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Linking DPSIR Model and Water Quality Indices to Achieve Sustainable Development Goals in Groundwater Resources

Dimitrios E. Alexakis

Laboratory of Geoenvironmental Science and Environmental Quality Assurance,
Department of Civil Engineering, School of Engineering, University of West Attica, 250 Thivon & P.Ralli Str.,
12241 Athens, Greece; d.alexakis@uniwa.gr; Tel.: +30-210-5381256

Abstract: The achievement of sustainable development goals in groundwater resources related to water quality issues is a critical question in many regions. This study aims to combine powerful tools for helping stakeholders and policymakers achieve sustainable development goals in groundwater resources of agricultural areas. The DPSIR (Driver–Pressure–State–Impact–Response) model in combination with the Canadian Council of Ministers of Environment Water Quality Index and Groundwater Directive 2006/118/European Community—Threshold Values was applied using a hydrogeochemical dataset derived from the analysis of groundwater samples collected from 31 monitoring sites in an unconfined alluvial aquifer. Elevated Cl^- (up to 423.2 mg L^{-1}), $NO_3{}^-$ (up to 180.1 mg L^{-1}) concentration and electrical conductivity (up to 2037 μS cm^{-1}) value are observed for groundwater samples of the study area. The outcome of the "One Out-All Out" procedure revealed that the groundwater in 42% of the monitored sites is unsuitable for drinking according to the health-based guideline values established by Directive 98/83/European Community. A difficulty to achieve targets under Sustainable Development Goals 3 and 6 in the study area is revealed. The proposed response actions are reported.

Keywords: DPSIR; WQI; SDG; sustainability; water quality; nitrate contamination; Peloponnese; Greece

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1. Introduction

All countries have to achieve sustainable development goals (SDGs) as introduced by Agenda 2030 [1]. The SDGs include, among others, the protection of water resources and prevention of pollution for water intended for human consumption, hygienic uses, irrigation uses, industrial uses or other purposes. Water quality is crucial for achieving sustainable development goals, as introduced by Agenda 2030 [1]. Water quality and quantity issues are directly related to socio-economic development and sustainable development goals (Goals 3 and 6) as presented by Agenda 2030. Goal 3 is on ensuring healthy lives and promoting well-being for all at all ages [1]. Goal 6 is on ensuring availability and sustainable management of water and sanitation for all [1]. Water quality issues are included in the SDGs as Target 6.3 [1]: until 2030, improve water quality by (a) reducing pollution; (b) minimizing release of hazardous materials and chemicals and eliminating dumping; (c) halving the proportion of untreated wastewater; and (d) increasing recycling and safe reuse.

Pressure on the environment and ecosystems has been compounded mainly by the intensive agricultural activities and rapid growth of the economy, resulting in soil and water resources degradation, which significantly limit sustainability. The Driver–Pressure–State–Impact–Response (DPSIR) model state how socio-economic development influences the environment and indicates the associations between environmental, economic and social "causes-effects" [2,3]. The DPSIR model has also been commonly applied to investigate environmental systems' connection processes [4]; where communities, economies and cultures operate as drivers (D) that produce pressure (P) on ecosystems and the environment, which may affect the status (S) of the environment and thus impact (I) it [3]. The related impacts subsequently encourage scientists, policymakers and stakeholders to respond (R) indirectly or directly to the environmental status [3]. In order to generate a clear picture of threats against soil and water resources, many researchers have applied the DPSIR model [5–12]. Recent developments in the application of the DPSIR framework include research topics related to: (a) a pressure-oriented water quality monitoring approach to ecological river restoration [5]; (b) the support of water governance [6]; (c) integrated analysis of the eutrophication process in a water reservoir [7]; (d) an investigation of the drivers related to agricultural activities leading to nitrogen pressures on water [8]; (e) identification of socio-ecological stressors affecting aquatic ecosystems in semi-arid countries [9]; (f) a sustainability assessment of water resources in Beijing (China) [10]; (g) implementation of a comprehensive evaluation model of regional water resource carrying capacity [11]; and (h) the evaluation of hydrologic characteristics of streamflow [12].

According to Song and Frostell [5], the DPSIR approach contributes to the systematic exploration of the links between water-related impacts on ecosystems and socio-economic drivers. Moreover, they reported that an ecology-based pressure-oriented water quality monitoring system might contribute to restoration plans and water quality management [5]. The DPSIR framework is also applied to quantify the importance of various water quality factors in reservoirs and propose mitigation measures [7].

Groundwater resources play a crucial role in human well-being, food production and socio-economic development. Many researchers reported that deterioration of groundwater quality is a common issue worldwide, mainly attributed to geochemical processes, overexploitation, extensive use of fertilizers and other anthropogenic activities [13–27]. Moreover, Water Framework Directive [28] aims to promote sustainable water use by fixing quality objectives for surface water and groundwater resources. The increasing demand for water in Mediterranean and Middle East countries will threaten the achievement of SDGs in groundwater resources [29,30].

Various land uses and anthropogenic activities in the study area contribute to regional variation in sustainable development efficiency. The increased water demand for irrigation purposes and intensive application of fertilizers in the cultivated areas of Troizina basin could lead to apparent threats against rural sustainable development efficiency. Therefore, the formulation of sustainable development strategies for stakeholders in the Troizina basin should address the questions mainly related to the mass of fertilizers used in the cultivated areas and the water volume abstracted from the wells. The outcome of this study will contribute to the international database of investigations on groundwater quality assessment based on the DPSIR model and water quality index. Moreover, the results of this research study may be helpful for scientists and stakeholders monitoring agricultural areas. The primary objectives of this study are to present a DPSIR-WQI framework for the specific issue of groundwater resources of an alluvial aquifer and propose responses to achieve SDGs in groundwater resources. The novelty of this research study lies in the use of a combination of DPSIR model and water quality indices for sustainable development management of groundwater resources in intensively cultivated areas. No other previous studies are attempting to combine the DPSIR model, water quality indices and spatial analysis to achieve sustainable development goals in groundwater resources to the best of the authors' knowledge.

2. Methods

2.1. Study Area

The study area is located in Troizina basin (southeast Peloponnese, Greece) and lies within the coordinates 37°29′ N to 37°33′ N latitude and 23°17′ E to 23°27′ E longitude (Figure 1).

Figure 1. Map showing the location of the area studied (modified from [31]).

Based on the Köppen–Geiger climate classification [32], the study area is characterized by a Temperate-Dry-Hot Summer climate, which belongs to Csa type, where at least one month's average temperature is above 22 °C, the temperature of the hottest month is above 10 °C and the average temperature of the coldest month ranges from 0 to 8 °C [32]. The rainfall of the driest month is up to 40 mm and is less than 33% of the rainfall in the wettest month [32]. The relief in the study area is quite plain with hills. The Troizina basin is drained by three seasonal streams that join the sea along to the Epidavros Gulf coast, five seasonal streams that enter the sea along to the coast of Saronic Gulf and one seasonal stream that joins the Psifta lagoon (Figure 2).

The geology of the area studied is mainly composed of alluvial formations, flysch sediments, limestone bodies within the flysch, limestones, mixed volcanic series and serpentinites [33] (Figure 2a). Mixed volcanic series consists of diabases, locally with pillows, tuffs and tuffites, small serpentinite lenses and thin-bedded radiolarites [33]. The alluvial formations belonging to the Quaternary period cover a significant part of the area studied, which according to Fytikas et al. [33], include sand, loam, loose material, pebbles and conglomerates. The thickness of the alluvial formations in the central part of the study area is estimated as higher than 100 m, decreasing to 30 m towards the western and eastern part of the study area [34]. Alluvial deposits constitute an unconfined aquifer, which is the most important aquifer of the area studied. The flysch sediments consist of marls (usually reddish or greenish near the base), sandstones, breccias and conglomerates [33]. The thickness of the flysch sediments is higher than 1000 m [33]. The impermeable flysch components (marls and silts) are the basement rock beneath the alluvial deposits. The impermeable flysch components drive groundwater from south-southwest to north-northeast, discharging into the Epidavros Gulf and Saronic Gulf (Figure 2a). According to Bezes [34], the bottom of the Quaternary alluvial aquifer is reached at altitudes below sea level. The high transmissivity values control the groundwater flow path through the alluvial aquifer of the study area. Transmissivity (T) values from five pumping tests conducted in the alluvial aquifer of the study area ranged from 864 to 6048 m^2/day [34]. The unconfined Quaternary alluvial aquifer is connected along its length by six ephemeral streams (Figure 2a). The recharge processes of the alluvial aquifer of the area studied involve (a) water infiltration from the precipitation and six ephemeral streams; and (b) water from lateral recharge of the flysch sediments (Figure 2a).

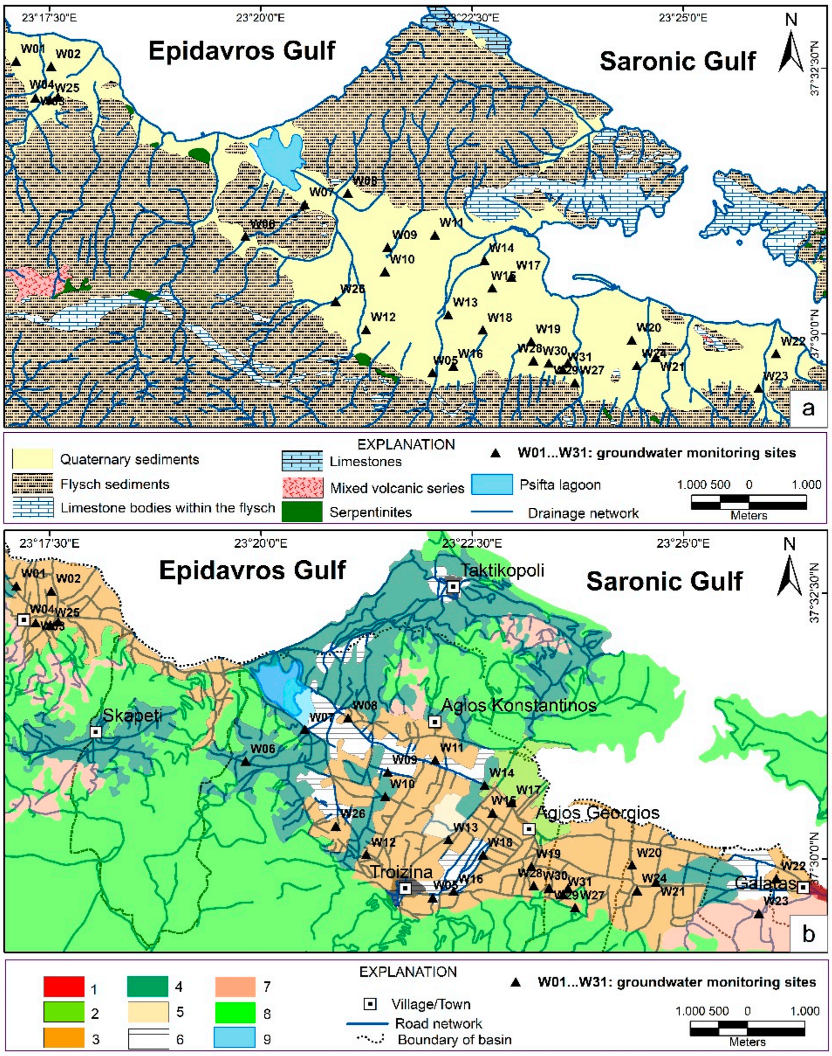

Figure 2. Map showing study area and groundwater monitoring sites compared with (**a**) geology and (**b**) land use [(1) urban fabric, (2) non-irrigated arable land, (3) fruit trees (orange trees, citrus trees), (4) olive groves, (5) annual crops associated with permanent crops, (6) complex cultivation patterns, (7) agricultural land, (8) shrubby and/or herbaceous vegetated areas, and (9) Psifta lagoon].

The land in the study area is characterized by intensive agricultural activities, especially the cultivation of olives, vegetables, flowers, establishments of greenhouse cultivation of carnations, citrus and orange fruit trees that take place in the study area where the application of nitrogenous fertilizers is very intensive (Figure 2b).

2.2. DPSIR Model

The DPSIR (Driver–Pressure–State–Impact–Response) model was developed by OECD [35] and illustrates a causal chain of the drivers (D) that concern the underlying needs of the society and economy (e.g., food production). The DPSIR approach has been extensively applied for investigating environmental issues emanating from anthropogenic activities [18,36–39]. According to Kristensen [39], the DPSIR approach is powerful in delineating the relationships between the consequences and the apportionments of environmental issues. The pressure (P) results from meeting a need (e.g., compound emissions, contaminants). The changes in the chemical, physical or biological state of the environment have impacts (I) on human health, ecosystems and socio-economic aspects.

The state (S) of the environment is affected by pressures and reflects the combination of physical, geochemical, chemical and biological conditions. Evaluating the potential ability of selected responses (R) aims to prevent adverse impacts on natural resources (e.g., type of irrigated crop, irrigation technology). The DPSIR approach in this study aims to link data from the studied aquifer with the proposition that human activities have contributed to groundwater contamination.

Table 1 shows the outputs of the DPSIR framework analysis with a set of indicators focused on achieving sustainable development goals in groundwater resources of an agricultural area. Furthermore, Table 1 tabulates the information, which includes the basis for the discussion in Sections 2.2.1–2.2.5 regarding the steps in the DPSIR model.

Table 1. Set of indicators for each DPSIR index focused on achieving sustainable development goals in groundwater resources of an agricultural area.

Indicator	DPSIR Index
Total population	D
Agricultural land	D
Livestock activity	D
Water consumption	D
Fertilizer consumption	D
Water demand	P
Compounds emissions from agriculture	P
Compounds emissions from livestock	P
Maximum concentration of Cl^- in groundwater	S
Maximum concentration of Na^+ in groundwater	S
Maximum concentration of NH_4^+ in groundwater	S
Maximum concentration of NO_2^- in groundwater	S
Maximum concentration of NO_3^- in groundwater	S
Maximum concentration of SO_4^{2-} in groundwater	S
Maximum value of electrical conductivity in groundwater	S
Hydrogen ion concentration (min and max) in groundwater	S
Maximum Water Quality Index (WQI) value	S
Higher WQI class	S
Higher Groundwater Directive (GWD) 2006/118/EC threshold value (TV)	S
Percentage of wells whose water is unsuitable for drinking	I
Percentage of wells whose water is classified into "marginal-poor"/"poor" category	I
Difficulty to meet Goals 3 and 6	I
Seawater intrusion	I
Groundwater monitoring (quality and quantity)	R
Policies to control compounds emissions	R
Managed aquifer recharge	R

2.2.1. Drivers

The drivers (D) considered in this research study were associated with hydrogeologic and socio-economic factors that wield indirect or direct pressures on groundwater resources. Especially, population, tourist offers in terms of the number of beds, agriculture and livestock rearing were considered in this approach.

2.2.2. Pressures

Pressure indicators (P) included parameters that could directly affect the groundwater quantity and quality, such as fertilizers, piles of livestock excrements, and water demand. Nitrate-nitrogen (NO_3^--N), phosphorous (P), electrical conductivity (CND) and pH participates as applicable water quality indicators in the following SDGs [40]: (a) zero hunger (SDG 2); (b) good health and well-being (SDG 3); (c) clean water and sanitation (SDG 6); (d) affordable and clean energy (SDG 7); (e) climate action (SDG 13); and (f) life on land (SDG 15).

2.2.3. State

Sixteen water quality parameters of the alluvial aquifer were monitored to evaluate the state (S) of the groundwater. Thirty-one groundwater samples were collected from wells distributed over an area situated in the Argolis Peninsula (Peloponnese, Greece) (Figure 1). Water samples were gathered from an unconfined alluvial aquifer, the primary local irrigation water source. All possible precautions were taken during the collection and handling of samples to minimize contamination. Preservation, preparation and chemical analysis of water samples were implemented, applying the procedures to treat water samples described by Alexakis [15]. The CND, pH, and total dissolved solids (TDS) were determined immediately after collection. The samples were stored in 1000 mL pre-cleaned polyethene bottles, kept in an air-tight plastic portable cooler at 4 °C and transported to the laboratory within 24 h for further treatment. Then, samples were vacuum filtered with 0.45 μm pore size membrane filters and placed in 5 mL vials for dissolved ions analysis. Ammonium (NH_4^+), chloride (Cl^-), nitrate (NO_3^-), nitrite (NO_2^-), fluoride (F^-), bromide (Br^-), sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}) and lithium (Li^+) were measured by an ion chromatography system (IC; ICS-3000 system, Dionex, Thermo Fisher Scientific, Waltham, MA, USA). Bicarbonate (HCO_3^-) was determined by applying a digital titrator (HACH, Loveland, CO, USA). The precision and accuracy of results were assessed using replicate analysis of blanks, standards and certified in-house reference materials for water testing.

The merging of a vast amount of water quality data into a single value is the main benefit of the WQI, contributing to the rigorous and rapid evaluation of groundwater resources and, consequently, their chemical status. Canadian Council of Ministers of Environment Water Quality Index (CCME-WQI) [41,42] and the Groundwater Directive 2006/118/EC-Threshold Values (GWD-TV) [43] approach were applied for assessing the groundwater quality of the Quaternary alluvial aquifer of the study area. The CCME-WQI is calculated depending on selecting appropriate water quality parameters to produce a single number varying between 0 and 100, with 100 denoting “excellent” quality [41,42]. A freely available software code developed by CCME is applied for the calculation of the CCME-WQI score, which classifies the water quality status into the following categories: “poor”, “marginal”, “fair”, “good”, and “excellent”. The Groundwater Directive 2006/118/EC-Threshold Values (GWD-TV) procedure is applied to assess the chemical status of groundwater resources. According to GWD-TV, the chemical status of groundwater resources can be classified as “poor” and “good”. Threshold values (TV) for the water quality parameters following the approach set out in Groundwater Directive (GWD) 2006/118/EC proposed by the Hellenic Republic were used in this study [44]. The water quality parameters used for the calculation of CCME-WQI and GWD-TV classes and the associated criteria are the following: Cl^- (250 mg L^{-1}), NH_4^+ (0.50 mg L^{-1}), NO_2^- (0.50 mg L^{-1}), NO_3^- (50 mg L^{-1}), SO_4^{2-} (250 mg L^{-1}), CND (2500 μs cm^{-1}) and pH (6.5–9.5). The relation of each calculated CCME-WQI and GWD-TV variable value is tabulated in Table 2. A more detailed description of the application of WQI for the evaluation of groundwater resources is discussed by Alexakis [13,14].

Table 2. Harmonization of CCME-WQI classes to GDW-TV classes based on guidelines provided by CCME [41,42] and European Community [43,44].

		Class	**1**	**2**
CCME-WQI		Rating	marginal-poor	excellent-good-fair
		Range	0–64	65–100
GWD-TV	Units	Rating	poor	good
Cl^-	mg L^{-1}	Range	>250	<250
NH_4^+	mg L^{-1}		>0.50	<0.50
NO_2^-	µg L^{-1}		>0.50	<0.50
NO_3^-	mg L^{-1}		>50	<50
SO_4^{2-}	mg L^{-1}		>250	<250
CND	µS cm^{-1}		>2500	<2500
pH	-		<6.5 or >9.5	6.5–9.5

2.2.4. Impact

The impact (I) of anthropogenic activities on the groundwater resources was determined as the percentage of alluvial aquifer wells whose water is unsuitable for human consumption based on parametric values established by the Directive 98/83/EC [45] or is classified into "marginal-poor"/"poor" category based on the CCME-WQI [41,42] and GDW-TV [43] evaluation procedures. The suitability for drinking purposes from the 31 monitored wells was evaluated as a function of the values observed for the parameters Cl^-, NH_4^+, NO_2^-, NO_3^-, SO_4^{2-}, CND and pH. The "One Out-All Out" (OOAO) procedure imposed by the WFD [28] selects the worst quality of water evaluated by different parametric values given by the Directive 98/83/EC [45].

2.2.5. Responses

Any proposed responses should improve both the quantity and quality of groundwater of the area studied. The proposed responses should mainly include policies to control pollution (e.g., reduction in the usage of fertilizers), agricultural policies, management plans for water abstraction and groundwater monitoring of quantity and quality.

2.3. Data Treatment

The statistical software code IBM® SPSS v.26.0 (International Business Machines Corporation; Statistical Product and Service Solutions; Armonk, NY, USA) was applied for studying the geochemical dataset of the groundwater. The univariate descriptive statistics of the geochemical dataset of the alluvial aquifer were calculated.

2.4. Linkage between DPSIR Model, WQI Values and Spatial Analysis

Since WQI is an efficient and helpful tool to reflect water quality, its integration with the state (S) may improve the application of the DPSIR model to monitor an aquifer. The calculated WQI values were grouped into three classes considering guidelines provided from the literature [43,44]. The Geographical Information System (GIS) interface ArcView 10.4 (ESRI®-Environmental Systems Research Institute; Redlands, CA, USA) was used for spatial analysis of the data. A satellite image of Greece obtained from Google Earth® [31] was inserted as a basemap in the spatial database. A topographic map at a scale of 1:50,000 issued by the Hellenic Army Geographical Service (H.A.G.S.) covering the study area and including the monitoring sites was scanned. Geological formations were obtained by digitizing the scanned and georeferenced geological map at a scale of 1:50,000 (sheet "Methana") published by the Institute of Geology and Mineral Exploration-IGME [33]. The topographic and geological map required referencing to the region coordinates according to the Hellenic Geodetic Reference System 1987 (HGRS87). The images of topographic and geological maps were incorporated into the spatial database as the basic layers showing the drainage network, boundary of the basin, road network, villages, towns and lithology.

The image of the georeferenced geological map is digitized to create polygon layers representing the location of lithological formations. Types of land use were obtained from the CORINE/Land cover Copernicus program [46] and inserted as a separate polygon layer into the GIS database. The developed GIS database was used for processing, analyzing and presenting the spatial analysis output. The calculated GWD-TV and CCME-WQI classes were projected on the digital map using the tool of column charts. The developed maps indicated the spatial distribution of water quality parameters with continuous numerical values using the tool of graduated symbol plots.

3. Results and Discussion

3.1. Drivers

The DPSIR and WQI framework adopted in the investigation of causal interrelationships for the alluvial aquifer of the Troizina basin is presented in Figure 3. The area studied has a total area of about 85 km^2 and 6507 inhabitants [47]. The major part of the area studied is used for agriculture (Figure 2b). The tourist offer is considerably low and includes 332 tourist beds in five accommodation structures [47]. Agriculture activity is carried out intensively in the study area and corresponds to the most critical pillar of the local economy. Livestock activity in the study area is mainly based on sheep/goat/pig farming.

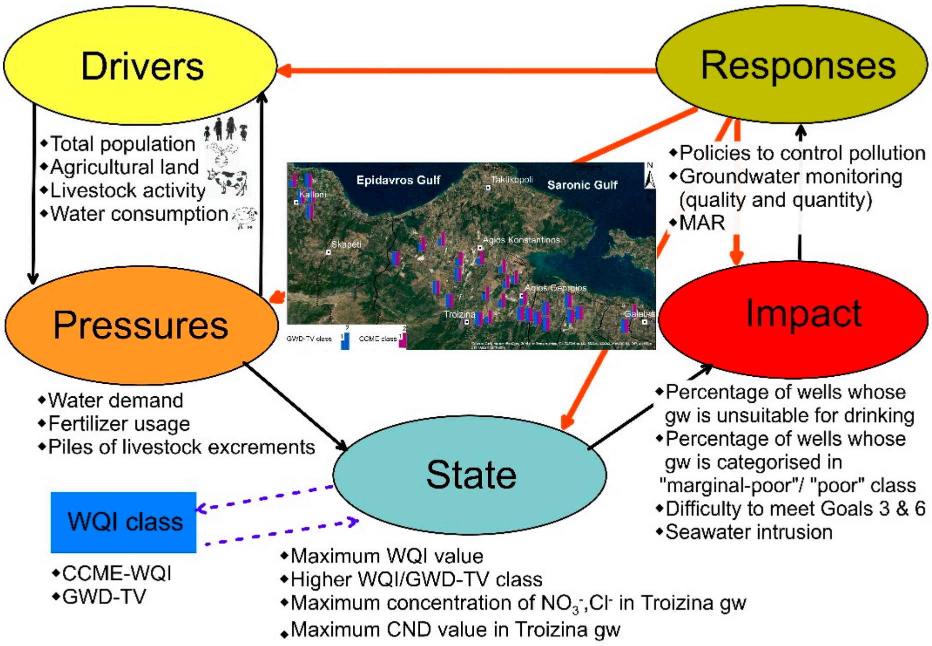

Figure 3. The DPSIR and WQI framework adopted in the investigation of achievement SDGs for groundwater resources of the area studied (MAR: Managed Aquifer Recharge, gw: groundwater).

3.2. Pressures

Annual withdrawals in the Troizina basin are distributed as follows: 5.7 × 10^6 m^3 for irrigation, 0.087 × 10^6 m^3 for livestock farming and 1.3 × 10^6 m^3 for drinking water supply [47]. The utilized agricultural area is mainly given over to arable land (6.11 × 10^3 m^2), cultivation of vegetables (1.04 × 10^3 m^2), vineyards (199 × 10^3 m^2), permanent crops (55.26 × 10^3 m^2), consisting mainly of orange fruits, citrus fruits and olive trees [47]. The total irrigated area in the Troizina basin is 10.24 × 10^3 m^2), and the total annual water demand for irrigation is 27.7 × 10^3 m^2 [47], while the total annual water volume abstracted for irrigation is 47.96 × 10^3 m^2 [33]. Agricultural activities are often a stress producer for an alluvial aquifer, not only for the size of its water consumption compared with drinking purposes, but also for the impact of agrochemicals utilization on groundwater quality [48,49]. The information about the amount of fertilizers applied in the Troizina basin is not available.

Piles of animal waste deposited in the proximity of poultry farms were reported in the Troizina basin [47], suggesting another diffusion source of nitrate contamination. The primary contaminants released from animal farming activity are nitrogen, phosphorous and organic load. The main issue related to animal farming is sludge spreading, which is directly applied to cultivated areas. Sometimes the animal manure is used for the fertilization of cultivated areas. The animal farming in the study area includes the following numbers of animals: (a) 81 horses; (b) 28 bovine; (c) 426 pigs; (d) 18,200 sheep and goats; (e) 870 rabbits; and (f) 7618 poultries [47]. Though data on the animal farms' spatial distribution is not available, only the diffuse pollution load from the total number of animal farms of the Argolis district can be estimated. The diffuse pollution load originated from Argolis district corresponds to total nitrogen (TN) [47]: 268.9 t/year and total phosphorous (TP): 144 t/year. The exerted pressures from livestock are the following (kg/day/1000 kg of alive animal) [47]: (a) bovine 0.36, 0.044 and 0.125 for TN, TP and TK, respectively; (b) pigs 0.39, 0.044 and 0.083 for TN, TP, and TK, respectively; (c) 0.99, 0.336 and 0.291 for TN, TP and TK, respectively; and (d) sheep and goats 0.47 for TN.

The pressures generated by driving forces affect the alluvial aquifer of Troizina in the following ways (Figure 3): (a) contaminating by NO_3^-; (b) contaminating by Cl^- and SO_4^{2-}; and (c) increasing CND values.

3.3. State

Table 3 tabulates the water quality parameters determined in the examined water samples. It should be mentioned that only the water quality parameters for which a parametric value is established by Dir.98/83/EC [45] are considered as indicators of state (S) for the proposed approach applied in this study (Tables 1 and 2). Lithium, NH_4^+, NO_2^-, and PO_4^{3-} in all analyzed groundwater samples presented concentration lower than the corresponding detection limit (Table 3).

Table 3. Water quality parameters determined in groundwater samples collected from wells located in the study area (DL: Detection Limit; CND: Electrical Conductivity; PV: Parametric Value [45]).

	Units	DL	N	Min	Mean	Median	Max	PV
Br^-	$\mu g\ L^{-1}$	0.01	5	0.2	0.5	0.4	0.8	_
Ca^{2+}	$mg\ L^{-1}$	0.05	31	46.1	128.6	118.9	240.0	_
Cl^-	$mg\ L^{-1}$	1.0	31	21.0	80.5	42.3	423.2	250
F^-	$mg\ L^{-1}$	0.05	2	0.1	0.3	0.3	0.4	
HCO_3^-	$mg\ L^{-1}$	1	31	207	283	286	361	_
K^+	$mg\ L^{-1}$	0.05	31	0.5	1.2	1.0	3.7	_
Li^+	$\mu g\ L^{-1}$	0.1	31	_	_	_	<0.1	_
Mg^{2+}	$mg\ L^{-1}$	0.05	31	6.9	20.1	16.3	54.7	_
Na^+	$mg\ L^{-1}$	0.05	31	16.6	30.6	24.5	115.4	200
NH_4^+	$mg\ L^{-1}$	0.1	31	_	_	_	<0.1	0.50
NO_2^-	$mg\ L^{-1}$	0.1	31	_	_	_	<0.1	0.50
NO_3^-	$mg\ L^{-1}$	0.5	31	1	46.6	26.7	180	50
PO_4^{3-}	$mg\ L^{-1}$	0.1	31	_	_	_	<0.1	_
SO_4^{2-}	$mg\ L^{-1}$	1	31	26	55	51	107	250
CND	$\mu S\ cm^{-1}$	1	31	597	1062	943	2037	2500
pH	_	_	31	7.4	7.7	7.7	8.2	6.5–9.5
TDS	$mg\ L^{-1}$	2	31	390	691	611	1326	_

The state of the alluvial aquifer of the study area has changed under the influence of pressures (Figure 3). The lower mean and median value of Cl^-, Na^+, NO_3^-, SO_4^{2-}, CND and, pH than the European Community health-based drinking water guidelines [45] was recorded in groundwater of the Troizina basin. Elevated Cl^- content in groundwater varying between 52 and 423 mg L^{-1} were observed in areas near the coastal zone and Psifta lagoon, suggesting the hydraulic connection of the Quaternary alluvial aquifer with the sea (Figure 4a,b).

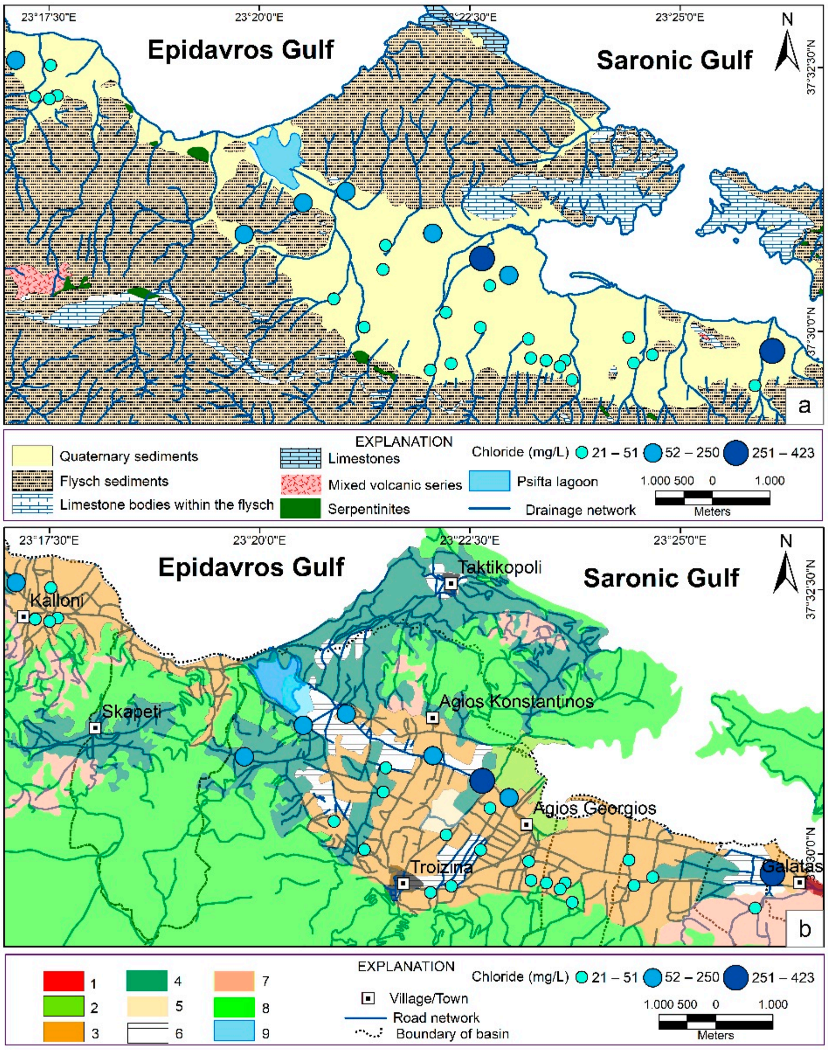

Figure 4. Graduated symbol plots of chloride content in groundwater of the study area compared with (**a**) geology and (**b**) land uses (the explanation of land uses is shown in the caption of Figure 2).

Nitrate concentration in groundwater exceeding the parametric value of 50 mg L^{-1} is recorded in the central and northeastern part of the basin (Figure 5a). The highest concentration of NO_3^- in groundwater ranging from 50.2 to 180.1 mg L^{-1} was observed in the central part of the study area, mainly related to agricultural land use exhibited intensive application of nitrogen fertilizers at the monitoring sites close to carnation greenhouse plants, orange trees and olive groves (Figure 5b). Nitrate contents in groundwater collected at monitoring sites in the central part of the study area also exceed the parametric value of 50 mg L^{-1} established by the Dir.98/83/EC [45], denoting that it is not suitable for human consumption. The high NO_3^- concentration in the Troizina aquifer was due to anthropogenic activities, mainly from the leaching of nitrogen fertilizers. Many researchers reported that the application of nitrogen fertilizers in agricultural fields is one of the most crucial non-point sources of contamination [15,21–23,50,51].

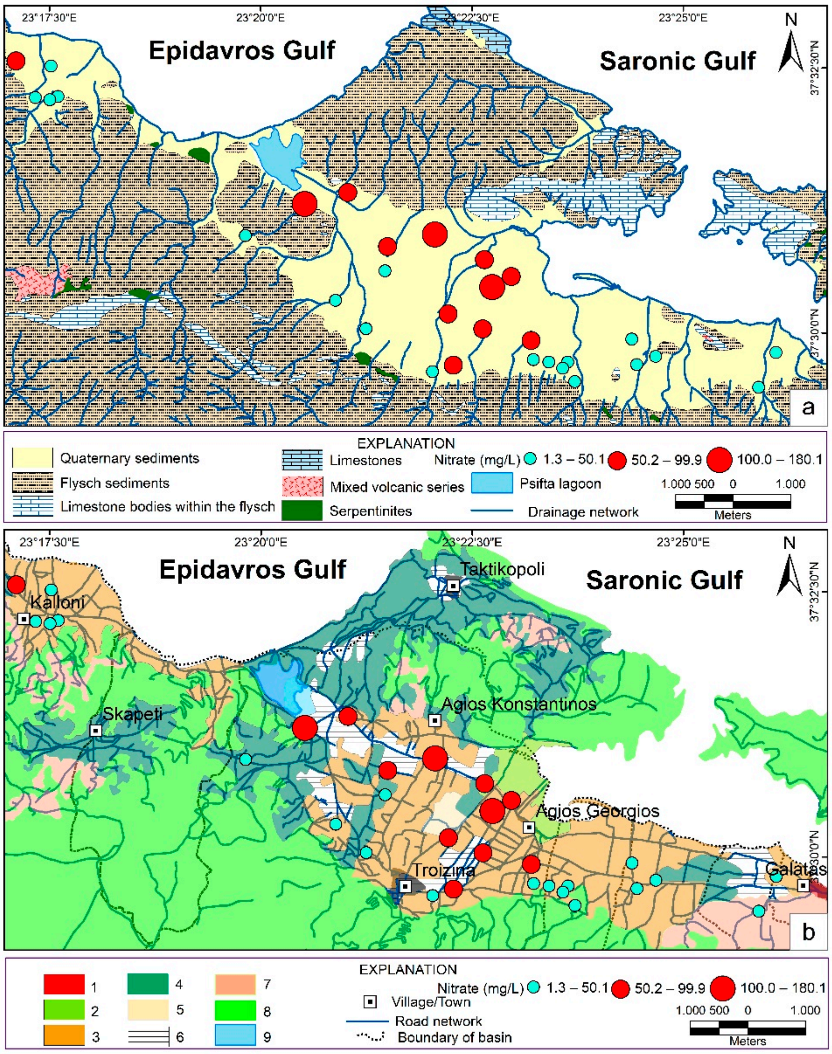

Figure 5. Graduated symbol plots of nitrate concentration in groundwater of the study area compared with (**a**) geology and (**b**) land uses (the explanation of land uses is shown in the caption of Figure 2).

The calculated CCME-WQI values for groundwater monitoring sites in the Troizina basin ranges from 76 to 100. The spatial distribution of GWD-TV and CCME-WQI classes are shown in Figure 6. It is observed that GWD-TV and CCME-WQI classes at the monitoring sites located at the eastern and western part of the study area (except for W01 and W22) are both equal to 2 (Figure 6), denoting that both classifications produce similar findings. Furthermore, similar results regarding the GWD-TV and CCME-WQI classes are also reported by Alexakis [13], who proposed a meta-evaluation methodology for CCME-WQI through the GWD-TV classification using a geochemical dataset of a Quaternary alluvial aquifer in the Megara basin (Greece). In contrast, GWD-TV classifies most of the monitoring sites located at the central part of the study area into the lowest class (Class 1); while CCME-WQI classifies these sites into the highest class (Class 2) (Figure 5). The poor performance of CCME-WQI and GWD-TV classes is a shred of evidence of groundwater unsuitability in the Troizina basin. The high NO_3^- content in groundwater show similar spatial distribution with the classes at sites that show differences between GWD-TV and CCME-WQI, suggesting that NO_3^- concentration is among the main factors controlling the classification results.

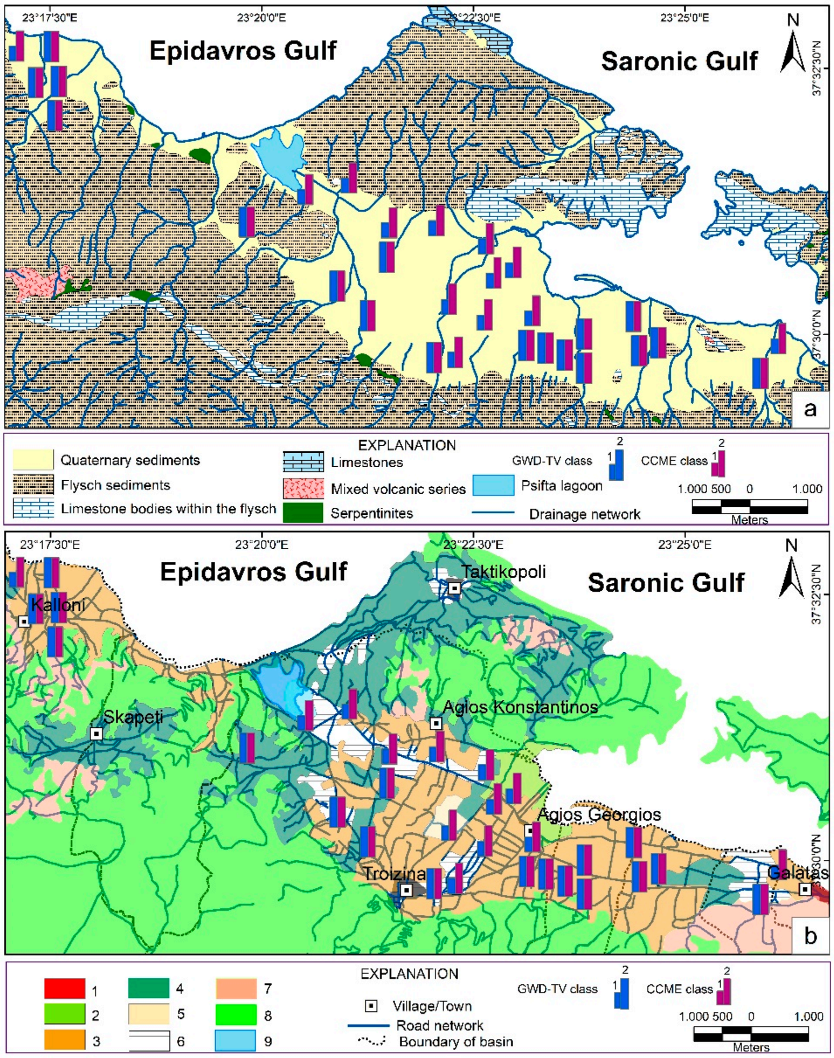

Figure 6. Spatial distribution of GWD-TV and CCME-WQI classes in groundwater monitoring stations compared with (**a**) geology and (**b**) land uses (the explanation of land uses is shown in the caption of Figure 2).

3.4. Impact

It was found that Na^+, SO_4^{2-}, CND and pH values in groundwater of the Troizina basin did not exceed the parametric values proposed by the Dir.98/83/EC [45]. The chloride content in groundwater in two sampling sites (6.5%; W14 and W22) was higher than the parametric value of 250 mg Cl^- L^{-1} established by the Dir.98/83/EC [45] (Figures 2 and 4). Nitrate concentration in groundwater in twelve sampling sites (38.7%; W01, W07–W09, W11, W13, and W14–W19) exceeded the parametric value of 50 mg NO_3^- L^{-1} given by the Dir.98/83/EC [45] (Figures 2 and 5). Intensive usage of fertilizers caused elevated NO_3^- contents in groundwater (up to 180.1 mg L^{-1}), suggesting a potential threat to human health (Figures 3 and 5). Based on the OOAO principle, the groundwater in 42% of the monitored sites is unsuitable for human consumption. The percentage of wells whose water is classified into "marginal-poor" and "poor" category is 0% and 38.7%, respectively. Therefore, the application of different methodologies, CCME-WQI and GWD-TV, produces appreciable differences in the estimated qualitative classification. The comparison of the classifications of CCME-WQI and GWD-TV in the study area revealed that GWD-TV produces a rather strict classification since it estimates a lower qualitative class than CCME-WQI. According to WHO [52], Cl^- concentration higher than 250 mg L^{-1} can give rise to detectable water taste. If inhabitants of the study area consume groundwater polluted by

NO_3^- for a long time, it will negatively affect their health. The adverse effect on human health mainly includes methemoglobinemia [53,54], impact on the thyroid gland [53], mellitus diabetes [53], congenital disabilities and gastric cancer [54]. Epidemiological studies in the United States of America from 1941 to 1995 revealed that consuming water containing NO_3^- concentration over 45 mg L^{-1} is the main reason for methemoglobinemia in infants [53]. According to Parvizishad et al. [53] and van Maanen et al. [55], when the NO_3^- concentration was above 50 mg L^{-1}, the interaction of competition between I^- (iodine) and NO_3^- caused a moderate increase in thyroid gland volume. In contrast, many researchers indicated the benefits of NO_3^- on human health include protective effects on the cardiovascular system and regulation of blood pressure [53,56]. Moreover, N plays a role as an essential nutritious element in protecting children [53]. An average NO_3^- content in drinking water of about 30 mg L^{-1} increased the incidence of gastric cancer in the inhabitants of Alborg city (Denmark) [57]. Morales et al. [58] analyzed the relationships between different NO_3^- content in drinking water and cancer of the prostate, bladder, stomach and colon among residents of Valencia (Spain) and concluded that deaths from prostate cancer and gastric cancer have increased with increasing exposure to NO_3^-. The elevated NO_3^- content in groundwater of the Troizina basin denotes that intensive application of fertilizers does not help achieve Goal 3 (Good health and well-being) and Goal 6 (Clean water and sanitation). Seawater intrusion happens in the proximity of the coastal area of the Troizinia basin and the area in the proximity of Psifta lagoon (Figure 4), suggesting a high level of the interrelationship between water use for agriculture and groundwater deterioration.

The connection between NO_3^-, Cl^- and CND and irrigated crop production in the Troizina basin go in the following directions: (a) overexploitation of the Quaternary alluvial aquifer and application of groundwater to cropland where it promotes the seawater intrusion and dispersion of salts; (b) requirement of water resources with low CND values to avoid the accumulation of salts in the crop root zone; and (c) elevated content in groundwater and possible adverse health effects on residents.

3.5. Proposed Responses

Regarding the adoption of measures for increasing the percentage of wells whose groundwater is suitable for human consumption or is categorized in "excellent-good-fair"/"good" class, the dissemination of the adverse effects of intensive application of fertilizers and overexploitation of water resources will trigger a fruitful dialogue for designing operational strategies in the study area. Through dissemination channels or by directly contacting the farmers of the study area, the most important findings of this study can be considered and captured in the design of short courses, seminars and educational activities. The installation of a network monitoring the water quality and quantity in the aquifer of the study area seems to be an effective practice for accelerating the achievement of Goals 3 and 6. Another proposed response for achieving Goals 3 and 6 is the Managed Aquifer Recharge (MAR). MAR will support the high water demands in the Troizina basin, control groundwater deterioration (e.g., decrease NO_3^- concentration in groundwater), and overcome seawater intrusion (e.g., decline CND value and Cl^- content in groundwater) and the mismatch between water demand and recharge of the alluvial aquifer. Various MAR processes and technologies are presented by Zhang et al. [59]. Meanwhile, the in-channel modifications and infiltration ponds are among the standard MAR techniques that could be applied in the Troizina basin.

4. Conclusions

Groundwater pollution in the Troizina basin is evidenced by the poor performance of CCME-WQI and GWD-TV classes. A difficulty to achieve targets under Goals 3 and 6 in the study area is revealed. The Cl^- concentration in the 6.5% of the groundwater sampling sites exceed the parametric value established by the Dir.98/83/EC. The NO_3^- content in the 38.7% of the groundwater sampling sites is higher than the health-based guideline value of 50 mg L^{-1} established by Directive 98/83/EC. The outcome of the "One Out-All Out" procedure revealed that the groundwater in 42% of the monitored sites is unsuitable for human consumption. The deterioration of groundwater quality in the study area mainly includes the following processes: (a) diffuse contamination from fertilizers application on agricultural soils; (b) local pollution by piles of livestock excrements around wells; and (c) over-exploitation of groundwater resources and seawater intrusion.

The inclusion of CCME-WQI in the state (S) improved the application of the DPSIR model to investigate the achievement of SDGs in groundwater resources. The installation of a network monitoring groundwater resources in cultivated areas seems to be an effective practice for accelerating the achievement of Goals 3 and 6. The proposed measures should be rationally evaluated if a continuous monitoring network of groundwater resources is installed and operated. The applied methodology would be helpful to provide stakeholders and policymakers with a framework to achieve sustainable development goals in groundwater resources of an unconfined alluvial aquifer.

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