FORMULATION, CALIBRATION AND VERIFICATION OF A MATHEMATICAL MODEL FOR KALAMAS RIVER, GREECE

GIANNOULIS S.[1], GKESOULI A.[1] and STAMOU A.I.[1]

[1]School of Civil Engineering, Department of Water Resources and Environmental Engineering, National Technical University of Athens, Iroon Polytechniou 5, 15780 Athens, Greece.
E-mail: anthi.gkesouli@gmail.com

ABSTRACT

The formulation, calibration and verification of a relatively simple 1-D model for the determination of water quality in Kalamas River, a very important Greek river which is situated in the Water District of Epirus, is presented. The mathematical model consists of mass balance equations for three water quality variables (BOD, total phosphorus and dissolved oxygen), which are derived by applying the mass conservation principle to a small, but finite, control volume within the flow. The model is validated using scarce field data from 3 monitoring stations of the National Monitoring Network while the pollution loads of Kalamas, including (i) effluent discharges originating from cities having or not a domestic Wastewater Treatment Plant (WWTP), (ii) industries having or not a WWTP with partial treatment, (iii) livestock farming, (iv) uncontrolled landfill sites and (v) loads from agricultural activities, were estimated using the literature, design information of the WWTP of Ioannina city and data from the Special Secretariat for Water. Taking into account the significant level of uncertainty and scarcity of the available field measurements and the uncertainty of the estimated pollution loads, the calibration and verification of the model can be characterized as satisfactory. The actual predicted concentrations of the examined water quality variables in Kalamas indicate that the water quality in the river is satisfactory since the ranges of the values of concentrations are within the limits established for the good water quality of Kalamas by the Special Secretariat for Water. Then, the model is applied to investigate the effect of an hypothetical scenario that assumes that the flow and pollution loads from the catchment of Ioannina city, including the effluent from city's WWTP, is not discharged to Kalamas River via Klimatias tributary but it is diverted elsewhere. Results show that the water quality of Kalamas is improved, taking into account a reduction of approximately 50 % of the concentration values of BOD and total phosphorous, while the concentration of DO is not affected significantly. The model can be used in its present formulation only as an approximate tool for the water management of Kalamas River because of the scarcity and uncertainty of the field measurements and pollution loads that are used for the validation of the model.

Keywords: BOD, Kalamas River, total phosphorous, dissolved oxygen, mathematical models, water quality, water management.

1. Introduction

A large number of water quality models for rivers can be found in the literature (Thomann and Mueller, 1987). The majority of these models are 1-D and deterministic, i.e. they describe the spatial and temporal changes of selected water quality constituents (variables) due to convection, dispersion and bio-chemical reactions, in the main (longitudinal) direction of flow. For the discretization of the partial differential equations of the models, the finite - difference methods are usually employed, which in most of the cases involve the low order upwind or central interpolation schemes. Water quality models are used for design or operational purposes (Stamou *et al.*, 2007, Thomann and Mueller, 1987). In the present work, we present and apply a methodology that deals with the formulation, calibration and verification of a relatively simple 1-D model for the determination of water quality in Kalamas River, a very important Greek river, which is situated in the Water District of Epirus.

2. The mathematical model

The mathematical model consists of mass balance equations for the water quality variables of interest, which are derived by applying the mass conservation principle to a small, but finite, control volume within the flow and are written as follows (Stamou and Rutschmann, 2011):

$$\frac{\partial \Phi}{\partial t} + U\frac{\partial \Phi}{\partial x} = D\frac{\partial^2 \Phi}{\partial x^2} - S_\Phi \qquad (1)$$

where Φ is the concentration of the water quality variable, t is the time, x is the longitudinal distance, U is the average velocity in the river (U=Q/A, where Q is the flow rate and A is the cross section area), D is the dispersion coefficient and S_Φ is the source term which includes all physical, biological or / and chemical processes. For each water quality variable, equation (1) is integrated over each control volume with its faces in the two directions (w=west and e=east) located midway between the grid points using explicit, forward time difference between n and n+1 time levels. For the determination of the values of the variables in the western and eastern faces of the control volumes, the first order Upwind Differential Scheme (UDS) is applied. More details for the derivation of the final form and the solution of equation (1) can be found in Stamou (1992).

In the present study the following water quality variables are examined: BOD (B), total phosphorus, TP (P) and dissolved oxygen, DO (O). The main processes described in the model are the following: (1) decay of organic matter, (2) sediment and algae uptake of phosphorous, (3) consumption of dissolved oxygen and (4) physical re-aeration. The equations of the source terms are the following (Stamou *et al.*, 2005):

$$S_B=-ck_1B \qquad (2)$$

$$S_P=-c_PP \qquad (3)$$

$$S_O=ck_2\left(O_{SAT}-O\right)-ck_1B \qquad (4)$$

where ck_1 is the BOD decay rate coefficient, c_p is the total phosphorous reduction rate (including sedimentation and algae uptake), ck_2 is the re-aeration rate coefficient, and O_{SAT} is the saturated DO concentration. The dependency of ck_1 and ck_2 on the temperature (T) is described by the following equations:

$$ck_1=ck_{1,20}1.047^{T-20} \qquad (5)$$

$$ck_2=ck_{2,20}1.024^{T-20} \qquad (6)$$

where $ck_{1,20}$ and $ck_{2,20}$ are the values of ck_1 and ck_2, respectively, at T=20 ^{0}C. The range of the values for $ck_{1,20}$ is 0.1 ~ 0.5 d^{-1} (Stamou *et al.*, 2007, Thomann and Mueller, 1987), while $ck_{2,20}$ is calculated by empirical equations which are included in Stamou *et al.* (2007).

3. The area of study

3.1. General characteristics

The Kalamas River has a length of 128 km and there are 5 junctions with the main tributaries (see Figure 1).

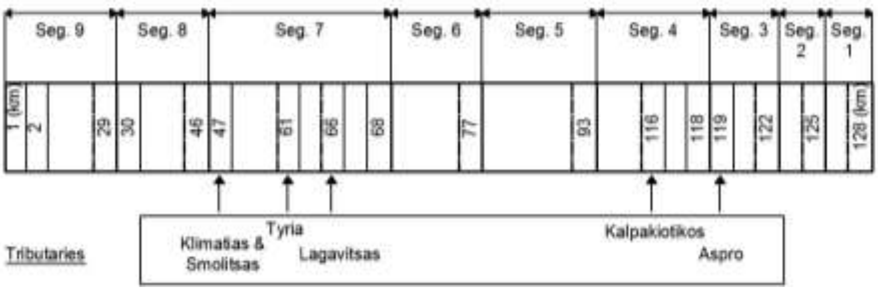

Figure 1: Schematic presentation of Kalamas River with its tributaries.

3.2. Sources of pollution

The main sources of pollution of the Kalamas River are the point sources of (i) effluent discharges originating from cities having or not a domestic Wastewater Treatment Plant (WWTP), (ii) industries having or not a WWTP with partial treatment, (iii) livestock farming and (iv) uncontrolled landfill sites, and the diffuse source of pollution from agricultural activities. The pollution loads of the domestic WWTP of Ioannina were estimated using the literature and design information of the WWTP, while the rest loads were estimated using information from the Special Secretariat for Water (2012). The estimated annual pollution loads are shown in Table 1.

Table 1: Annual pollution loads.

Source	BOD (tn/yr)	TP (tn/yr)
WWTP (Ioannina)	48.0	9.4
Industries	91.6	17.3
Livestock farming	2765.0	51.0
Uncontrolled landfill sites	48.0	24.0
Agriculture	-	24.0

4. Calculations

The calibration of the model was performed for September 2007 using scarce field data from 3 monitoring stations of the National Monitoring Network to determine the following values of the parameters: ck_1=0.5 d^{-1} and c_P= 0.3 d^{-1}. Then, the verification of the model was performed for July 2008 (summer period of low flow rates) and December 2008 (winter period of high flow rates). Indicatively, in Figure 2 calculated concentrations for TP are compared with field data during the calibration and the verification of the model. Taking into account the significant level of uncertainty and scarcity of the available field measurements and the uncertainty of the estimated pollution loads, the calibration and verification of the model can be characterized as satisfactory. Moreover, the ranges of values of predicted concentrations (see also Table 2, scenario: actual) indicate that the water quality of Kalamas is satisfactory since the values are within the limits established for the good water quality of Kalamas River by the Special Secretariat for Water (2012).

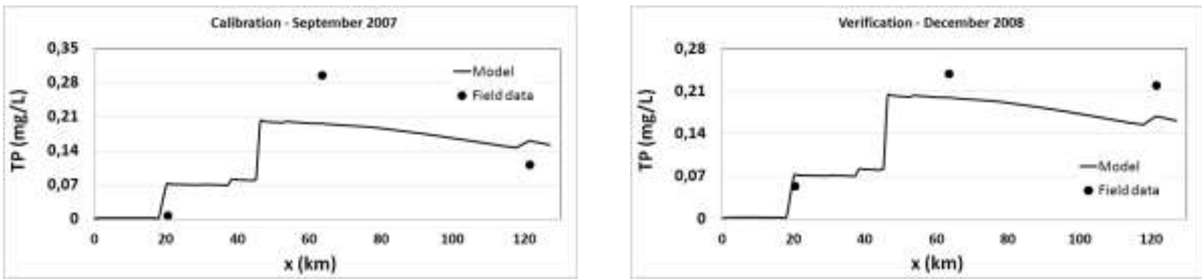

Figure 2: Calibration and verification for TP.

5. Application of the model

The model was applied for various scenarios to assess their impact on the water quality of Kalamas River. In the present paper, we present the results of just one scenario which assumes that the flow and pollution loads from the catchment of Ioannina city, including the effluent from city's WWTP, is not discharged to Kalamas River via Klimatias tributary (x=47 km, see Figure 1), but it is diverted elsewhere. The calculated concentrations of the water quality variables are shown in Figure 3 together with the values prior to the diversion. Furthermore, the calculated ranges of concentrations together with the ranges prior to the diversion, downstream of the discharge location (x= 47 km), are presented in Table 2.

For the scenario of diversion, the concentrations of BOD and TP (after x= 47 km) are reduced by approximately 40 % and 60 %, respectively, while the concentration of DO is not affected significantly (see Figure 3 and Table 2). The water quality of the river is improved taking into account that the concentrations of BOD and TP are reduced to the half of the actual predicted concentrations. However, it is noted the water quality of Kalamas River is already good based on the actual predicted concentrations.

Table 2: Calculated ranges of concentrations together with the ranges prior to the diversion, downstream of the discharge location (x= 47 km).

Water quality variable	DO (mg/L)		BOD (mg/L)		TP (mg/L)	
Scenario	Actual	Diversion	Actual	Diversion	Actual	Diversion
Minimum	8.97	9.47	1.14	0.44	0.15	0.06
Maximum	9.81	9.99	4.28	3.60	0.20	0.08
Average	9.54	9.87	2.12	1.27	0.18	0.07

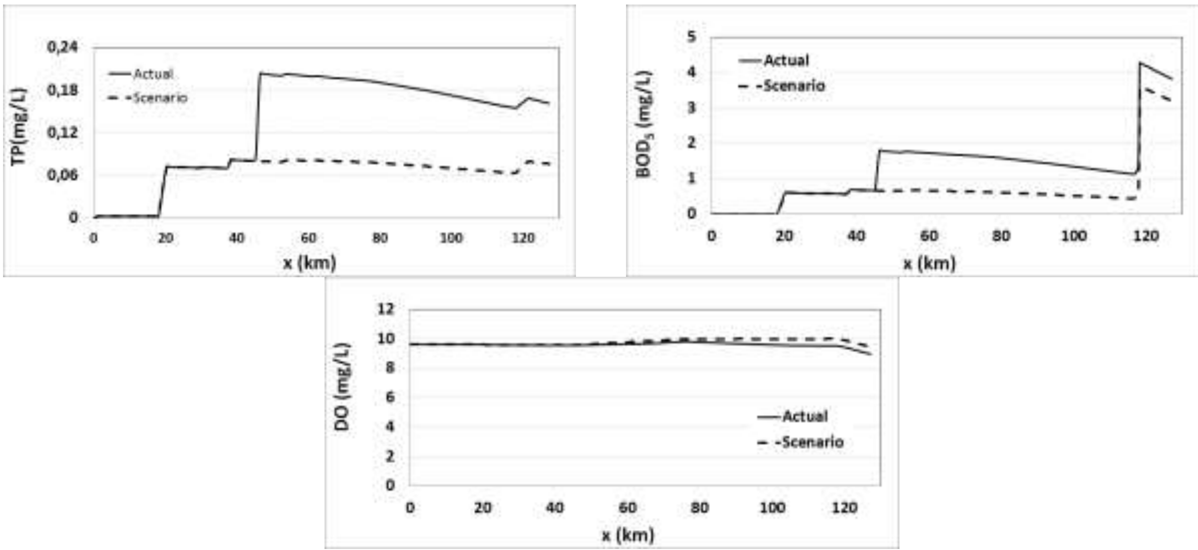

Figure 3: Actual predicted concentrations vs predicted concentrations for the scenario of diversion.

6. Conclusions

The formulation, calibration and verification of a relatively simple 1-D model for the determination of water quality in Kalamas River, was presented. The model was calibrated and verified successfully using scarce field data. However, the model can be used in its present formulation only as an approximate tool for the water management of Kalamas due to the significant level of uncertainty and scarcity of the available field data. The following water quality variables were examined: BOD, total phosphorus and dissolved oxygen. The ranges of actual predicted concentrations indicated that the water quality of Kalamas was satisfactory since the values were within the limits established for the good water quality of Kalamas by the Special Secretariat for Water (2012). Then, the model was applied to investigate the effect of an hypothetical scenario that assumes that the flow and pollution loads from the catchment of Ioannina, including the effluent from city's WWTP, was not discharged to Kalamas but it was diverted elsewhere. Results showed that the water quality of Kalamas River was improved. The concentrations of BOD and TP were reduced by approximately 50%, while the concentration of DO was not affected significantly.

REFERENCES

1. Ministry of Reconstruction of Production, Environment & Energy, Special Secretariat for Water (2012), Management of Water District of Epirus.
2. Stamou A. I., Douka E., Loukatos A., Tsouma M., Papapavlou K. (2007), Formulation, calibration and verification of a mathematical model for Pinios River, Greece, Proc. of the Intern. Conference on Environmental Science and Technology, Kos Island, Greece.

3. Stamou A. I., Douka E., Kapor R., Ivetic M., Branisavljevic N. (2005), Presentation and calibration of an integrated model for urban stream water quality management, Proc. of the Intern. Conference for the Restoration and Protection of the Environment IX, Kefallinia, Greece.
4. Stamou A. I. and Rutschmann P. (2011), Teaching simple water quality models, Education for Chemical Engineers, 6 (4), 132 - 141.
5. Stamou A. I. (1992), Improving the Numerical Modelling of River Water Quality by Using High Order Difference Schemes, Water Research, 26 (12), 1563 -1570.
6. Thomann R. V. and Mueller J. A. (1987), Principles of Surface Water Quality Modelling and Control, Harper and Row, New York.