A Model for Assessment and Prognosis of River Water Quality

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A model for analysis, evaluation and prognosis of river quality was developed, which is a modification of the time series analysis. The model was developed on the basis of information from the National Ecological Monitoring Network. The model was applied for an assessment and prognosis of water pollution of the Iskar River in the Iskar Dam catchment. Waters of the Iskar River are used for drinking water supply of the city of Sofia. Periodical seasonal and annual pollution variations were determined, as well as basic tendencies in the evolution of the water quality for the period from 1986 to 1990. A prognosis of the river pollution for the period from 1991 to 1993 was made. The statistical assessment of the models for different pollution parameters shows that they reflect adequately the pollution dynamics of the Iskar River for the investigated period.

Key words:
Modelling; pollution; polynomials; prognosis; retrospective analysis

Introduction

Retrospective analysis, present state survey, and pollution prognosis for a long-term period, are three interrelated stages in investigating the state of functioning of river ecosystems. The analysis of the information about water pollution gives a chance to define the trends and basic tendencies in the evolution of water quality for the determined period. On the basis of the retrospective analysis, it is necessary to make a prognosis of the pollution dynamic for a long period (from 1 to 3 years). Models of time series analysis are used for evaluation of environmental pollution.[3,5,8,9]

The analysis of the time series shows the availability of periodical and long-term changes of some indices for water pollution, which may be used in water quality management[11]. On analyzing the time series the physical, chemical, biological and biochemical characteristics of the processes are not directly taken into consideration; an attempt, however, was made for a description in the time of water quality in definite points as an integral result of water ecosystem functioning. The deterministic models describe the basic processes, which are subjected to an anthropogenic impact. The retrospective analysis with deterministic models for the water ecosystem functioning demands a complex information about the river system, the catchment pollution and ecological functioning, the seasonal and annual fluctuations of water quality for a period of long standing.[1] The time series analysis for water quality is a part of the retrospective modeling of water ecosystem functioning carried out with deterministic methods. Bearing in mind the hydrological, hydrochemical and hydrobiological characteristics in the river ecosystems, and the dynamics of the point and diffuse pollutants in the catchment, a conclusion may be drawn, that the analysis of the temporary series is suitable for the retrospective assessment of water quality. The integration of determination and statistical models for water quality is a necessary means of water ecosystem management. These models use information from environmental monitoring and their realizations.

The major goal of the investigation is to develop a model for the analysis and prognosis of water pollution; to be applied for modeling the water quality of the Iskar River in the Iskar Dam catchment. Waters of the Iskar River are used for drinking water supply of the city of Sofia. The model may be applied for the pollution assessment and prognosis discharge situations, for which systematic information about water quality is available.

The basic goal of the present investigation is the developing of a model for retrospective analysis and prognosis of water quality, which may be applied for determining the trend and basic tendencies in the dynamics of the organic pollution of the Iskar River waters in a point immediately before their inflow into the Iskar Dam.

Materials and Methods

The retrospective analysis of the pollution of the Iskar River in the Iskar Dam catchment is made on the basis of the information from the National Ecological Monitoring Network for the period from 1986 to 1990. The pollution prognosis is made for the period from 1991 to 1993, and the prognosis results are compared with observations from the Monitoring Network.

In the station below the town of Samokov and before the entrance of Iskar River into the Iskar Dam the following indices of water quality were examined: dissolved oxygen, biochemical oxygen demand (BOD), $KMnO_4$-oxydation, as integral indices of water organic pollution. Systematic information about water pollution in the Iskar River from the above mentioned station is used for the integral evaluation of the conditions influencing the run off of the investigated catchment.

The Iskar River water quality below the town of Samokov, 2 km away from its inflow into the Iskar Dam, is formed under the influence of simultaneously going off hydrological, hydrophisical, hydrochemical and hydrobiological processes in the stream water, and the anthropogenic impact in the catchment and the river net. The assessment of the organic pollution dynamics of the river in this point may be used at the integrated water management in the Iskar River catchment.

For a retrospective analysis of water pollution, a method of time series analysis was a determined component (trend) – y_T, describing the regularity of the development of the examined phenomenon, periodical component – y_P and stochastic variable – ε_t:[2,10]

$$y = y_T + y_P + \varepsilon_t \qquad (1)$$

The determined component (trend) – y_T is a polynomial of 1st to 3rd degrees and the periodical component – y_P is described by the order of Fourier.

Original modification of the method is applied for the purpose of the investigation.

Modelling and prognosis

Unlike the classical approach, a polynomial of a higher degree is proposed to be used as a trend function, which to a certain extent also describes the periodical (seasonal) component:

$$y_T = a_0 + a_1 t + \ldots + a_n t^n = \sum_{j=0}^{n} a_j t^j, \qquad (2)$$

where a_j are the coefficients of polynomial.

The availability of a trend in the studied processes is evaluated with the help of a trend test:[11]

$$T' = \frac{\dfrac{l}{n} \displaystyle\sum_{i=1}^{n-1} (Y_{i+1}^E - Y_i^E)^2}{\dfrac{l}{n} \displaystyle\sum_{i=1}^{n} (Y_i^E - \overline{Y}^E)^2} \qquad (3)$$

The limit of the test is determined by the equation: $T = 2.0 - \dfrac{2.0 - Z\,\alpha}{\sqrt{n}}$, where: $\overline{Y}^E$ is mean value, Z the bound of the standard normal distribution, S – probability for success.

In order to prove the availability of a trend it is necessary $T' > T$.

The basic trend shows the main tendencies in the alteration of the studied indices, and it is a straight line:

$$y_T^M = A_0 + A_1 t \qquad (4)$$

In contrast to the classical method for analyzing temporary series, where the Fourier series are used, the present research proposes the uses of the periodical functions sin or cos, where their determination is carried out on the basis of statistical criteria. The sin, $\sin^2$, cos and $\cos^2$ functions have been tested. The best results were shown by the function (comparison after correlation coefficient – R^2, Fisher function – F and minimization of the relative error – S_L):

$$y_P = \sum_{k=0}^{m} b_k \sin^2 \left(\frac{2\pi}{c_k} t + d_k \right) \qquad (5)$$

Then the model (1) for analysis and prognosis has the following form: ($\varepsilon_t = 0$)

$$y = \sum_{j=0}^{n} a_j t^j + \sum_{k=0}^{m} b_k \sin^2 \left(\frac{2\pi t}{c_k} + d_k \right) \qquad (6)$$

The adequacy of model (6) is proved by means of R^2, F, the statistical index WRMSE (the Weighted Root Mean Square Error) and S_L.

The statistical index WRMSE and the relative error are determined with the help of the following equations:[4,13]

$$\text{WRMSE} = \sqrt{\frac{l}{n} \cdot \sum_{i=1}^{n} V_i (Y_i^E - Y_i^M)^2} \qquad (7)$$

$$S_L = \sqrt{\frac{l}{(n-\nu)} \cdot \sum_{i=1}^{n} \left(\frac{Y_i^E - Y_i^M}{Y_i^E} \right)^2}, \qquad (8)$$

where Y_i^E are the experimental values, Y_i^M are the values calculated with the help of the model, ν – degrees of freedom, n is the number of the investigations according to a given index, V_i is the deviation factor, which is reciprocal to the standard deviation of the experimental results.

Results

The coefficients in the model (6) are determined on the basis of experimental investigations and with algorithms and software elaborated for this purpose. The Origin 5.0 software is also used. The algorithm for determining the coefficients in the periodical functions is as follows:

1. The experimental data are selected by years, where the change for each year is from 1 to 12 months. The variable component is ignored, i.e. $\varepsilon_t = 0$.

2. The coefficients A_0, A_1 are determined in the main trend (4), and the coefficients a_j, $j = 0,\dots, n$ in trend (4). The degree of the n-polynom is determined, comparison with R^2 and F. The procedure is carried out with the help of the programme Origin 5.0.

3. T' and T are calculated. A control is carried out for an availability of a trend. The experimental values of the periodical function: $y_P = y - y_T$ are calculated. The coefficients b_k, c_k and d_k in (5) and their numbers are determined; comparison according to R^2, F and S_L.

4. A control for adequate model (6) according to the following criteria: R^2, F, WRMSE and S_L, is carried out.

Determination of the basic trend and the trend function

The coefficients in the basic trend are determined with the help of the Origin software. On determining the trend function (2), on the basis of the described algorithm, it was found that the increase of the polynomial degree over the fifth degree influences the results faintly (comparison with R^2, F and S_L). That is why we have chosen for the trend function a polynomial of the fifth degree:

$$y_T = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \quad (9)$$

Determining the periodical component

On identifying the periodical functions it was found, that two periodical functions are adequate (comparison with R^2, F and S_L), i.e.:

$$y_P = b_0 \sin^2\left(\frac{2\pi}{c_0}t + d_0\right) + b_1 \sin^2\left(\frac{2\pi}{c_1}t + d_1\right) \quad (10)$$

Then the model in the concrete case for analysis and prognosis according to the studied indices is as follows:

$$y = a_0 + a_1 t + a_2 t^2 + \dots + a_5 t^5 + \\ + b_0 \sin^2\left(\frac{2\pi}{c_0}t + d_0\right) + b_1 \sin^2\left(\frac{2\pi}{c_1}t + d_1\right) \quad (11)$$

Table 1 shows the coefficients of correlation – R^2, the experimental function of Fisher – F_E, the statistical index WRMSE, the relative error – S_L and the test for trend – T', for the studied indices on modeling and prognosis.

T a b l e 1 – *Statistical information for models and prognosis. The theoretical correlation coefficient at the degrees of freedom n=56 at a probability of error α = ±5 % is a value of $R^2_t = 0.273$, theoretical function of Fisher $F_T = 2.11$. For n = 57, Z = 0.998 and α = 0.90, there is T = 1.742.*

Models	R^2	WRMSE	F_E	S_L	T'
Dissolved Oxygen	0.81	0.55	1.11	0.099	1.803
BOD	0.75	0.66	1.20	0.117	1.988
KMnO$_4$-oxidation	0.75	0.70	1.50	0.118	1.832
Prognosis	R^2	WRMSE	F_E	S_L	-
Dissolved Oxygen	0.77	0.60	1.75	0.112	-
BOD	0.73	0.68	1.91	0.120	-
KMnO$_4$-oxidation	0.72	0.70	1.94	0.146	-

The model for retrospective analysis of the pollution of the Iskar River for the period from 1986 to 1990, and for prognosis of the pollution for the period from 1991 to 1993 in the point-station downstream of the town of Samokov, is described by equation (11). Model (11) may be used for the prognosis for a period during which there are no changes in the character and intensity of the anthropogenic impact from the point and diffuse sources of pollution; water usage and hydrotechnical building are envisaged. For this purpose, a prognosis for a period from 1 to 3 year in conformity with the social and economic development in the catchment, is suitable.

The trends in the evolution of the pollution for the above-mentioned indices are determined with the help of this model and a prognosis for a 3 year period is made, too. The model describes the periodical, seasonal and annual changes in water quality according to the investigated indices. The main tendency in the pollution dynamics is determined as a linear function.

This modification for the analysis and prognosis was applied for modeling and prognosis of the pollution of the Iskar River waters. The experimental results obtained from the models for the analysis of the pollution of the Iskar River downstream the town of *Samokov*, are shown in Fig.1–3.

The calculated correlation coefficients of the investigated pollution indices range in the interval from 0.75 to 0.81 and are larger than the theoretical correlation coefficient. The statistical index
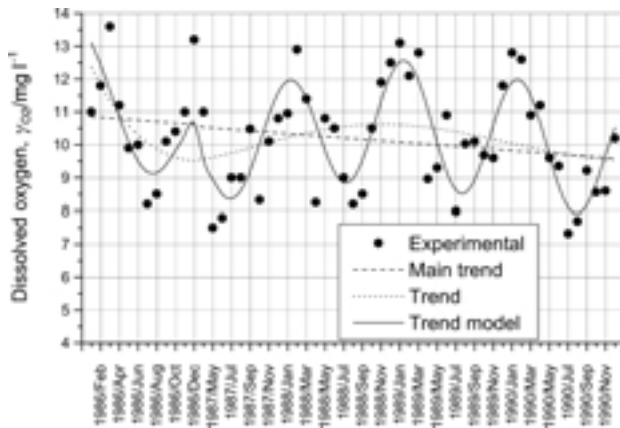
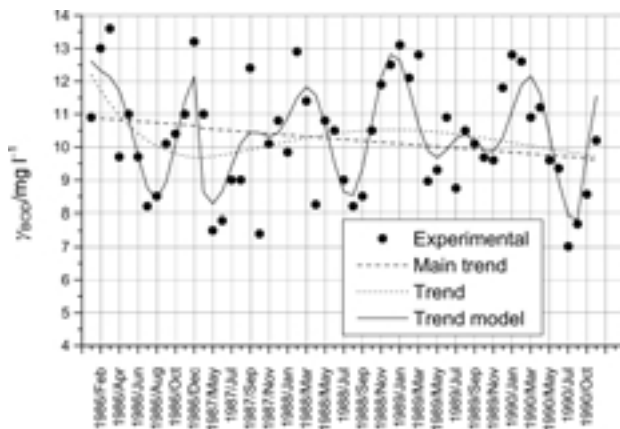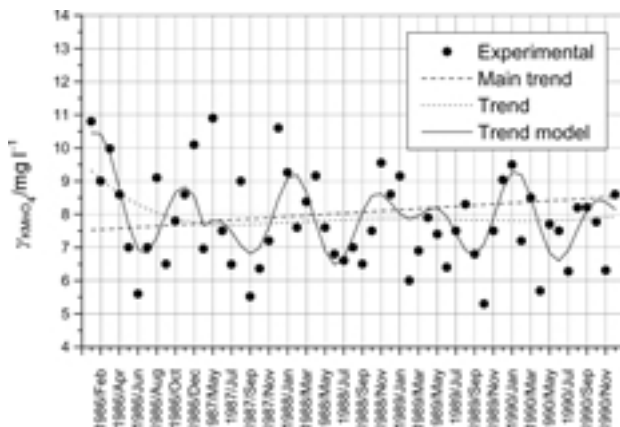WRMSE varies from 0.55 to 0.70 for different pollution indices, which proves the adequacy of the models (Tabl. 2). This fact proves that the elaborated trend functions characterize adequately the tendencies of the pollution dynamics of the Iskar River before its inflow into the Iskar Dam.

Pollution Prognosis

In Fig.4-Fig.6 the prognoses for each of the investigated indices for a 3-year period are shown.
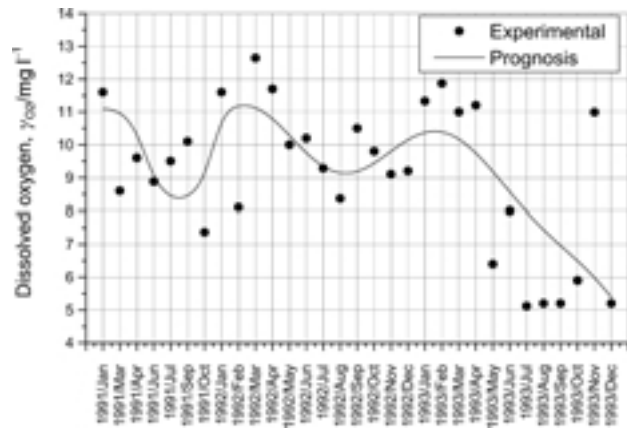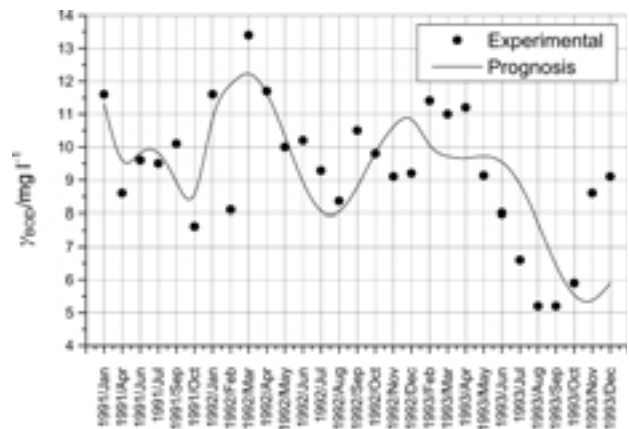

F i g . 1 – *Dynamics of dissolved oxygen*

F i g . 4 – *Prognosis of dissolved oxygen*

F i g . 2 – *Dynamics of biochemical oxygen demand (BOD)*

F i g . 5 – *Prognosis of BOD*

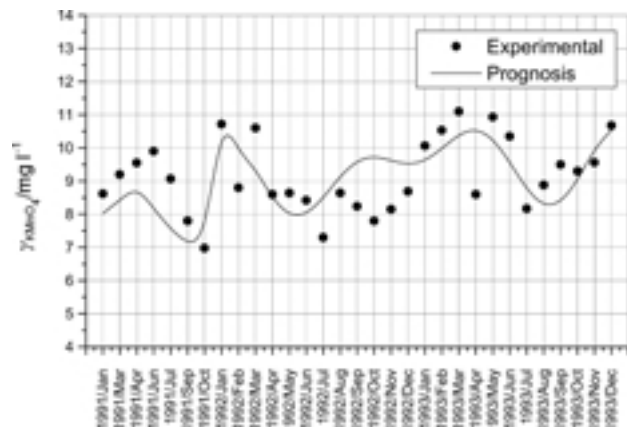F i g . 3 – *Dynamics of the KMnO₄-oxydation*

F i g . 6 – *Prognosis of the KMnO₄-oxydation*

The prognosis is made with the help of the model described with equation (11). The theoretical correlation coefficient of the pollution prognosis at degrees of freedom N = 34 and a probability of error $\alpha = \pm$ 5% has a value of $R^2_t = 0.325$. The calculated values of the correlation coefficients for the investigated pollution indices are in the interval of 0.72–0.77. This fact shows that the model for prognostication characterizes adequately the pollution dynamics for a 3-year period for a prognosis.

The statistical index WRMSE varies from 0.60 to 0.70 for the different pollution indices, which proves the adequacy of the models. The model gives a comparatively high precision of the prognosis of the river flow pollution with minimum costs for its realization.

The comparative assessment of the models for river water quality for adequacy after the method for minimization of the relative error proved that the proposed models are adequate to the experimental results. The values of the relative error for the studied indices are in the limits of $0.099 < S_L < 0.146$ (Table 2.) and they show better results than when the deterministic models[13]: $0.134 < S_L < 1.179$ are applied.

Discussion

The elaborated model for retrospective analysis and prognosis of water pollution gives a possibility to determine the tendencies of the pollution evolution of the Iskar River and to make a prognosis for a longer period.

According to the dissolved oxygen index a variable course of the trend function is observed, as well as a slightly expressed tendency towards a reduction of the oxygen concentration during the investigated period. The results of the prognosis for the period from 1991 to 1993 show a variable course of the model function with a slight tendency to decrease of the oxygen concentration. The changes of the oxygen concentration do not infringe the requirements for a First Water Quality Class (I[st] WQC $\geq$ 6 mg l^{-1}).

Regarding to the biochemical oxygen demand (BOD) index, a variable course of the trend function with a basic tendency to a pollution increase is observed. The pollution level is below the Permissible Concentrations (PC) for the I[st] WQC $\leq$ 5 mg l^{-1}. The prognosis for the period from 1991 to 1993 shows tendencies to a pollution increase, and concentrations exceeding PC for the I[st] WQC are prognosticated.

With respect to the KMnO$_4$-oxidation index a slightly variable process of the trend function was established, and a basic tendency to retain the pollution level. The prognosis results show retaining of the changeable course of the model function, as well as of the pollution level. The pollution changes do not exceed PC for the I[st] WQC $\leq$ 10 mg l^{-1}.

The research team from the Institute of Ecology-BAS carried out the above-mentioned investigations on water pollution of the Beli Iskar River, Cherni Iskar River and the Iskar River upstream of the town of Samokov. Single excesses of the PC for the I[st] WQC by the BOD index, due to various diffuse sources such as small urban areas, forestry and agricultural sites, erosion the investigator's ascertained processes etc.

The retrospective analysis of the pollution dynamics gives a possibility for an integral assessment of water quality influence processes on the catchment scale. The model can be included into the system of deterministic models necessary for the aims of the integrated management of water quality.[6,7,12]

The model is also applied for analysis and prognosis of the pollution of the Iskar River, according to the indices: nitrate, solved and dissolved substances, and it showed the adequacy between the model and the experimental results.

The model allows the quantitative assessment of the dynamics of the impact from point pollutant on the river ecosystems, as well as the planning of the necessary measures.

Conclusion

From the analysis and prognosis of the pollution of the Iskar River in the Iskar Dam catchment the following conclusions can be drawn:

A model for analysis and prognosis of the river pollution is developed, which adequately expresses the dynamics of the pollution for a defined period.

For model implementation, systematic information about water pollution according to concrete indices at concrete points of the river course, is necessary.

The integration of the determinate and statistical methods is necessary for the retrospective analysis and prognosis of water quality and the ecological processes in river flows.

The models for assessment and prognosis of pollution are necessary for an integrated management of water quality and ecosystem protection.

The proposed modified approach for time series analysis can be used on solving different problems connected with ecosystem management.

The retrospective analysis and prognosis of the Iskar River upstream of the town of Samokov provides a possibility for an integral evaluation of the physical and geographical conditions, of the anthropogenic impact and of the self-purification capacity as basic factors for the water quality development in the catchment basin.

The waters of the Iskar River and Iskar Dam are used for drinking water supply, and that is why it is necessary to develop a model for integrated management of water quality in the investigated region.

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