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METHODOLOGY OF RIVER POLLUTION ASSESSMENT AND PRELIMINARY RESULTS

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ABSTRACT

The present work proposes a methodology to monitor and predict river water pollution in regard to the requirements posed by the European Union (EU) Water Framework Directive (WFD) 2000/60/EC and taking into consideration current peculiarities of the Greek status (water management diffused in several authorities, multiple stakeholder conflicts, irregular and inadequate pollution monitoring programs, low financial resources e.t.c.). Particular cost-effective tools of quick performance for either predicting or measuring river pollution have been identified. The Erymanthos River watershed (360 km^2), which is a sub-basin of the Alfeios River basin, Greece, was selected as a case-study. The total nitrogen and phosphorus loads of the watershed occurring during each season of the year were estimated on the basis of typical inputs due to municipal and agricultural land uses met in the study area for the period 1999-2001. The river discharge was simulated using a rainfall–runoff model calibrated for the period October 1963 – September 1976 with daily rainfall data and sufficient discharge data. Simulated discharge values in monthly basis were used to compute the necessary mean seasonal discharge, its standard deviation, as well as the minimum and maximum values, and then the seasonal values of the pollution loads of total phosphorus and total nitrogen were estimated. Finally, the relevant pollution factors were calculated as the ratios of the corresponding watershed loads and river-transported loads. During the year 2006, four expeditions (one per season) were made for direct discharge and concentration measurements to allow direct computation of the related pollution loads transported in the river and subsequent pollution factors. The discharge was determined by employing quick measurement techniques combined with the logarithmic–parabolic velocity distribution. Present findings show justifiable behaviour and could be used as preliminary results in incoming river pollution monitoring and watershed management programs imposed by the WFD.

Keywords: Water Framework Directive 2000/60/EC, river basin management, hydro-geologic information management, geographic information management, water quality, pollution loads, point sources, non-point sources, hydrological modelling

1 INTRODUCTION

The Water Framework Directive (WFD) 2000/60/EC (WFD, 2000) is an important tool of the European Union (EU) aiming to harmonize a sustainable water resources management among member states by establishing a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. The formal compliance of Greece with the WFD was made by adopting Law 3199/03 (Official Gazette 280A/2003) for water protection and management. The main environmental target of the WFD is the achievement of a good ecological potential and a good water quality within 15 years after formal compliance (in 2018 for Greece). Therefore, it is necessary to monitor the ecological and chemical status of surface waters, the chemical and quantitative status of groundwaters, in addition to the specifications of the protected areas under which these areas have been established. Monitoring must cover physico-chemical, hydro-morphological, biological and chemical parameters (Allan et al., 2006). The monitoring programs must be introduced by December 2006 and include *Surveillance*, *Operational* and *Investigative monitoring* modes (US-EPA, 2005). A simplified scheme has been given by Allan et al. (2006), who have furthermore reviewed emerging biological and chemical monitoring tools that may be incorporated in the techniques for water quality assessment. The decision support of water resources in river basins following WFD must be based on the pollution loads estimations.

The several natural phenomena and anthropogenic activities occurring in a river basin constitute pollution sources with subsequent pollutant emissions. The surface-water pollution sources are generally distinguished in two types: (a) Point sources, where the pollution loading is made at a well defined location or an area of limited extent compared to the watershed size or the river length. Such sources include mostly wastewater discharges by sewerage and biological treatment systems for domestic, municipal, industrial, agro-tourist and other installations, as well as livestock wastewater discharges. (b) Non-point sources (NPS), where the pollution loading is linearly or area diffused (along river banks and groundwater loadings by infiltration). NPS–pollution loading is caused by runoff moving over and through the ground, carrying natural (wildlife or geologic pollutants) and man-made pollutants from illicit discharges of residential and industrial wastes, roadways, grassed areas, cropland, pastures, livestock operations and dry or wet deposition of air pollutants and finally depositing them into surface waters. The NPS pollution contributes mainly to nutrients, pesticides and sediments. Both point and NPS pollutants contribute to surface-water pollution and cause eutrophication.

The present work aims to (a) propose convenient monitoring programs to be applicable in the specific types of Greek river basins in regard to the complicated frame of authorities and stakeholders involved, and (b) identify particular cost-effective tools of quick performance for either predicting or measuring the river pollution. Such tools may be incorporated in river basin management plans, as it has primarily indicated by Yannopoulos (2005). General descriptions of pertinent management plans for river basins of particular complexity, as the Alfeios River Basin, are given by Manariotis and Yannopoulos (2004, 2006). In order to highlight the most appropriate tools for the aforementioned purposes, a case-study is additionally carried out herein.

2 METHODOLOGY OF POLLUTION LOAD ESTIMATION

2.1 METHODS

Pollution load of a specified pollutant is the quantity of mass emitted per time unit from point or non-point sources of a defined area. Each pollution load in river waters is computed by multiplying the river discharge with the pollutant concentration measured at a prescribed river cross-section. The methods for estimation of the NPS pollution can be classified in two main categories: a) Direct approach and b) indirect approach. The direct approach addresses directly to NPS pollution and the events and causes that contribute to NPS pollution are mathematically described (Hartigan et al., 1983). On the other hand with the indirect approach, the NPS pollution is correlated to water quality data available for surface bodies. Several methods have been developed for the assessment of NPS pollution and include computer-based models for the analysis of the water quantity and quality of river basins. Recently Geographic Information Systems (GIS) are in use to facilitate data processing and management (Hsieh and Yang, 2006). Integrated GIS models, which include data analysis and modelling, have been developed for the assessment of point and NPS pollution (BASINS) (US-EPA 1997, Matejisek et al., 2003; Hsieh and Yang, 2006). Furthermore, control strategies have been developed for the management or nutrient pollution for watersheds and surface waters (Peters, 1973; Chapra and Tarapchak, 1976; Haith and Dougherty, 1976; Somlyody and Wets, 1998; Yeh and Labadie, 1997; Harrell and Ranjitham, 2003).

2.2 POLLUTION LOADS

To estimate the pollution loads at sources in a river basin, the application of the following procedure is proposed:

(a) Discretize whole river basin to sub-basins and these to smaller watersheds, as shown in Fig.1.
(b) Locate each point source
(c) Define the area loaded by each NPS
(d) Define each source characteristics, as pollutants and emission loads, season of the year and duration of each pollution loading, e.t.c.

Entire loads of pollutants, in case of direct emission into the river, or only a portion of them may reach river waters in case those pollutants migrate gradually to neighbouring surface waters as washed up by runoff or to groundwaters by infiltration. To estimate pollution loads at a river cross-section simultaneous measurements of the river discharge and pollutant concentrations are required.

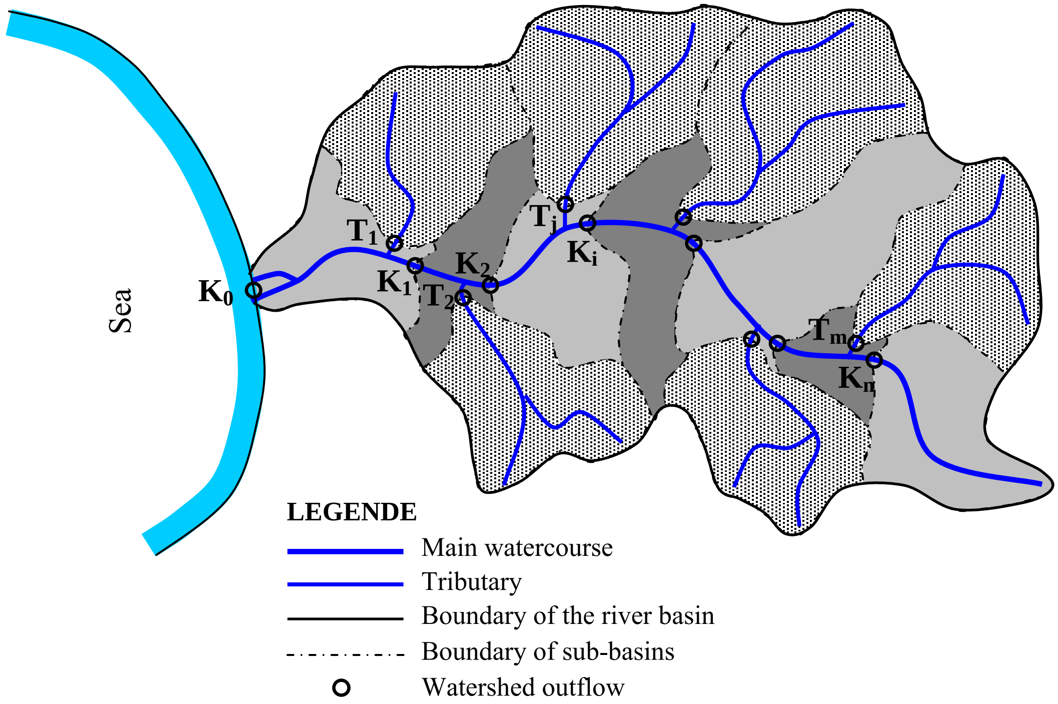

Fig. 1. A typical descritized scheme for a river basin.

Alternatively, the river discharge may be predicted by a calibrated rainfall-runoff model using available hydro-morphologic and geologic information. For both river discharge and pollutant concentrations at several river cross-sections, systematic monitoring programs must be in direct execution and specific databases linked to GIS management tools have to be created and continuously updated. All these data are necessary for calculating the pollution factors at selected river cross-sections.

2.3 POLLUTION FACTORS AT A RIVER CROSS-SECTION

For a prescribed period (month, season or year) and each particular pollutant, a pollution factor for the river waters contaminated by the related watershed may be calculated. This factor is defined as the ratio of the total mass entered the river from the watershed during the reference period, divided by the total mass estimated during the same period at all watershed sources. Similar to run-off factors that introduce the water contribution of a sub-basin to a prescribed river cross-section, pollution factors can be employed to estimate the pollution contribution of the same sub-basin to this cross-section. A synoptic scheme indicating all the modules of a simplified methodology for monitoring and quick predicting river pollution is given in Fig. 2.

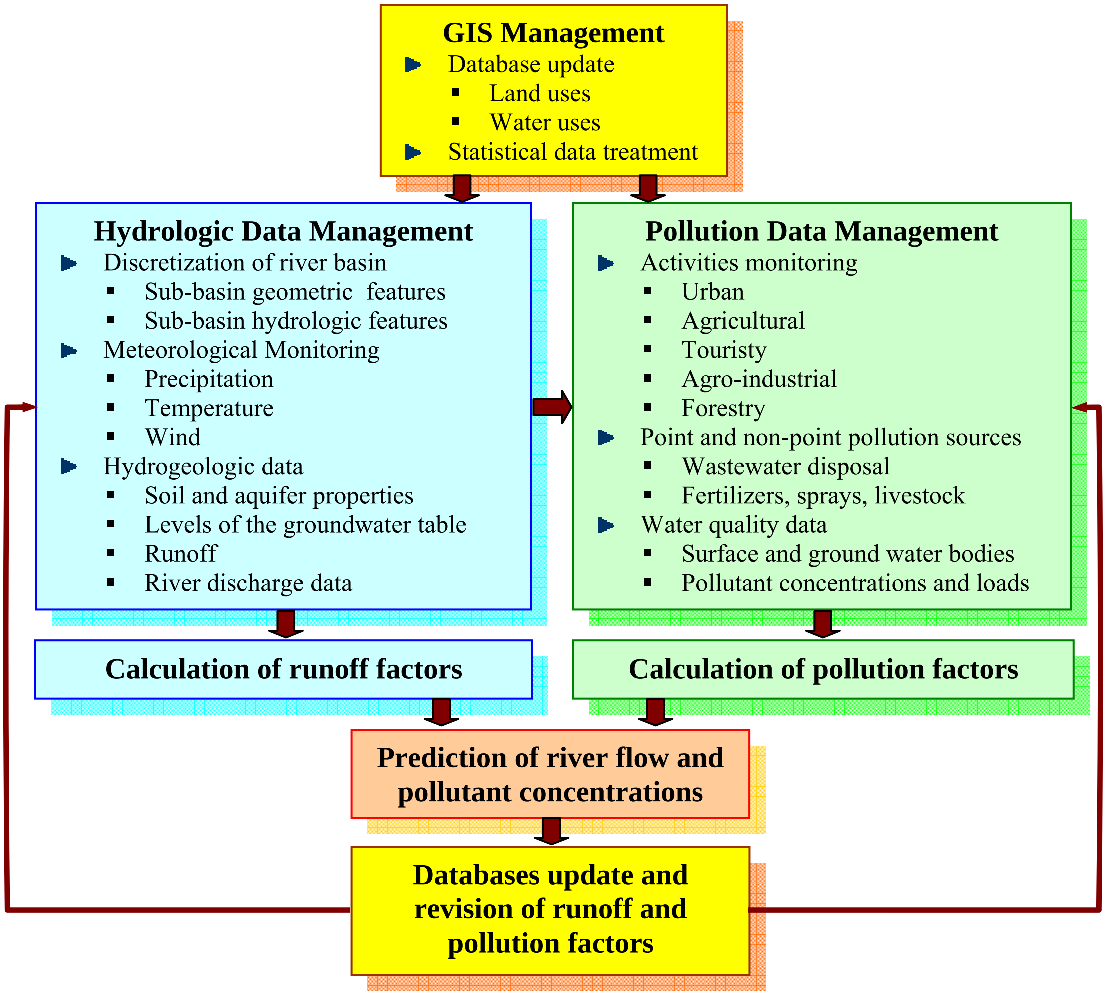

Fig. 2. Modules of a methodology to monitor and predict river pollution.

3 APPLICATION IN THE RIVER BASIN OF ERYMANTHOS, GREECE

3.1 CHARACTERISTICS OF THE STUDY AREA

The Alfeios River Basin covers a drainage area of 3658 km^2, which extends to western Peloponnisos distributed in three prefectures (Ileias, Achaias and Arkadhias). Detailed description of this basin is given by Manariotis and Yannopoulos (2004) and Yannopoulos and Manariotis (2005). Figure 3 shows the major geographic information of the Alfeios River Basin and highlights the Erymanthos River Sub-basin, hereafter called *Erymanthos watershed*, where the present case-study is carried out. The Erymanthos watershed has an area of 360 km^2 and the main morphological characteristics are: mean altitude of 861 m, 50% of the basin surface above an altitude of 835 m and a mean slope of 35.3%. Watershed delineation and morphological characteristics calculation have been carried out using the WMS 7.0 software (WMS, 1998). The Erymanthos River is approximately 50 km long with an annual water yield 179×10^6 m^3 and the third in flow-rate tributary of the Alfeios River, after Ladhon and Lousios tributaries.

According to the Geographical Information System Vector Database available by the Program of CORINE LAND COVER GREECE (CLCG) of the Hellenic Mapping & Cadastral Organization (HEMCO) (http://www.okxe.gr), the land uses of the Erymanthos watershed for the year 2000 are indicated in Fig. 4. The National Statistical Service of Greece (NSSG) has provided data of population, beneficial land uses and livestock. For the Erymanthos River watershed, the land-use categories that contribute to nitrogen and phosphorus loads in the watershed, which are available by NSSG for the period 1999-2000, are annual agricultural cultivations, croplands, grape lands, grassed areas and pastures, and family vegetable gardens.

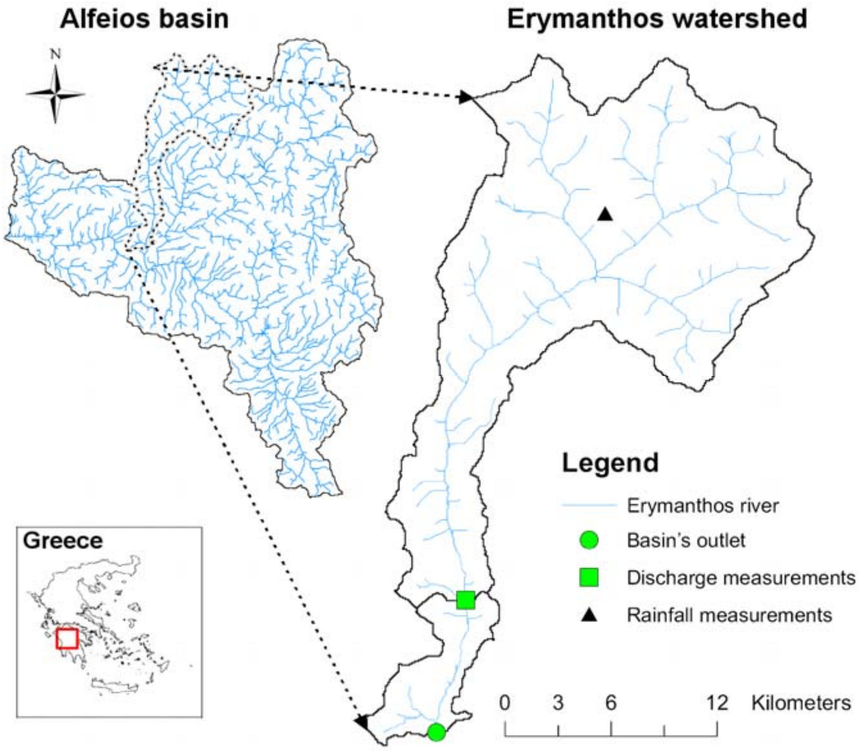

Fig. 3. A general aspect of Alfeios River basin highlighting the Erymanthos watershed.

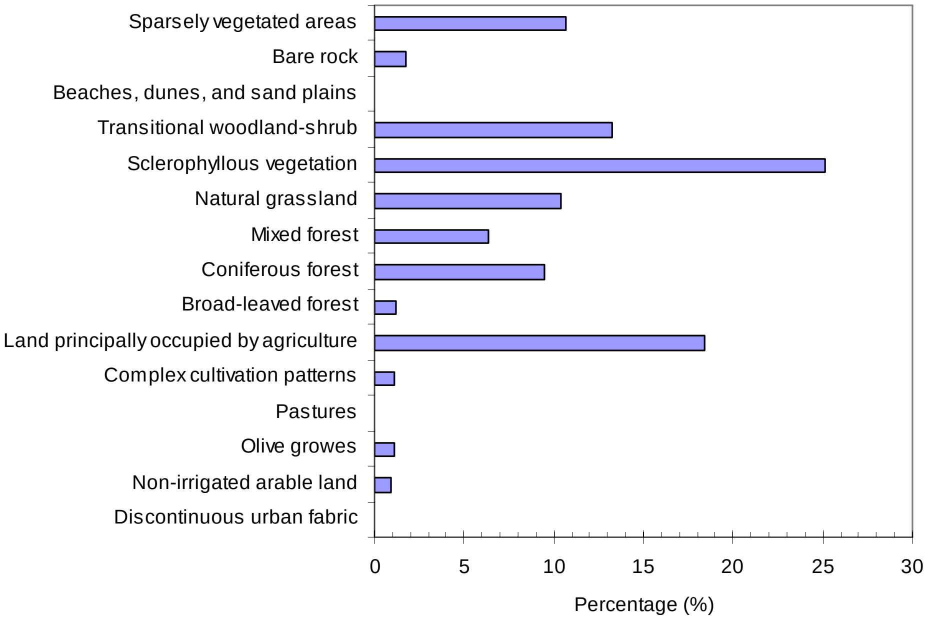

Fig. 4. Distribution of the land uses of the Erymanthos watershed for the year 2000. Source: HEMCO (http://www.okxe.gr).

In addition, for the same period the relevant livestock categories provided are cow, sheep, goat, swine, horse/donkey, rabbit, and poultry. Population data (census 2001) were used to estimate wastewater loads, which contribute to total nitrogen and phosphorus in the watershed. According to data available by Prefectures, agro-industrial activities in the area under examination constitute a rather small number of olive-oil mils, while other industries do not exist.

3.2 ESTIMATION OF INPUT POLLUTION LOADS IN THE WATERSHED

The seasonal loads of total nitrogen (N) and total phosphorus (P) due to anthropogenic activities are estimated using all aforementioned data and are shown in Table 1. The pollution loads due to agricultural activities have been estimated by considering the most usual fertilizer programs for cultivations met in the Erymanthos watershed areas and typical loading values available in the literature regarding livestock, wastewater and olive-oil mil contributions.

Furthermore, natural sources like forests and wild life, fauna and flora in general, contribute to total nitrogen and phosphorus loads. In the present study, watershed pollution loads due to forests and wild life have been neglected, due to the fact that it is very difficult to estimate. However, following the procedure proposed herein, this contribution is included in the river pollution loads. Consequently, the pollution factors are slightly overestimated (approximately 10%) owing to the fact that neglected watershed natural pollution loads are of order 10% of the total P and N (Cho et al., 2004). The total mass of P and N entering the river results from the concentration of these pollutants in the river water multiplied by the river discharge during the reference period. Up to now in the Erymanthos basin four expeditions have been made during one year period, one by season, in order to measure the Erimanthos River discharge and pollutant concentrations regarding total P and nitrate nitrogen (NO_3^-–N) plus ammonium nitrogen (NH_4^+–N). The discharge and concentration values measured are given in Table 2.

Table 1. Seasonal loads (in 10^3 kg) of total nitrogen and phosphorus in the Erymanthos River watershed due to anthropogenic activities

Sources	**Winter**		**Spring**		**Summer**		**Autumn**		**Year**	
	N	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**
Fertilizers	243.7	11.4	1475.9	15.7	337.5	0.0	1534.3	76.8	3591.4	103.9
Animal farms	81.3	14.8	81.3	14.8	81.3	14.8	81.3	14.8	325.2	59.2
Olive-oil mills	1.6	0.3	-	-	-	-	0.8	0.1	2.4	0.4
Domestic/Municipal Wastewater	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	1.2	0.4
Total loads (10^3 kg)	326.9	26.6	1557.5	30.6	419.1	14.9	1616.7	91.8	3920.2	163.9

Table 2. Erymanthos river discharge and pollutant concentration measurements concerning total phosphorus (P) and nitrate nitrogen (NO_3^-–N) plus ammonium nitrogen (NH_4^+–N)

Parameter	**Winter** (8 Jan. 2006)	**Spring** (9 Apr. 2006)	**Summer** (24 Aug. 2006)	**Autumn** (17 Nov. 2006)
Discharge (m^3/s)	23.06	11.65	2.63	4.14
Total P (μg/l)	67	26	20	105
NO_3^-–N plus NH_4^+–N (μg/l)	-	190	520	531

The values in Table 2 should be considered as preliminary seasonal values of these pollutants, as no other measurements are currently available. However, according to Kirchner et al.'s (2000) implications, contaminants are initially flushed rapidly from the watershed, but then low-level contamination is delivered to streams for a surprising long time. Chemical variations on timescales that are long compared to the travel time distribution will be transmitted through the watershed without significant attenuation. In that sense, since travel times in the Erymanthos watershed are of order of one day and chemical-variation time scales are of order of one season of the year, it is expected that the one day concentration measurement should represent fairly well the average situation of an extended past period.

3.3 RIVER DISCHARGE

Since for the period 2005–2006, for which the pollution load has to be estimated, there are no systematic measurements of the river discharge, seasonal discharge values were estimated as:

- A rainfall–runoff model has been calibrated for the period October 1963–September 1976 using daily rainfall data and temperature values for the whole period and discharge data for sufficient intervals of this period.
- Using daily rainfall data and temperature values for the period 1976–1996 the river discharge for this period has been estimated.
- From the simulation results seasonal values of the river discharge for the years 1963–1996 as well as mean seasonal values for the whole period have been calculated. The mean seasonal values will be used for the estimation of the pollution load.

The rainfall–runoff model ENNS (Nachtnebel et al., 1993) has been used for the simulation. It is a lumped parameter hydrologic model. The hydrological processes are being simulated by a single soil layer and a series of three linear reservoirs, while a fourth linear reservoir provides for the routing of surface runoff at the outlet of the basin. The input data required are daily precipitation and temperature. The calibration is performed using daily discharge measurements. Daily precipitations data have been measured at a rain station located near the centre of the basin (Fig. 3) and are available for the period 1955–1997. Temperature data for Erymanthos watershed are not available. Instead, mean monthly values of temperature were used, measured through the periods 1966–1968, 1974–1976 and 1981–1988 at Ladhon dam located in a nearby basin, southeast of the centre of Erymanthos basin. Data preparation included completion of the temperature time series for the precedent time period and reduction to new values, suitable for the altitude of Erymanthos watershed's centre. The completion of temperature time series was based on the average monthly temperature computed from all available data from Ladhon basin. These values were measured at an altitude of 430 m. A gradient of -0.6 ^{o}C/100m was used for the reduction of the temperature values to the altitude of 838 m (centre of Erymanthos watershed). The resultant monthly values were used as daily temperature input data for the model.

Measurements of daily discharge of Erymanthos River are available for sufficient intervals of the period 1964–1976 and have been carried out 8 km upstream from the basin's outlet (Fig. 3). Thus, the simulated sub-basin is slightly smaller with an area of 329.5 km^2. The simulation results of basin discharge have been transformed to correspond to Erymanthos' watershed with an area of 360 km^2, using a factor f = 360/329.5 = 1.092.

The comparison between measured and simulated discharge for the model calibration has been performed using the correlation coefficient of linear regression between measured and simulated values of river discharge at the outlet point and the root mean square error of simulated values. In addition, annual values of actual evapotranspiration were calculated using the Turc method and compared to the simulated values, serving as a third criterion. Figure 5 shows the measured values of river discharge in comparison with those resulted from the calibrated model. The correlation coefficient of linear regression between measured and simulated values is 0.88, while the root mean square error 3.22 m^3/s. The average annual actual evapotranspiration computed with the Turc method, for the 13-year period from 01/10/1963 to 30/09/1976, is 578 mm/year, while the corresponding value resulted from simulation is 521 mm/year. Figure 6 shows the seasonal values of discharge calculated from the results of the simulation for the period 1963–1996.

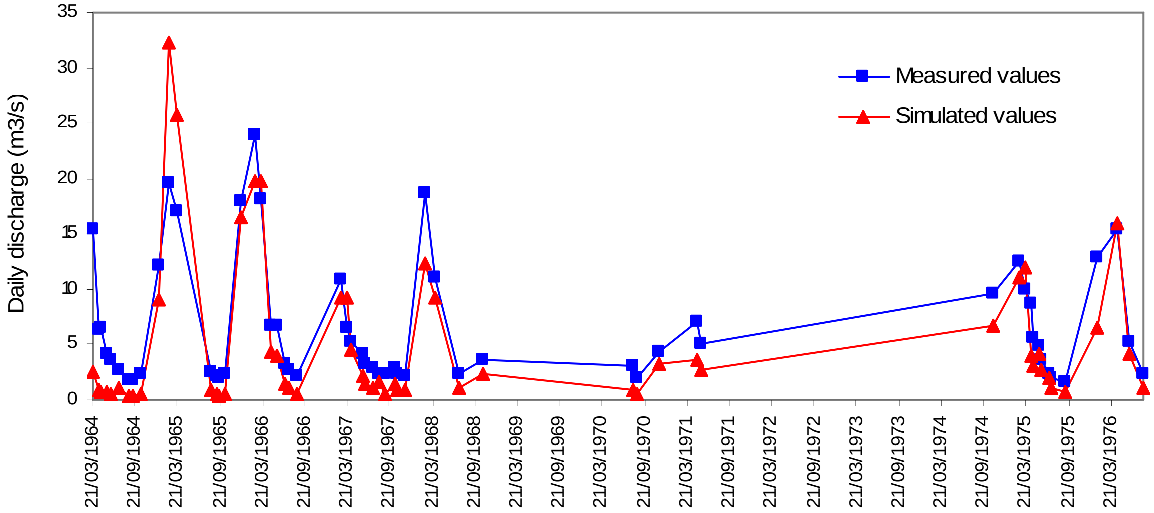

Fig. 5 Measured values of river discharge versus those resulted from the simulation.

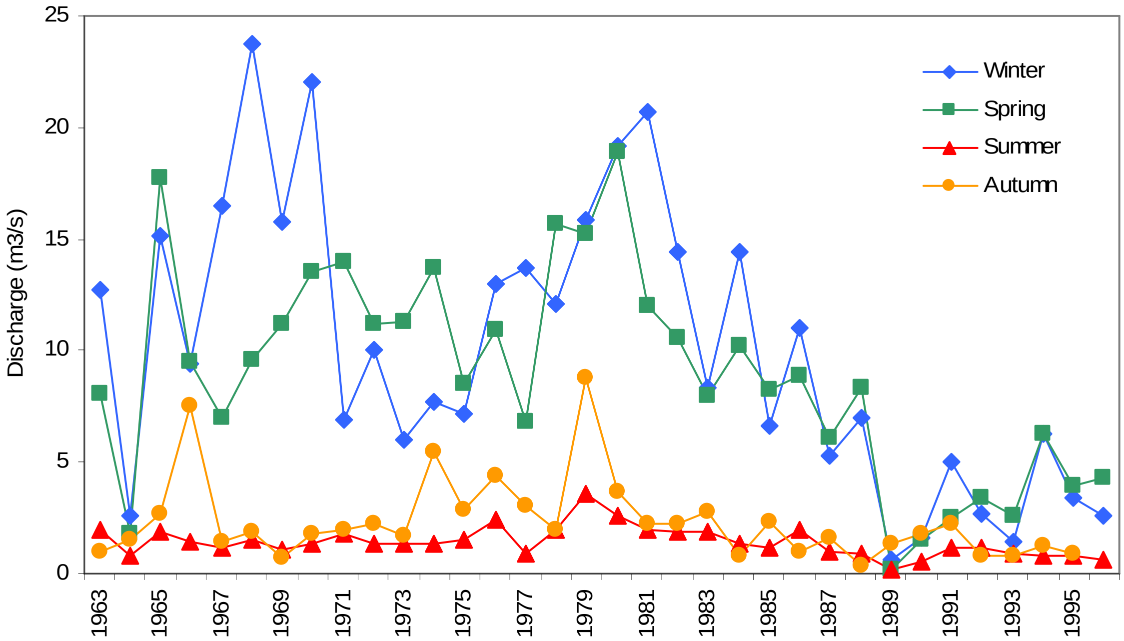

Fig. 6 Seasonal values of discharge, calculated from the results of the simulation for the period 1963–1996.

The mean seasonal values of the river discharge for this period, their standard deviation, as well as the minimum and maximum values, are given in Table 3. The comparison with the values measured (Table 2) shows that the latter are between the minimum and maximum values predicted and in the range of two standard deviations of the simulation results.

3.4 CALCULATION OF POLLUTION FACTORS

Each pollution load is estimated by multiplying discharge by pollutant concentration and is converted to seasonal load. After dividing it by the corresponding load estimated through the anthropogenic activities occurring in the Erymanthos River watershed, the seasonal value of the pollution factor, C_P or C_N, for total P or N, correspondingly, was calculated. Moreover, yearly loads along with the related pollution factors can be estimated. All these factors are shown in Fig. 7. It is interesting that the highest contribution of the Erymanthos River watershed to the river waters regarding total P occurs in winter and decays in an approximately hyperbolic manner from winter to summer, when actually vanishes, while in autumn starts increasing again. A possible justification is the more intense washout of matter containing P by runoff during the winter period being considerably larger compared to that occurring during the other year seasons.

Table 3. Simulated mean seasonal values and standard deviations of river discharge for the period 1963–1996

Parameter	**Winter**	**Spring**	**Summer**	**Autumn**
Mean discharge (m^3/s)	10.02	8.88	1.42	2.35
Minimum/maximum (m^3/s)	0.63/23.76	0.15/18.90	0.15/3.55	0.32/8.74
Standard deviation (m^3/s)	6.29	4.72	0.66	1.86

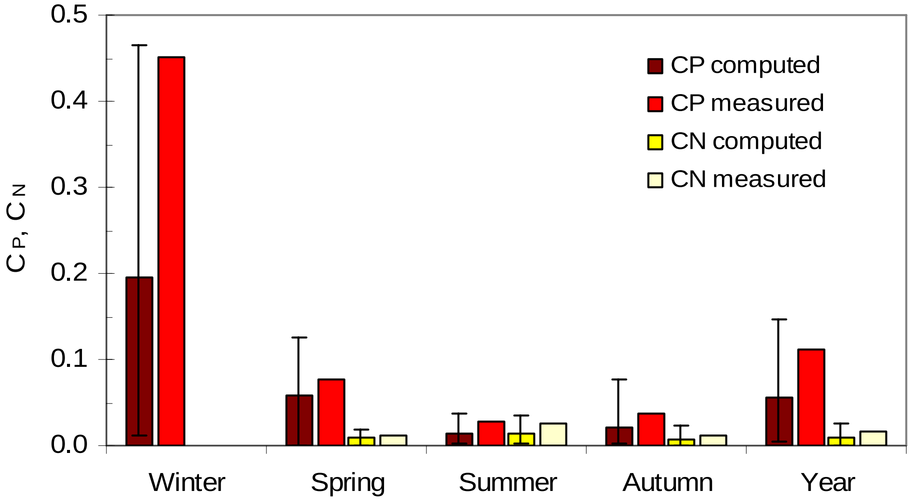

Fig. 7. Annual variation of pollution factors C_P and C_N, regarding the contribution of the Erymanthos River watershed to the river waters. Computed values come from modelled runoff using precipitation data from 1963 to 1996, while measured values come from direct measurements of the river discharge, one time within each corresponding period of the year 2006. Upper and lower bars indicate the calculated extreme values of factors corresponding to minimum and maximum discharge values predicted.

The values of pollution factor regarding N, C_N, show considerably lower rates of contribution during spring and autumn compared to C_P, while comparable rates occur during summer. Unfortunately, the river water sampled in the winter expedition had not been analysed for N content and therefore no value can be estimated for N contribution during the winter period. The approximately comparable rates of pollution factors, C_P and C_N, during summer may be attributed to the low precipitation heights, which cause very limited runoff. The P and N contribution to the river water originates from groundwater, which is less contaminated by these constituents that runoff. The observed lower values of C_P compared to C_N may be attributed mainly to the different retention rates in the watershed. An indication may be taken by Kronvang et al. (1999), who measured that the organic N retention in stream bed sediments and riparian zones during a low-flow period was approximately 2.6 times higher than the corresponding P retention. In addition the N content of soil in subsurface samples (20-25 cm depth) was about 20 times higher than P content (Craft and Chiang, 2002).

4 CONCLUSIONS

The Erymanthos watershed case-study showed that the proposed methodology provides reasonable results for the pollution factors estimations. Due to the iterative procedure proposed between pollution monitoring and assessment of pollution factors, the methodology gains the advantage of the gradual improvement of the results. Authors believe that it could be incorporated in the incoming monitoring and management plans required by WFD.

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