data (i.e. between SHMS and ESP data; Fig. 4(c)). The average range of the measured and simulated nickel concentrations in the river water for the period of 2.5 years at sampling point 1 (Fig. 4(b)) is 0.018–0.035 mg/L (background level), at point 2 located downstream from all point sources contributing to the Kolos-Yoki River 0.3–0.7 mg/L (Fig. 4(c)), and at points 3 and 4 on the Luottn-Yoki River 0.10–0.20 mg/L (Fig. 4(d), (e)).

Many different numerical experiments were performed to explain the behaviour of nickel in the river basins, and to evaluate the contribution of various components to river water pollution. In particular, the following two scenarios were considered. The first scenario includes only one source of pollution: the wastewater, whereas the effect of the polluted soil is excluded (scenario 1). The second scenario reflects the situation when the PIC does not operate anymore (there are no emissions and wastewater), and river water pollution is caused only by subsurface inflow of water passing through the polluted soil (scenario 2).

The results of scenario simulations for the Kolos-Yoki River basin show the following (Fig. 5). Significant contribution of Ni pollution to the river water (on average from 50 to 90% of the observed levels in different periods of the year) comes from the subsoil and groundwater which are highly contaminated as a result of considerable air emissions over the long period of plant operation. Even pure rain water passing through the contaminated soils becomes polluted and enters the river network as dirty subsoil and groundwater flows. The simple balance calculations confirm this finding: in 2002 the total amount of nickel removal from the basin by river waters was 49.0 tons according to measurements by SHMS, 43.3 tons according to ESP, and 37.3 tons as a result of the model simulations, and the total amount of nickel dumped into the river system from all point sources was only 2.83 tons. In 2003, the corresponding values were 29.7, 48.7, 31.1 and 7.4 tons, respectively. The simulation results show that if the plant operation were terminated (no more emissions of any kind), it would take about three decades for purification of river waters to the background level.

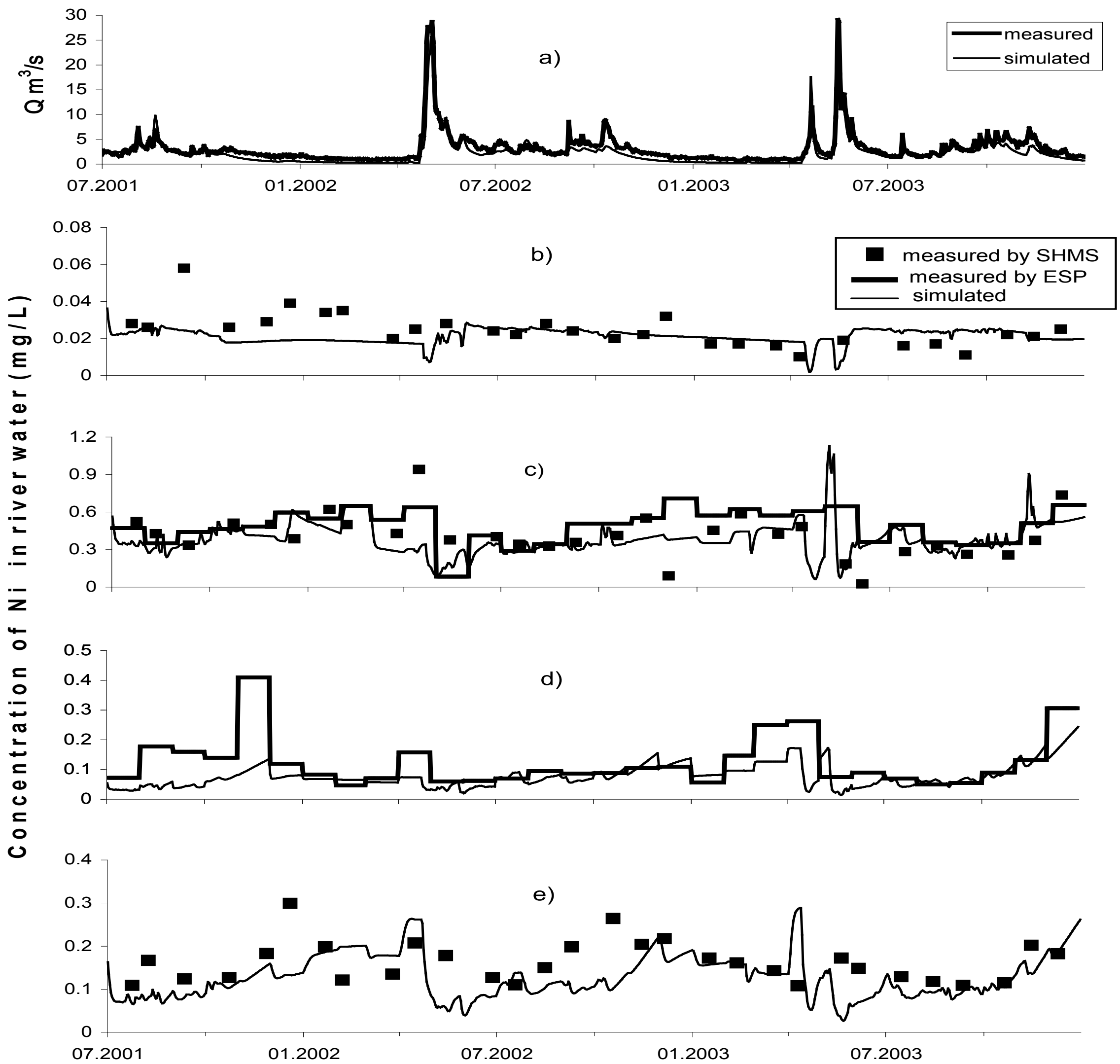

Fig. 4 The measured and simulated hydrograph (a), and Ni concentrations in the river water at sampling points 1 (b), 2 (c), 3 (d) and 4 (e) for the period 1 August 2001–31 December 2003.

In contrast to the Kolos-Yoki River, the results of numerical experiments for the Luottn-Yoki River basin show that the dumping of polluted wastewater into the river network makes a significant contribution to the pollution of river water (Fig. 5). This is primarily associated with the significantly lower air emissions at the Zapoljarny plant site than at the Nickel site, and thus significantly lower soil contamination in the Luottn-Yoki River basin. The contribution of Ni dumping from all point sources into the Luottn-Yoki River network to river water pollution is 50–70% in summer and 80–90% in winter and spring, on average.

CONCLUSION

Application of the ECOMAG model for assessing the anthropogenic contribution to river pollution over the area of influence of the Pechenganickel Industrial Complex is presented in the paper. It has been shown that the model reproduces the observed nickel concentrations in river water quite well and, in addition, allows one to simulate the dynamics of nickel concentrations with finer space-time resolution than is possible from the existing monitoring network. The ability of the model to assess possible changes in river water pollution under the different scenarios of PIC activity has been demonstrated.

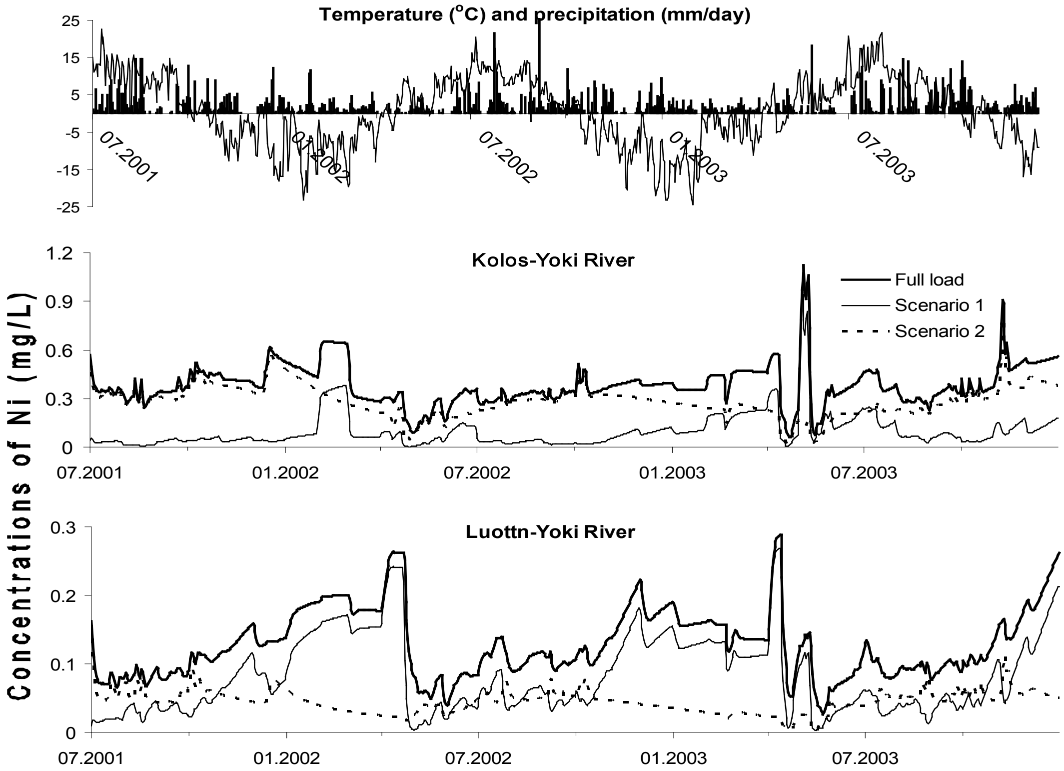

Fig. 5 Daily precipitation and air temperature (top) and simulated Ni concentrations in the river water in the mouth of the Kolos-Yoki and Luottn-Yoki rivers under full anthropogenic load and scenarios 1 and 2 for the period 1 August 2001–31 December 2003.

REFERENCES

Feddes, R.A., Bresler, E. & Neuman, S.P. (1974) Field test of modified numerical model for water uptake by root systems . *Water Resources Research* 10(6), 1166–1206.

Gelfan, A.N. & Motovilov, Yu.G. (2009) Long-term hydrological forecasting in cold regions: retrospect, current status and prospects. *Geography Compass*, 3/5, 1841–1864, 10.1111/j. 1749 – 8198.

Jones, H.G. & Stein J. (1990) Hydrogeochemistry of snow and snowmelt in catchment hydrology. In: *Process Studies in Hillslope Hydrology* (ed. by M.G. Anderson & T.P. Burt), 255–297, Wiley.

Motovilov, Yu.G. & Belokurov, A. (1996) Modelling the pollution transfer and transformation processes in river basin for the tasks of environmental monitoring. *Proc. Inst. Appl. Geophys*. 8, 32–35 (in Russian).

Motovilov, Yu.G., Gottschalk, L., Engeland, K. &.Belokurov, A. (1999a) ECOMAG – regional model of hydrological cycle. Application to the NOPEX region. Department of Geophysics, University of Oslo, Institute Report Series no.105, ISBN 82-91885-04-4, May 1999.

Motovilov, Yu.G., Gottschalk, L., Engeland, K. & Rodhe, A. (1999b) Validation of a distributed hydrological model against spatial observation. *Agric. Forest Meteor*. 98–99, 257–277.

Ratkin, N.E. (1999) Comparative evaluation of the accumulation and the intensity of the atmospheric deposition of sulphate, nickel and copper in the various forms of relief. In: *Ecological and Geographical Problems of the Kola Peninsula*, Russian Academy of Sciences, Kola Science Center, Institute of North Industrial Ecology Problems, Apatity, 54–60 (in Russian).

Sauve, S., Manna, S., Turmel, M.-C., Roy, A.G. & Courchesne, F. (2003) Solid-solution partitioning of Cd, Cu, Ni, Pb and Zn in the organic horizons of a forest soil. *Environ. Sci. Technol*. 37(22), 5191–5196.