Article

Integrated Groundwater Resources Management Using the DPSIR Approach in a GIS Environment: A Case Study from the Gallikos River Basin, North Greece

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Abstract: The Gallikos River basin is located in the northern part of Greece, and the coastal section is part of a deltaic system. The basin has been influenced by anthropogenic activities during the last decades, leading to continuous water resource degradation. The holistic approach of the Driver-Pressure-State-Impact-Response (DPSIR) framework was applied in order to investigate the main causes and origins of pressures and to optimize the measures for sustainable management of water resources. The major driving forces that affect the Gallikos River basin are urbanization, intensive agriculture, industry and the regional development strategy. The main pressures on water resources are the overexploitation of aquifers, water quality degradation, and decrease of river discharge. Recommended responses were based on the Water Framework Directive (WFD) 2000/60/EC, and sum up to rationalization of water resources, land use management and appropriate utilization of waste, especially so effluent. The application of the DPSIR analysis in this paper links the socioeconomic drivers to the water resource pressures, the responses based on the WFD and the national legislation and is as a useful tool for land-use planning and decision making in the area of water protection.

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1. Introduction

Several changes are noted at the European river basins, especially their coastal parts, due to land use alterations, urbanization, shrinkage of estuarine zones *etc* [1]. These changes are attributed predominantly to human activities in conjunction with poor management practices, which have caused numerous negative consequences such as development of deficient water balance and reduction of groundwater resources, water resource quality degradation [2], groundwater head decline, saline water intrusion along coastal areas and surface and ground water quality deterioration [3,4].

The Water Framework Directive (WFD) 2000/60/EC clearly sets the basis and principles for effective protection of groundwater, internal, transitional and coastal waters at the river basin scale. Several techniques and methodologies have been proposed for the optimization of water resource management at this scale, and the Driver-Pressure-State-Impact-Response (DPSIR) methodology [5] is one of the methods that is being extensively applied in the framework of integrated water resource management [6–8].

In this paper the DPSIR technique is applied in a geographic information system (GIS) environment aiming at contributing to the optimization of water resources management of Gallikos River basin and developing a useful tool for local authorities, stakeholders and the regional water authority that is by law responsible for setting up the regional water resources policy. Through its application it also aims at proposing a suite of measures and actions towards rational development and sustainable management of the water resources. The selection of the GIS environment ensures that the results of the DPSIR analysis will be presented in a dynamic context that will be easily modified, as new data will be added and the comparison or change over the oldest data will be simple.

A preceding hydrogeological survey enabled, amongst other things, identification of the aquifer units that exist within the river basin and an estimation of their exploitable resources. This was the first attempt to study the water resources of the basin based on systematic measurements at specified time intervals. Monitoring points of the network had an adequate spatial distribution that sufficiently covered the entire basin. In a consequent phase, water demands per use were calculated and a thorough assessment of the quantity and chemical quality of water resources was performed. At the time that the fieldwork was conducted, the research team was in continuous communication with the farmers/breeders of the area and had established sincere cooperation. Most of the farmers were willing to assist with the monitoring network operation, in contrast to some local authorities that exhibited strong reservations to any cooperation on the assessment of environmental parameters. Based on these results, the DPSIR technique was applied and actions for measures for the sustainable management of the river basin's water resources were proposed. The presentation of the proposed approach serves as a demonstration of the applicability of the proposed methodology in other basins, opting for efficient and effective data analysis that leads to reliable, easy and precise water resource management practiced with the help of a dynamic and versatile tool.

2. Materials and Methods

2.1. Regional Setting

The Gallikos River is located in northern Greece and flows across the Prefectures of Kilkis and Thessaloniki before discharging into the Gulf of Thermaikos, northern Aegean Sea. The hydrological basin was delineated using ArcView GIS (Figure 1) and it was measured at approximately 1050 km^2. Most of the area lays at elevations of lower than 600 m whilst in the northeast its watershed boundary reaches an altitude of 1180 m. The mean altitude was calculated at 308.5 m. The coastal part of this basin forms part of an extensive estuarine system that has an extension of 428 km^2. The sediment discharges of Gallikos, Axios, Aliakmon and Loudias rivers have resulted in the addition of a coastal plain that covers an area of 1500 km^2 [9].

The Gallikos River is of high importance due to the proximity of the basin to Thessaloniki, the second largest city of Greece. The total length of the river is about 73 km. It is characterized by shallow water depths, the gradient of which is, of course, relatively high. Consequently, the river flow characteristics resemble both a river and a torrent. This may also be concluded by the seasonality and peak discharge events that characterize its flow regime. Maximum discharges occur during summer and have been estimated at 700 m^3/s [10]. The predominant flow direction is from NNE towards SSW and the basin comprises four sub-basins that are discharged by the four main tributaries of the river. The high density of the basin's hydrologic network suggests a high runoff percentage compared to infiltration, which essentially suggests that the geological formations of the basin are impervious.

The mean annual precipitation and temperature over the basin is about 480 mm and 16.5 °C respectively [10] and the mean annual surface runoff is about 45×10^6 m^3 as measured at its exit at Nea Philadelphia monitoring station over the period of 2005–2006. Although the flow of the Gallikos River is seasonal, at Nea Philadelphia the river exhibits a permanent flow, except for very dry years. According to Poulos and Chronis [11], the annual load of suspended solids is 4 t/km^2 and the annual load of diluted solids is 0.51×10^3 t/km^2. A denudation rate of 320 m^3/km^2 has been estimated by Eumorphopoulos [12].

The vertical continental moves to which the wider region has been subjected during the recent geological times, along with the considerable sedimentation processes of the rivers Axios, Aliakmonas, Gallikos and Loudias, have resulted in the rapid withdrawal of the sea and the creation of new land thereby delimiting the Gulf of Thermaikos [13]. Based on existing data, Konstandinidis [10] also suggests withdrawal of the sea in favor of the land during historical times and up to date.

Geodetic surveys carried out at the coastal part of the basin (Kalochori) over the period of 1992–1998 reveal subsidence phenomena in the order of 2.8–5 cm/year and an overall subsidence of 2.5 m for a time period of thirty years [9]. These phenomena are attributed to overpumping of groundwater and to the ongoing compaction and solidification of the contemporary loose silty-clay deposits and the quick sand phenomenon that occur along the coastal environment of the system [14,15].

Geologically, the Gallikos basin is filled with Quaternary and Tertiary sediments. Quaternary sediments consist of fluviolacustrine deposits, whereas Tertiary sediments essentially are comprised of Neogene marls. The total thickness of these deposits, which form the main aquifer system of the basin,

is up to 160 m at the downstream flat parts of the basin and has an average of about 32.5 m. They thin out progressively towards the upstream northern part of the basin, which is bounded by the bedrock alpine formations. The bedrock of the basin is formed of argillaceous schists, limestones to dolimites, quartzites and gneiss [16–18].

Figure 1. Topographic map of the Gallikos River basin.
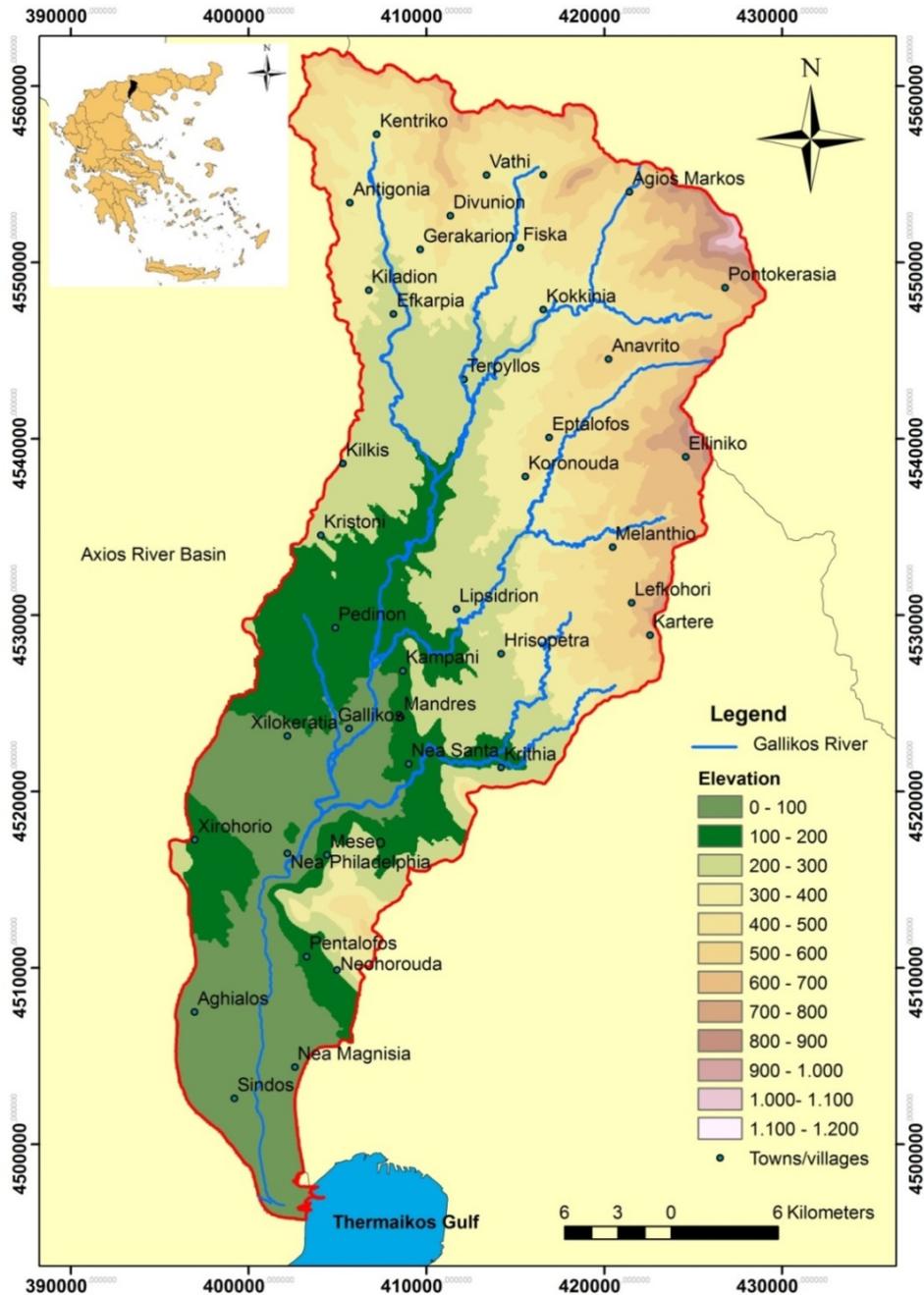
2.2. Socio Economic Features

In the catchment area there is a spatial differentiation regarding the economic activities. Agricultural activities and livestock are the main occupation of the majority of the inhabitants, especially at the areas along the Gallikos River. The industrial sector is developed in two zones close to the main urban areas. The industrial zone, south of Kilkis city, consists of small and medium size

enterprises, while the industrial zone of Sindos town consists of large-scale enterprises since it is part of the industrial zone of the broader metropolitan area of Thessaloniki. The areas of service provision, transport and trade are also developed near major urban areas. A domestic effluent treatment plant operates in the areas of Sindos (Figure 1) and Kilkis. Despite the existence of the aforementioned operating treatment plants, the Gallikos River still remains receptor of untreated sewages from small size settlements that are located along the riverbed. The river is also affected by agricultural and industrial effluents.

2.3. DPSIR Analysis Approach

The widely used Driver-Pressure-State-Impact-Response (DPSIR) analytical framework has been adapted to the definitions given in Groundwater Risk Assessment; Technical report developed on the basis of the Guidance Document 2004, No. 3 [19]; as follows:

- Driver: An anthropogenic activity that may have an environmental effect. Drivers produce a series of pressures and are quantified by aggregated data, e.g., population density, hectares of irrigated land, industrial units *etc*.
- Pressure: The direct effect of the driver. Pressures form the manifestation of the effects the Driving Forces have on the water bodies. Pressures degrade the State of water bodies and have an Impact on them as well as on humans. Increased irrigation-industrial-domestic demands, precipitation decrease, point or non-point source pollution could be considered as pressures.
- State: The condition of the water body resulting from both natural and anthropogenic factors (e.g. chemical or ecological characteristics, water quantity, *etc*.).
- Impact: The effect upon human well being.
- Response: The measures taken to improve the state of the water body.

The DPSIR framework for Gallikos river basin is illustratively and briefly presented in Figure 2. Despite having been frequently employed in the environmental domain, DPSIR has been criticized for several shortcomings [20,21]. The main criticism is that the framework creates stable indicators and cannot take into account the dynamics of the system. Another criticism related to the aforementioned is that the framework cannot capture trends, but it analyses them by repeating the same indicators at regular intervals [20,22]. Finally critics argue that it suggests linear unidirectional causal chains of environmental problems and that it provides unclear cause-effect relationships of complex environmental problems [20,22]. The response to criticism is that the focus should be on the links between the nodes of DPSIR by applying specific socio-economic and natural science based models so as to understand the cause-effect dynamics [20,23].

The implementation of the DPSIR framework in a GIS for the Gallikos River basin is based on water resource quality and quantity data. The selected key indicators for the monitoring of the water resources quality are some easily measured physicochemical parameters. These parameters are related to the anthropogenic activities that are in accordance with the socio-economic processes in the area. The changes in measured quantity parameters such as groundwater level or river discharge can be attributed to climate changes in a long-term examination or to anthropogenic activities in a short-term examination. For the Gallikos River basin, the recorded changes in quantity parameters are in line with

the increased anthropogenic activities during recent years. The application of the DPSIR framework in a GIS environment allows the spatial visualization and better integration of the various indicators [7]. For example, the GIS application gives the opportunity to depict in the same picture the areas of intense industrial or agricultural activities (cause) and the spatial distribution of the surface or groundwater resources that show an excess of the admissible values (impact) of the associated pollutants (nitrate from agriculture, sodium and potassium form industrial activities in the Gallikos River basin). The GIS environment is dynamic since it enables the stakeholders to adapt the available information according to the problem they have to confront at that time. The great advantage of the GIS is that it can lead to a clear relationship between cause (driving forces), pressure (environmental problem), and impacts, which is a very useful tool for the planning of the appropriate measures for sustainability by the water resources decision makers.

Figure 2. A generic DPSIR framework for water resources of Gallikos River basin (illustrated by the authors based on the framework of Kristensen [24]).
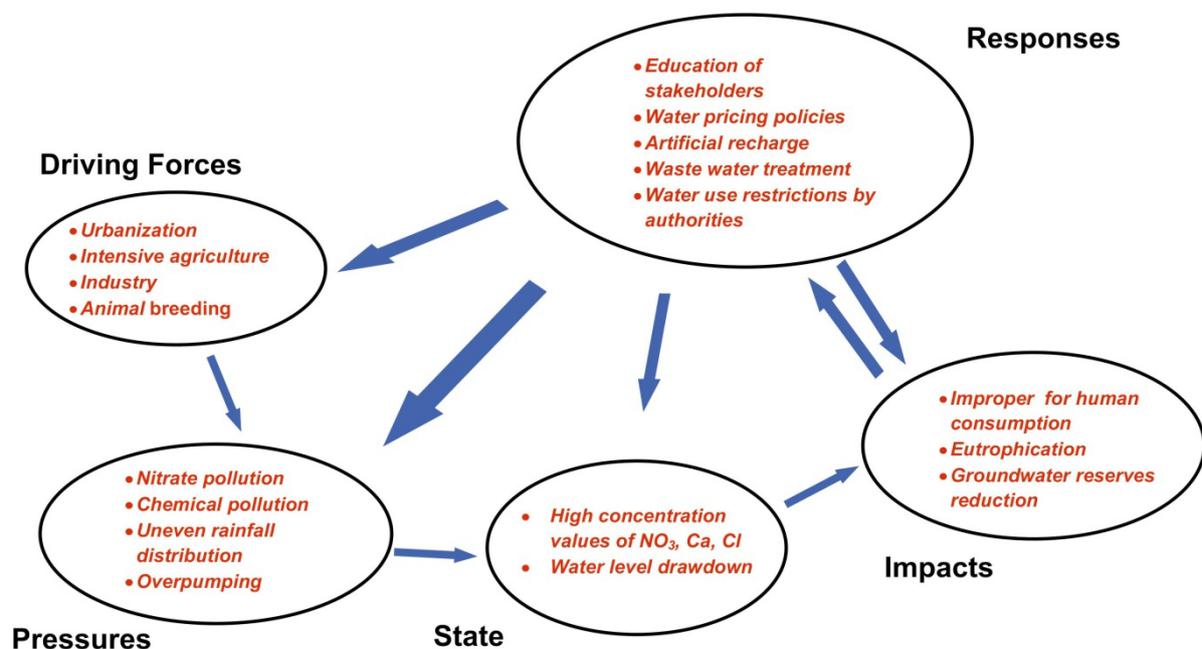
2.4. Data Collection, Sampling, Methodology

In the framework of a supporting new doctoral researchers program (project name: ECHEDOROS) funded by the General Secretariat for Research and Technology, data concerning the hydrogeological investigation of the Gallikos River basin were collected for the time period of 2004–2006. Surface and groundwater samples were collected two times a year (in April and September). These periods represent the highest and lowest ground and surface water levels, respectively, and are thus considered to be the most appropriate to study possible hydrochemical variations. The sampling points were chosen in order to have an adequate spatial distribution. Samples were shipped chilled to the laboratory in an appropriate isothermal, box. Samples collected for determination of heavy metals were filtered *in situ* through 45 μm filters and treated with HNO_3. *In situ* measurements of pH, Electrical Conductivity (E.C.), Dissolved Oxygen (D.O.) and water temperature were also taken. Samples were

analyzed in the Laboratory of the Land Reclamation Institute (National Agricultural Research Foundation, Thessaloniki, Greece), and the following parameters were determined: Ca, Mg, Na, K, Cl, NO_3, NO_2, SO_4, B, HCO_3, Fe, Mn, Cu, Pb, Cd, Zn. Meteorological data were derived from the existing operating meteorological stations. In addition, the Laboratory of Engineering Geology and Hydrogeology, installed three extra rain gauges to complete the network. River discharge measurements were carried out at regular intervals at the upper part of the basin, near the Nea Philadelphia village. Data concerning cultivated land in the region were obtained from the appropriate local authorities.

Evaluation of hydrochemical results, *i.e.*, water quality examination, was performed in line with the WFD principles and the methodological approach adopted by Greece in the characterization of groundwater bodies [25], where in absence of specific ecological indices and/or threshold values, the maximum admissible concentrations (MAC) for water intended for human consumption have been adopted. This approach, which is also adopted by other Member States, is justified by the fact that in most of the basins a multitude of water uses occurs, amongst which domestic use is considered the most sensitive due to the final receptor. In fact, based on the adopted methodology, as a threshold of 75% of the MAC value is adopted n an attempt to set strict environmental quality criteria and also to account for the lack of comprehensive modeling tools that influence projections of future evolution of water quality. With regards to surface water bodies, the same principles were applied, with the exception of NO_3 concentrations, whereby the threshold concentration of 15 mg/L was adopted. This is 75% of 20 mg/L, which is one of the concentration levels above which eutrophication phenomena occur. This particular concentration refers to wintertime average values. According to other researchers, this value should be decreased to 10 mg/L. This approach is also incorporated in the national water resources management plans and is also followed by several Member States in the framework of the Nitrates Directive. In principle, characterization in the framework of aforementioned approach is based on the P90 values, except for the cases where data are too sparse or inadequate to perform such an analysis. In such cases, the median or mean approach is preferred. This is especially the case for surface waters for which winter-time average values are not readily available.

Prior to all the aforementioned works that were carried out, all the available data from the databases of local authorities, public services and relevant references had been collected. The evaluation of these data was used to identify the "driving forces" and "pressures" of the Gallikos River basin. Data obtained from the above-described monitoring program were used to illustrate the "state" of the water resources. From the analysis of the three first parameters of the DPSIR methodology it is possible to identify the "impacts" and to propose a "response" to the appropriate set of measurements for water resources management in accordance with the WDF.

3. Results

3.1. Driving Forces

Urbanization, intensive agriculture, industry—especially along the coastal part of the basin—and to a minor extent animal breeding along the mountainous region, form the main driving forces of the

study area (Figure 3). Quantification of driving forces is based on population density and the spatial distribution of agricultural land, industry and animal breeding units.

Figure 3. Land cover in the Gallikos River basin (illustrated by the authors, based on available online digital archives [26]).
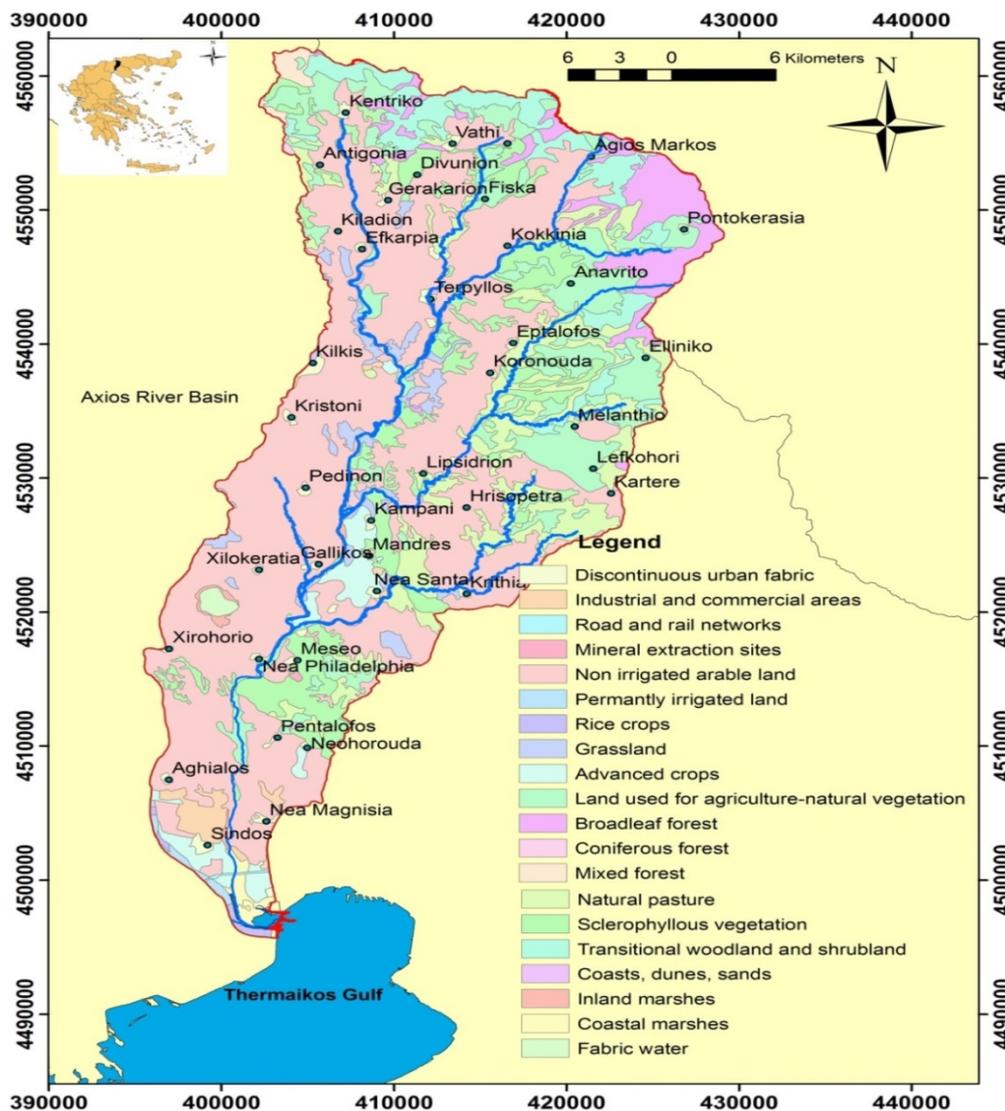
The Municipality of Kilkis, which is the capital city of the homonymous Prefecture, has by far the largest population amongst the Municipalities of the study area. According to the National Statistical Service of Greece, over the period of 2001–2011, the population exhibited an increasing trend (6.42%). The population of the basin was 55,359 residents in 2001 and reached 58,915 in 2011 [27]. In the area of Sindos, population growth is substantial and follows a considerable expansion of urban development, both of which are attributed to the establishment of the Technological Educational Institute of Thessaloniki. Population density varies from 58.41 inhabitants/km^2 in the lowland area, to 10.22 inhabitants/km^2 in the mountainous part of the studied region. Total cultivated land is 14,448 stremmas (*i.e.*, ca 1448.8 ha) 57.6% of which is irrigated. Arable land (corn, tobacco, cotton, sunflower) accounts for most of the cultivated land and is fully irrigated. Cereals for forage, trees (mainly almonds and oil producing olives) and vegetables are also cultivated (Figure 4).

Figure 4. Irrigated land (in stremmas, 1 ha = 10 stremmas) in the upper part of the Gallikos River basin.
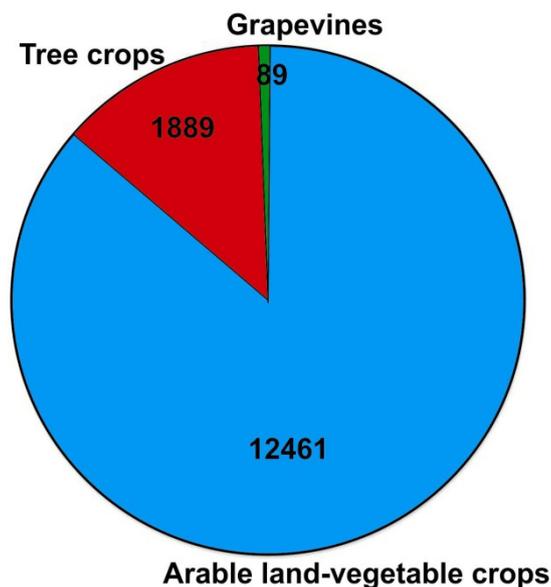
Stabled and non-stabled livestock is a very important driving force since the Kilkis Prefecture is one of the most productive in this field. More than 100 industries operate within the boundaries of the Gallikos River basin in various sectors like food, chemical products, plastics, paints and varnishes, production and processing of iron and steel, production of oil refining products, textile dyeing, *etc*. There are 14 industries [26], which are mainly located in the southern part of the basin, that lie within the requirements of Seveso Directive whilst the number rises to approximately 30 if those located in short distances are included. Mines and quarries exist as well. In the basin there are many sand extraction sites, without any control in most of the cases. Many of the villages do not have sewage a network or wastewater treatment plants, and this forms another very important driving force for the area.

3.2. Pressures

Thoughtless use of fertilizers—especially in the framework of documented and practiced intensive agriculture—leads to nitrate pollution and elevation of phosphorus compounds in both surface and ground waters, since there is no direct control by any state agency of the used amounts of fertilizers and pesticides. The total load of nitrogen and phosphorous from agricultural activities that pollute surface waters is estimated to be 2049 tn/yr and 25.6 tn/yr, respectively. Superficial receptors receive an annual load of approximately 806.6 tn of nitrogen and 102.5 tn of phosphorous from stabled and non-stabled livestock [21]. The urban effluent that ends up in superficial receptors consists of 1240 tn/y of nitrogen and 199 tn/yr of phosphorous.

Water demands for irrigation combined with uneven rainfall distribution throughout the year is also a major pressure related to agricultural activities. The overpumping of boreholes leads to groundwater level drawdown resulting in a decrease of reserves. Pressure due to the industrial activities is expressed in terms of chemical pollution of predominantly surface waters, but also of ground waters due to existing hydraulic interactions. The majority of the industries do not have wastewater treatment plants

and the river and aquifers are the direct receptors of their effluents. However, industries are not wide spread within the study area. They are mainly located at the south part of the basin and the area near the city of Kilkis. The most important identified pollutants in this area were Na^+ and Cl^- ions from the textile dyeing industries.

3.3. State

The current state of surface and ground water is based on sampling, groundwater level measurements, surface water discharge measurements and chemical analyses and is discussed in details by Mattas *et al.* [28,29]. A brief description of the surface and ground water state is provided in the following paragraphs.

3.3.1. Surface Water Quality

The water quality of the Gallikos River is influenced by the geological structure, agricultural activities as well as the untreated waste effluent that is discharged from the city of Kilkis and of numerous villages and industrial units spread along the river basin. Hydrochemical data from 49 samples were used in order to assess the water quality (Table 1) and estimate the nutrient inputs from the river to the Thermaikos Gulf. Aforementioned samples were collected from fourteen sites (Figure 5) of the hydrographic network during the period of 2004–2005. Four sampling campaigns were conducted for the wet (April–May) and dry periods (September–October). Dry period sampling was not always possible, since some of them had already dried out.

**Table 1.** Summary statistics for concentrations of surface water samples.

Parameters	Minimum	Maximum	Mean value	Standard deviation
pH	7.42	9.01	8.21	0.39
E.C. (µS/cm at 25 °C)	210.0	1760.0	768.0	313.0
T (°C)	6.2	26.0	14.17	5.92
Ca^{2+} (mg/L)	24.0	136.3	72.11	23.12
Mg^{2+} (mg/L)	18.0	68.0	38.93	11.79
Na^+ (mg/L)	17.0	220.0	50.0	40.0
K^+ (mg/L)	2.0	16.0	4.86	2.85
HCO_3^- (mg/L)	214.0	536.8	329.88	69.42
Cl^- (mg/L)	17.8	332.4	67.81	74.47
SO_4^{2-} (mg/L)	11.1	135.6	51.65	30.92
NO_3^- (mg/L)	0.5	28.55	10.03	7.04

Surface water temperature ranges from 6.2 to 26 °C, depending on atmospheric temperature fluctuations. Electrical conductivity ranges between 210 and 1760 µS/cm; the highest values are recorded at the Nea Philadelphia sampling point and are attributed to anthropogenic pollution. In general, the composition of the surface water for cations is $Ca^{2+} > Mg^{2+} > Na^+ > K^+$. The composition of the surface water for anions is $HCO_3^- > Cl^-$ or $SO_4^{2-} > NO_3^-$.

Iron (Fe) and manganese (Mn) concentrations are below the detection limit (d.l.), which is less than 0.1 and 0.03 mg/L, respectively, in most of the examined samples. Likewise, the zinc (Zn) concentration in the majority of water samples is under 0.05 mg/L, which is the d.l.; whereas a maximum value of 0.24 mg/L is recorded in a sample from a location adjacent to an industrial area.

Dissolved oxygen concentrations are reasonable for potable use, apart from a sampling point near Kolhida village (EN9 sampling point, Figure 5), where the minimum value of 0.35 mg/L is recorded. The same situation exists for the oxygen saturation, which ranges from 4% to 182%.

**Figure 5.** Surface water sampling points.
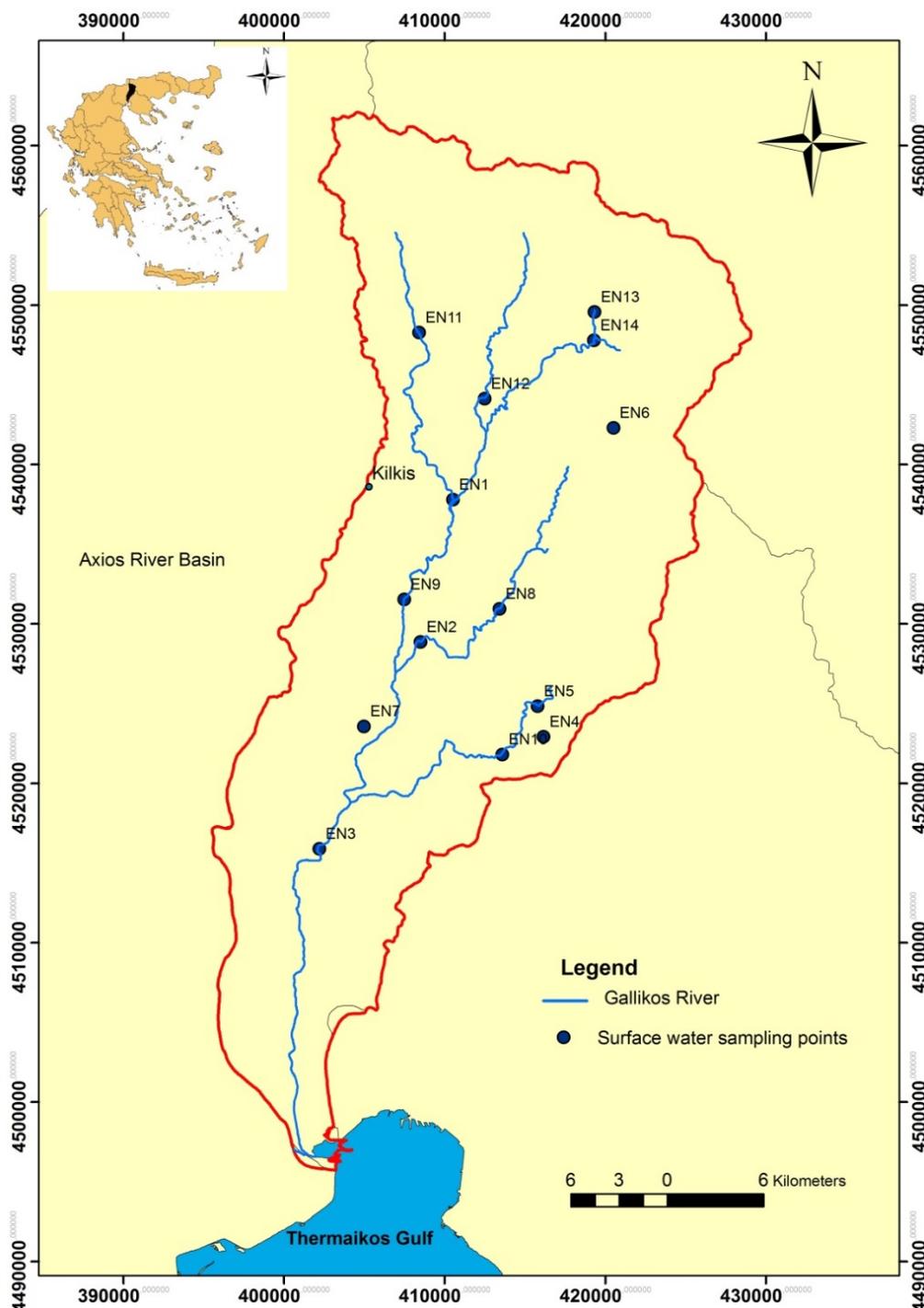
Oxygen content of the surface water depends mainly on the surface water temperature, but is also highly dependable on its pollution loads. Significant temporal and spatial variations of the chemical oxygen demand COD (from 0 to 87.1 mg/L) are noted, the highest values are recorded in the Nea Philadelphia area (EN3 sampling point). The majority of the samples have biochemical oxygen demand (BOD$_5$) values under d.l., which is 2.4–3 mg/L, depending on the sample quantity. Higher values (8 mg/L) are recorded at a sampling point near Kolhida village (EN9). In general, as river discharge decreases, both BOD$_5$ and COD values increase.

River water seepage is known to considerably contribute to groundwater recharge of aquifers of the Gallikos River basin. Thus, surface water quality affects groundwater quality of the aquifer system that is formed in the basin, which is the main source of potable water [29]. Eutrophication has been recorded in the Thermaikos Gulf, and this is the major problem that requires management action [6].

3.3.2. Surface Water Discharge

The mean annual discharge of the Gallikos River at the Nea Philadelphia station over the period of 2004–2006 is 45 Mm^3. Based on the analysis of monitored discharge data over this period (Figure 6), it becomes apparent that the flow regime is not regular throughout the year. On the contrary, discharge exhibits distinctive temporal variations that resemble a torrential character. Lowest discharge rates are exhibited during the dry season, whilst peak discharges are normally exhibited during spring time. In the past years, several flood discharge events have occurred, the most extreme of which being the one of 18 June 2004, which resulted in extensive damage to infrastructure, including the destruction of the monitoring station.

Figure 6. Mean monthly discharge of Gallikos River for period 2004–2006.
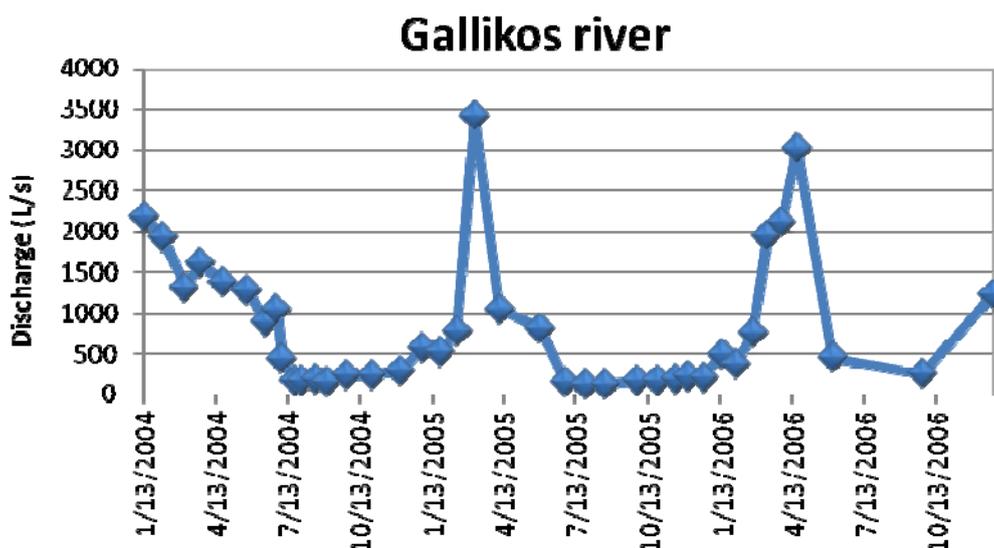
Over the period of 2004–2006, the minimum and maximum recorded discharge rates were 0.13 m^3/s and 3.42 m^3/s, respectively. Due to the documented hydraulic relationship between the Gallikos River sediments and the underlying aquifer system, surface runoff contributes significantly to groundwater balance, and this is the main reason that domestic water needs of the city of Kilkis are covered by a well field located within the fluvial deposits of the Gallikos River, the same is true for the

well field that operated until recently for the domestic needs of the metropolitan area of Thessaloniki. Part of the summer-time base flow is used for the irrigation of cultivations along the river course.

Numerous springs of low potential emerge that discharge from the weathered zone of the crystalline rocks. Average discharge rates of these springs range between 5 and 30 m^3/day, according to a recent study conducted in the region [30]. Several springs emerge at the contact of the karstified limestones with the crystalline rocks, and according to the same study estimated discharge averages to 0.5–3 m^3/h. Spring water serves as a means for partial coverage of local domestic and animal breeding needs.

3.3.3. Groundwater Quality

The main aquifer of the basin is formed in the permeable sediments (Quaternary deposits), whilst the karstified carbonate rocks are also considered hydrogeologically important. On the contrary, the crystalline rocks only play a secondary role to regional water resources. The spatial distribution of the three identified aquifers of the basin is illustrated in Figure 7.

Results of 34 chemical analyses from representative samples of the three aquifer systems collected during the wet and dry periods of 2005 are presented in Table 2 in order to outline the chemical characteristics of each aquifer. These samples were considered as representative because—according to their lithological profiles—they capture water from one aquifer and not a complex of aquifers. During the field survey that was conducted in the time period of 2004–2005, a much greater number of the samples was collected. The following conclusions can be drawn.

Table 2. Summary statistics for concentrations of groundwater samples (min-max and mean value) from 34 samples.

Parameters	Aquifer of permeable sediments	Karst aquifer	Aquifer of crystalline rocks
pH	(6.24–8.00) 7.01	(7.29–7.89) 7.64	(6.56–7.82) 7.4
E.C. (μS/cm at 25 °C)	(786–3810) 1873.9	(447–790) 651.85	(282–1220) 756.55
Ca^{2+} (mg/L)	(72.1–308.6) 167.62	(76.3–96) 87.15	(60.1–138) 75.82
Mg^{2+} (mg/L)	(32–116.7) 60.65	(19.5–31.6) 26.05	(16–87.6) 53
Na^+ (mg/L)	(31–850) 158.17	(15–61) 28.8	(15–73) 50.22
K^+ (mg/L)	(1.9–28) 7.26	(1.2–22) 9.61	(6.3–45) 15.51
HCO_3^- (mg/L)	(280.7–524.8) 429.9	(305.1–366.1) 341.7	(122–561.4) 345.77
Cl^- (mg/L)	(56.7–1519.4) 342.8	(21.3–63.8) 41.04	(24.8–99.3) 67.76
SO_4^{2-} (mg/L)	(0–530.7) 114.9	(2.5–39) 19.85	(18.5–145.4) 65.02
NO_3^- (mg/L)	(0.7–88.3) 41.8	(12.2–25.9) 18.2	(0–52) 12.4
Total Hardness (mg/L $CaCO_3$)	667.6	324.6	407.9

High E.C. values are recorded in the Quaternary deposits aquifer at sampling point, which is located in an agricultural and industrial area (Figure 8). The groundwater quality of the karst aquifer is better than the other aquifers. The Ca(Mg)-HCO$_3$ water type is the dominant type in the basin. Nitrate concentrations in excess of the threshold value of 37.5 mg/L, which is 75% of the maximum admissible concentration of 50 mg/L set by the EU Council for drinking water, are documented on several occasions, especially in the shallow aquifer of the permeable sediments as is shown by the

contours in Figure 8 that were drawn using the kriging method. Nitrate sources are agricultural activities and sewage effluent through seepage from septic tanks. Increased concentration values of Na^+ and Cl^- due to human activities are recorded at the southern part of the basin (near Nea Philadelphia area). The maximum admissible values for Na^+ and Cl^- are 200 mg/L and 250 mg/L, respectively. The threshold value is 150 mg/L for Na^+ and 187.5 mg/L for Cl^-. The increased values of the aforementioned parameters lead to degradation of water resources making them inappropriate for certain uses, such as human consumption or irrigation. During the sampling period (2004–2005) textile dyeing factories were in operation. As it is shown in Table 2, exceedance of the maximum admissible values was recorded in the aquifer of the permeable sediments. The karstic aquifer seems to be of quite good quality.

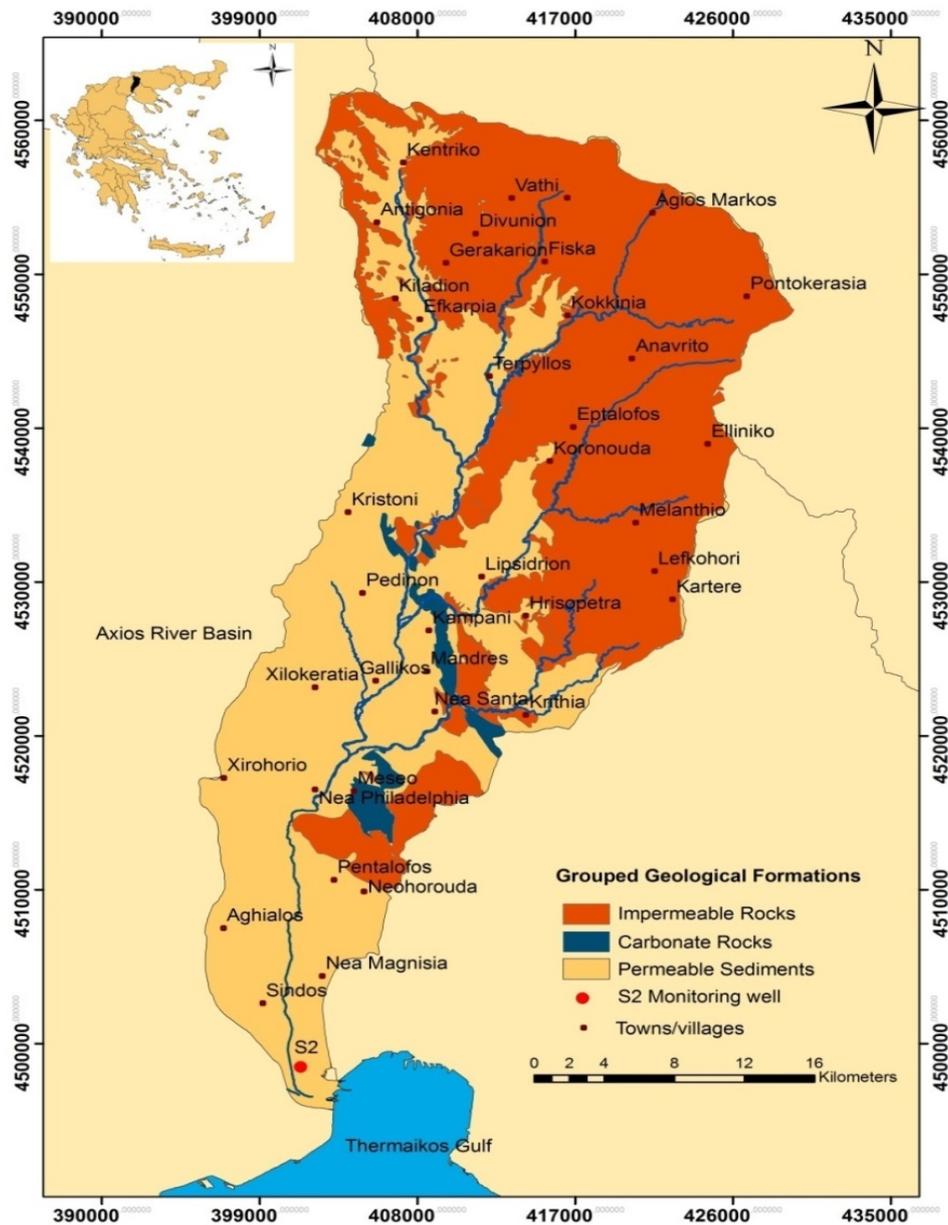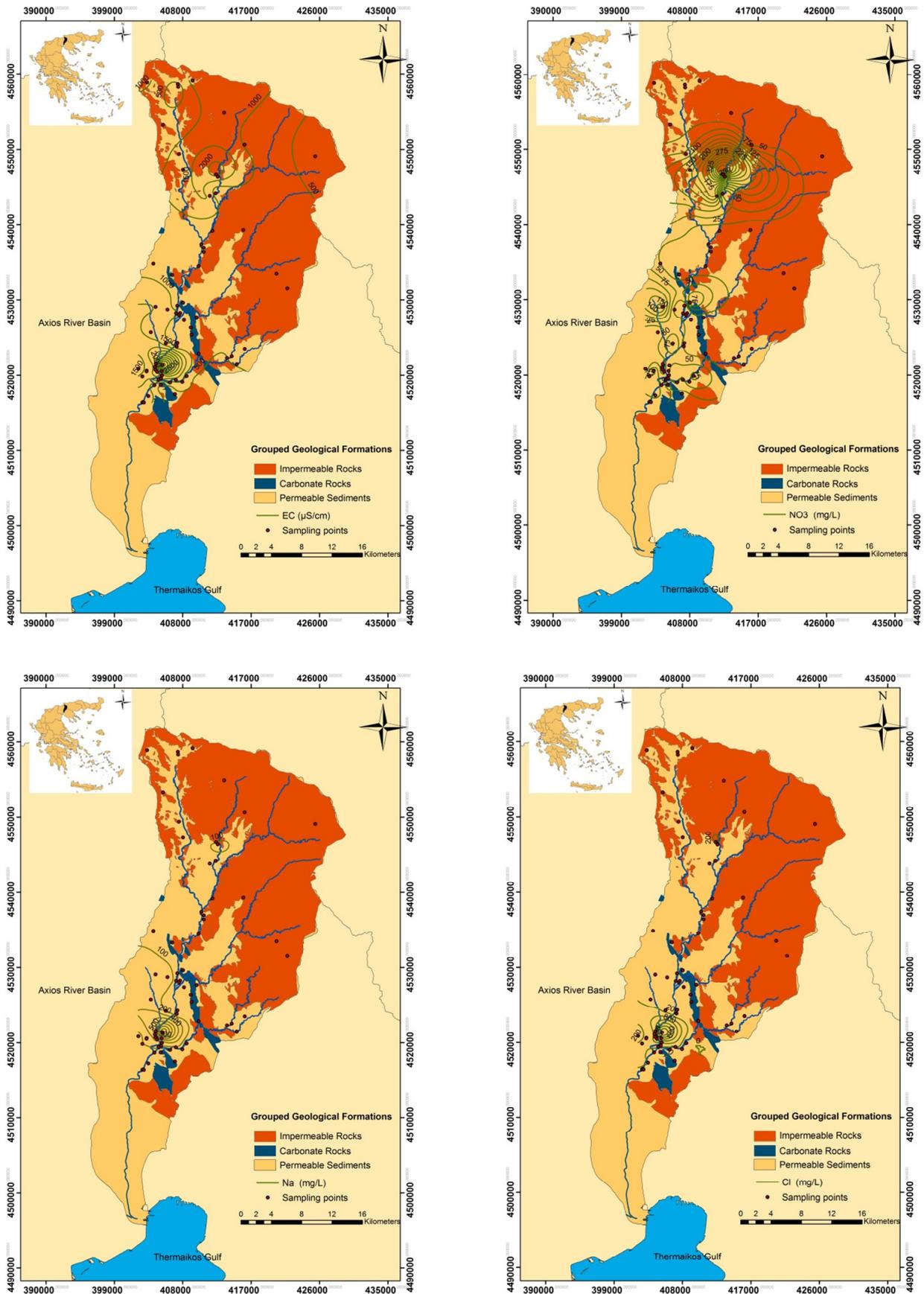**Figure 7.** Grouped geological formations in the Gallikos River basin.

Figure 8. Spatial distribution of electrical conductivity, nitrates, sodium and chloride for the upper part of the Gallikos River basin.

Groundwater is characterized by relatively low heavy metal concentrations. High concentrations of Fe and Mn are recorded in the crystalline rocks and are attributed to the lithological composition of the area. In some cases the values are over the maximum acceptable limit for drinking water, making the treatment of the water with the appropriate filters obligatory for the local authorities in order to meet the domestic needs.

The values of Dissolved Oxygen (D.O.) and Oxygen Saturation (%), which were determined *in situ*, are obviously lower than in surface water, and in general, they decrease proportionally to the distance of the wells from the river course. It is therefore suggested that [25] the uncontrollable discharge of untreated domestic and industrial effluent into the river leads to groundwater quality deterioration due to infiltration of water of the Gallikos River basin into the aquifer systems.

3.3.4. Groundwater Resources

According to the available data from the field survey that was carried out during the time period 2004–2006 for the upper part of the Gallikos River basin (from the mountainous area to Nea Philadelphia village) the general characteristics of the main aquifers are described below:

(1) Permeable Sediments Aquifer

The alluvial aquifer, defined by permeable sediments is being exploited through numerous shallow boreholes and large diameter wells that have been constructed along the courses of the Gallikos River and its tributaries in order to cover irrigation demands and the domestic needs of the city of Kilkis. The preference of that particular zone lays on the deposition of essentially coarse fluvial deposits along the river courses, namely intercalations of sands, gravels, pebbles and clays. On the one hand, these deposits favor infiltration of precipitation and deep percolation of river water and on the other hand, they are characterized by high water storage capacities (high storativitiy) and ease of groundwater withdrawal (high transmissivity).

In hydrologically dry years, many of these boreholes become dry over the peak water demand irrigation period. Groundwater level fluctuation between the dry (October) and the wet period (April) of the hydrologic year 2004 was 0.08 to 3.41 m. Similarly, for the year 2005, groundwater level fluctuation between the dry and the wet period was 0.13 to 8.84 m. The continuous groundwater water level decline causes major problems for the financial sustainability of the farmers, because it deteriorates the amount of their production, it restricts the type of crop that they can cultivate and forces them to spend money to ensure new water resources, mainly by drilling new boreholes, which is linked with considerable costs.

A well field for domestic water supplies to the metropolitan area of Thessaloniki exists at the area of Sindos and has a nominal operation capacity of about 10.5×10^6 m^3/year. Nowadays it acts as an auxiliary reserve. Since pumping was discontinued from this well field in the year 2004, a considerable groundwater head recovery is documented from borehole S2, as illustrated in Figure 9.
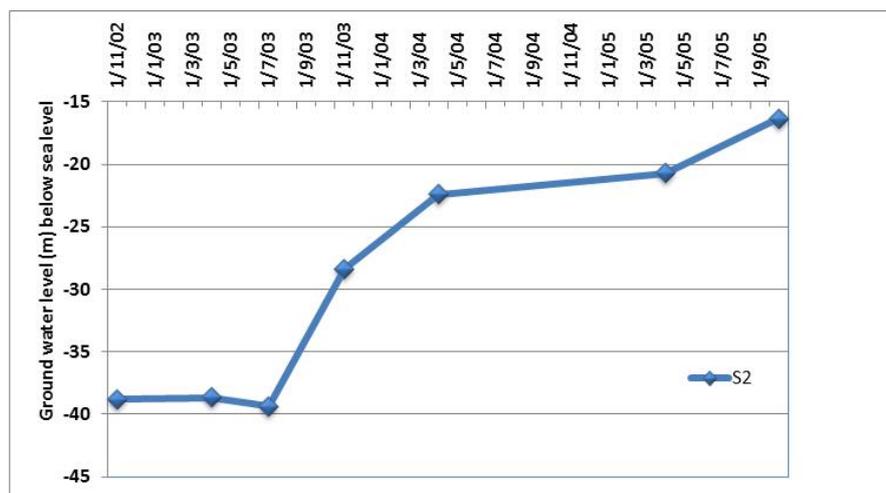
The exploitable dynamic groundwater reserve of the studied system (Q_{ed}) is calculated using the following equation:

$$Q_{ed} = A \times S_y \times l_d \tag{1}$$

where, A = effective area of groundwater recharge (km^2); S_y = specific yield; l_d = average water level decline (m) in dry period.

In the loose quaternary deposits aquifer that has an areal extent of 345 km^2, the mean annual groundwater level fluctuation is 1.15 m (from April 2004 to April 2005 a decline trend is observed). Assuming an average value of specific yield S_y = 0.09 [26,28], Equation (1) yields the annually exploitable groundwater reserves: $Q_{ed} = 345 \times 10^6 \text{ m}^2 \times 0.09 \times 1.15 \text{ m} = 35{,}707{,}500 \text{ m}^3 = 35.7 \text{ Mm}^3$.

Figure 9. Groundwater level fluctuation in the S2 monitoring well located in the Sindos area. Values represent absolute elevation relative to the mean sea level.

It should be mentioned that according to other studies the estimation of the annually exploitable groundwater reserves varies in respect to the available data and other assumptions. Kalousi [30] estimated the reserves to be approximately 4.4×10^6 m^3 for a different time period and different active area but did not take into consideration the area of the Gallikos River bank deposits.

(2) Karstic Aquifer

It is characterized by considerable resources and the production rate of the wells ranges between 40 and 90 m^3/h and the average value is 60 m^3/h. In the year 2004, groundwater level fluctuation between the dry and the wet period was 0.18 to 5.95 m. In the year 2005 groundwater level fluctuation between the dry and the wet period was 1.20 to 4.03 m. The effective recharge area of the karst system was 22 km^2. The average annual groundwater head decline is 1.88 m (from April 2004 to April 2005) and assuming an average specific yield value S_y = 0.1 [31,32], the annually exploitable groundwater reserves were estimated to be (Equation 1): $Q_{ed} = 22 \times 10^6 \text{ m}^2 \times 0.1 \times 1.88 \text{ m} = 4{,}136{,}000 \text{ m}^3 = 4.13 \text{ Mm}^3$.

The need to conserve the reserves of this aquifer is very important since it is the main supplier of water intended for human consumption.

(3) Aquifer of the Crystalline Rocks

The crystalline rocks that form the bedrock of the basin are normally classified as impermeable. Limited water reserves exist predominantly due to the secondary porosity of the weathered zone of these rocks. A limited number of large diameter wells and boreholes have been constructed to meet water demands mainly of the hilly and mountainous zones of the basin.

In the year 2004 groundwater level fluctuation between the dry and the wet period was 1.22 to 2.54 m. In the year 2005 groundwater level fluctuation between the dry and the wet period was 0.30 to 3.21 m. The effective recharge area was 505 km^2 and the average annual groundwater head decline was 1m (April 2004 to April 2005). Assuming an average specific yield value $S_y = 0.04$ [26,28], the annually exploitable groundwater reserves were estimated to be (Equation 1):

$$Q_{ed} = 505 \times 10^6 \text{ m}^2 \times 0.04 \times 1 \text{ m} = 20{,}200{,}000 \text{ m}^3 = 20.2 \text{ Mm}^3.$$

The estimation of the reserves of the crystalline rock aquifer poses significant error possibility, since the hydrogeological behavior and hydraulic characteristics of these rocks differ from place to place and the aquifers are of local interest. Table 3 lists the main hydrogeological characteristics of the identified aquifers of the Gallikos River basin.

Table 3. Hydrogeological characteristics of the Gallikos River basin aquifers. (A = effective area, D_{av} = average thickness, T = average transmissivity, K = average hydraulic conductivity, S_y = specific yield, Q_{ed} = exploitable dynamic groundwater reserves).

Aquifer	Geological formations	Hydraulic characteristics
Permeable sediments aquifer	Alluvial deposits; Sand-gravel-clay	$A = 345$ km^2 $D_{av} = 33$ m $K = 2.4 \times 10^{-4}$ m/s $T = 4 \times 10^{-3}$ m^2/s $S_y = 0.09$ $Q_{ed} = 54.33$ Mm^3/year
Karstic aquifer	Carbonate rocks	$A = 22$ km^2 $D_{av} = 76$ m $K = 2.4 \times 10^{-3}$ m/s $T = 2 \times 10^{-1}$ m^2/s $S_y = 0.1$ $Q_{ed} = 4.79$ Mm^3/year
Crystalline rocks aquifer	Crystalline rocks; Schists, quartzites, gneiss	$A = 505$ km^2 $D_{av} = 230$ m $K = 4.8 \times 10^{-6}$ m/s $T = 4 \times 10^{-4}$ m^2/s $S_y = 0.04$ $Q_{ed} = 26.05$ Mm^3/year

(4) Treated Domestic Effluent

The domestic effluent treatment plant of the metropolitan area of Thessaloniki operates in the area of Sindos and processes on average 200,000 m^3 of effluent daily. Normally, processed water is discharged to the sea (Gulf of Thermaikos) through a submerged pipeline. In addition a treatment plant that handles the industrial effluent of the adjacent industrial zone of Thessaloniki exists, and treated water is discharged to the sea via an open gravitational canal.

Long-term experiments have been conducted in the area, followed by extensive feasibility studies on the potential to utilize the treated domestic effluent of Thessaloniki to cover part of the irrigation needs of the homonymous basin where some 100,000 ha are being cultivated. The results of the

long-term experiments clearly suggest that rational and controlled application of this valuable resource would alleviate the water shortage problem leading to excellent results regarding crop yields [33].

In addition it would lead to the actual utilization of a considerable volume of essentially usable water, whilst in parallel it would be beneficial to the plants due to the rich content in nutrients and the growers due to the reduced requirements for fertilization. Indeed, over the summer of 2007 the severe drought conditions that led to prolonged water shortage over the plant growing period were successfully faced with the systematic and carefully controlled use of this resource in irrigation.

3.4. Impacts

Impacts are essentially focused on the well-being of humans. Within the study area, water is mainly used for domestic needs and for animal breeding and agriculture, the latter being by far the biggest consumer. Intensive and thoughtless fertilization results in aquifer pollution and renders groundwater improper for human consumption. Several municipalities already suffer from this effect, especially south of Kilkis and north of Nea Philadelphia according to primary data that were collected by the authors. Another side effect of the intensive agricultural practices is the overpumping that has as a result the reduction of the reserves. An increase of the karstic aquifer exploitation has been recorded in the recent years in order to cover the human consumption needs of the settlements that are located in the flat area. In other cases, such as in municipal compartments at the N-NE part of the basin (e.g., villages of Antigonia, Vathi, Pontokerasia, Terpillos), groundwater is improper for human consumption due to elevated concentrations of Fe and Mn that are attributed to the geological structure of the region. Although in the framework of the management by local authorities the water is treated using the appropriate filters, it is not always possible to achieve the desired effect. Hence according to residents, the water is sometimes slightly colored, has a faint smell or sometimes stains household items. In some cases treatment is not possible and water transfer takes place between the villages via a local network.

Shifting from rain-fed to irrigated farming will increase irrigation water demands, part of which are currently met by surface water from the Gallikos River, although this might lead to increased pollution incidents. Groundwater overpumping in recent years has led to river water drying, as reported in newspaper articles and posts on the internet. Abandonment of water consuming-crops and the use of efficient irrigation methods, such as drip irrigation, can lead to considerable reduction of groundwater abstractions for irrigation purposes that account for the highest percentage of used water resources. Utilization of treated waste effluent can contribute significantly to the reduction of groundwater use. Uncontrolled disposal of industrial effluent in conjunction with discharge of treated domestic effluent from the Sindos plant into the Gallikos River is bound to worsen eutrophication of the Gulf of Thermaikos.

3.5. Responses

Education of farmers on the implementation of European Laws and Directives on environmental protection and water resource management is a major issue. The importance of integrated water resources management is emphasized in the European Water Framework Directive (2000/60/EC), which, amongst other things, promotes new opportunities and view points for the sustainable

management of water resources. A major objective is to reach a good quantitative and chemical status of groundwater within 15 years from implementation. In response to this directive, Greek authorities have taken suitable initiatives to harmonize the Greek water policy [34]. It is pointed out that Greece is ranked among the last countries in relation to the implementation of the directive and is quite behind schedule compared to other European countries [35].

A comprehensive Code for Good Agricultural Practice (COGAP) has been compiled on the basis of the elaborated action plan for the wider study region. It addresses the effective reduction of nitrate groundwater pollution of agricultural origin through reduction and appropriate application of fertilization. This Code [36], includes specific rules and instructions for the periods of time during which fertilization should not be applied, on the application methodologies and doses at which fertilizers should be applied depending on the soil type and conditions, and also on the crop and the irrigation method adopted. Moreover, it informs about specific fertilization plans per plot and crop, taking into account, amongst other things, nitrate background concentrations in the groundwater [37].

COGAP also informs about the use of logbooks for fertilizer handling and application and also for land management. In parallel, set-aside and crop rotation practices are proposed. As clearly examined and suggested in the action plan compiled for the vulnerable area of the Imathia Prefecture, which is located in Central Macedonia Region, proposed fertilization schemes may lead to a 30%–40% or even higher reduction in the applied fertilizers per year, whilst at the same time maintaining maximum crop yields [38]. It therefore follows that environmentally friendly policies and measures do not necessarily imply economic destruction of farmers, or at least shrinkage of their income. On the contrary, presented data suggests that environmentally friendly policies may also result in the increase of the farmers' income by cutting down their operational costs. In the study area, the proposed fertilization as calculated in the framework of the compiled action plan varies from 30 to 340 kg/ha/year, with an average of 167 kg/ha/year, *i.e.*, a reduction from 62.5% to 3%, or 22% on average, depending on crop type and soil conditions, compared to the discussed required amounts of nitrogen fertilization.

The idea of reduction and appropriate application of fertilization sounds good in theory, but if it is not accompanied by financial incentives that will ensure the income of the farmers, such as subsidies, then it cannot be realistic. In this sense, experience from other parts of the country where a reward scheme with a strong financial element was applied, has shown quite promising results: fertilizer application was reduced up to 40% or even 50% and yields were maintained at high levels. It has to be stressed that in those occasions appropriate fertilization doses and application methods were dictated to participating farmers. A specific legislative framework exists for the protection of the coastal estuarine part of the basin. According to the Joint Ministerial Decision 14874/3291 [39], the areas of Gallikos estuary and the Kalochori lagoon were designated as ecological important areas to be protected.

The Thessaloniki water supply and sewerage company S.A. (E.Y.A.Th., Thessaloniki, Greece) has undertaken a major project supervised and funded by the Greek Ministry of Environment, Physical Planning and Public Works to assess the impact of groundwater artificial recharge by means of injection of treated domestic effluent into a confined aquifer via deep boreholes at the area of Sindos [40]. Recycled water potentially represents one important portion of the water resources for covering the increased water demands in the basin. The reuse of treated waste will be diverted for artificial recharge and recovered to be used for irrigation or industrial use.

Furthermore, groundwater artificial recharge using the large volumes of winter-time runoff that are currently being discharged to the sea, is a well-documented method to initially delay aquifer mining and progressively achieve its replenishment and restoration.

Replacement of obsolete domestic water networks in order to reduce current losses, utilization of the mountainous zone springs, and informative campaigns to sensitize citizens to rational water use are only some extra measures in the framework of rational and sustainable management of water resources at the basin scale. Last year, the Greek State proceeded in licensing rights for existing water use, even for boreholes operating illegally. As part of this procedure the installation of flow meters will become mandatory. Depending on the registered crop, a maximum amount of water for irrigation will be allowed. Water pricing is a key issue in protection and restoration of water resources. Appointment and operation of landfill sites and appropriate waste effluent treatment and utilization instead of simple discharge into the local rivers and torrents would also contribute to groundwater quality restoration.

It is very important that the authorities and stakeholders that are involved in water resources management have clear responsibilities without overlaps that lead to an increased complexity of the decision system. It is also of major importance that the authorities—especially local authorities that are directly involved in the issue—have the power and the ability to control the implementation of the decisions and to impose penalties when violations are detected. Unfortunately, until recently, local authorities did not have this ability, and regional actors showed great reluctance in enforcing established regulations and acts regarding water resources management and environmental protection.

4. Discussion and Conclusions

In the case of the Gallikos River basin, application of DPSIR enabled the identification of the main driving forces and their direct effects on the studied system, it allowed a facilitated linkage of these with the state of the system and the identified impacts, thus in the end making it possible to suggest easier, comprehensive and focused measures in the framework of rehabilitation and protection of the system. There are two main issues to be addressed. The first is the degradation of the quality of water resources due to the untreated waste disposal and nitrate pollution resulting from anthropogenic activities. The second issue is in regard to the groundwater reserve reduction due to overpumping in order to cover the demands of any kind of activity (domestic, industrial, agricultural) in the basin. The water resource degradation has impacts on human well-being. The insufficient presence of state or regional control mechanisms and the lack of available data, as there is no network for systematic water resource measurements, have led to an ineffective and late response of the authorities. In current days things are worsening in this direction. The poor economic conditions of Greece do not favor efforts in the direction of protection and restoration of the environment, since priorities have changed and such efforts are considered a "luxury''. Despite the difficulties, some of the following actions are proposed. Some of these actions have already been implemented but they need to be implemented in a more systematic way:

(a) Programmed–precision irrigation, which will both reduce the volume of water thoughtlessly used for agriculture whilst at the same time optimally covering the irrigation demands. Appropriate irrigation water pricing policies, which are in-line with the guidelines set by the Water Framework Directive. Further reduction could be achieved through crop restructuring patterns in the framework of

the new Common Agricultural Policy (CAP), opting for less water-consuming crops that at the same time present a high added value to the producers, accompanied by subsidies that will cover the cost for the substitution of the crops and probably the income losses of the farmers.

(b) Optimized fertilization based on detailed knowledge of the soil characteristics and the crop needs may also dramatically reduce the pollutant loads whilst at the same time improving the competitiveness of the crop production through reduced production costs. To this end, a Code for Good Agricultural Practice (COGAP) has been compiled and specific fertilization plans have been issued.

(c) Improved management of livestock units shall only benefit the environment and the annual turnover from this activity. Proper management of manure and its subsequent utilization as a fertilizer will minimize health risks to the livestock, improve their breeding conditions and hence improve the turnover of the breeding units, minimize potential point pollution to the water receptors of the basin and cut down on the fertilization costs of crops in the region.

(d) Appropriate treatment and management of livestock breeding, industrial and domestic effluent can also turn into an asset for the region, both in terms of water resources and also nutrient source for agriculture, whilst in parallel safeguarding the environment. Dramatic improvement in the operation of the existing effluent treatment plants that operate in the region has been achieved over the past decade to ensure that such point pollution sources are progressively eliminated. Reuse of treated domestic effluent is has proven to be a viable solution to crop irrigation in the region, capable of addressing prolonged droughts whist also partially accounting for the nutrient needs of the plants. Hence, such practices are nowadays promoted through the regional government and are well-governed by legislative acts.

(e) Progressive abandonment of uncontrolled landfills to properly managed domestic waste sites is also under way in the region, thus reducing the number of potential point pollution sources of domestic origin.

It is important that these actions are realistic, since they do not always increase costs, but some of them are a matter of proper management and policy drawing. Many of the proposed action have been adopted by the Greek state and some have been adapted from European policies.

Rationalization of water and land use through the above discussed suite of measures has already been applied in the region exhibiting signs of recovery of the system in terms of quality and quantity characteristics. Signs are more apparent so far in the soil resources of the region based the systematic surveys carried out in the framework of the Nitrates Directive implementation in the region. The extensive depression cone and salinization fronts documented at the southern margins of the basin as a result of groundwater over-exploitation are not yet recovered. This phenomenon evolved over a long period of time and, based on international experience, will take several decades to be restored. Undoubtedly, some of the impacts of the miss-management are non-reversible, such as the extensive subsidence along the coastal zone; however it is imperative and feasible that it be avoided that the phenomenon evolves further.

Identification of key drivers and pressures to the studied basin enables structuring and adoption of the appropriate measures towards alleviation of the impacts it suffers, and overall protection of the studied system. The proposed suite of measures is not only seen as a means to protect the system and

attempt to restore it to its prior good state, but also as a guarding shield in the direction of preparedness and adaptation to climate changes.

DPSIR technique in a GIS environment is a valuable tool that contributes to the integrated appraisal of environmental and socio-economic pressures and their effects on the water resources at the basin scale. It provides a common basis of understanding and encoding of valuable information that can be easily conceived and reviewed in the framework of strategic planning and evaluation. This way, it enables direct correlation to adjacent basins, or comparative studies of the same basin at various points in time, whilst at the same time contributing to effectively designing and implementing site and problem specific measures towards protection and restoration of a given hydrogeological environment.

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Author Contributions

Christos Mattas collected the data and applied the methodology in collaboration with the other authors. He also constructed the maps in geographic information system (GIS) environment. Konstantinos Voudouris proposed the conceptual framework of the paper and evaluated the data. He also checked the results and enhanced the writings of the paper in collaboration with Andreas Panagopoulos.

Conflicts of Interest

The authors declare no conflict of interest.

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