

Chapter 9

Regional Groundwater Flow Systems: Their Role in Conserving the Marismas Nacionales Biosphere Reserve in Nayarit, Mexico



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Abstract The Marismas Nacionales de México, located on the Pacific coast of the state of Nayarit, is a protected area, internationally recognized as a RAMSAR site. Twelve rivers pass through the reserve, producing complex fluvial and geomorphological networks, which contain an abundance of ecosystems, rich in biodiversity. While there are studies on the general hydrology of these marshes, mainly from hydrographic and ecosystem perspectives, a fuller systemic understanding of the hydrological functioning of the area is needed, given the environmental importance of the area. Based on the Tothian theory of regional groundwater flow systems, this paper presents an analysis of the association between the hydrological features and ecosystems of the Marismas Nacionales. By integrating observations and measurements from various disciplines, the ecosystem interconnectivity of the area is described and proposed as a basis for future studies and sustainable interventions in the Marismas Nacionales and other, similar environments.

Keyword Biodiversity · Ecosystem services · Environmental hydrogeology · Groundwater recharge-discharge · Tóth's theory

9.1 Introduction

Despite recent advances in research, it is still common today for surface water and groundwater to be referred to as separate entities, parts of a water cycle that is divided into phases, with no acknowledgement of the uniqueness of water itself. When the planetary hydrogeological cycle is comprehended, the perception of water changes and appears as a single entity that simply changes place, physical state and/or physical-chemical composition in each of the stages of its cycle. In its atmospheric

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and surface phases, water is more evident for human beings. Its functions, main mechanisms, effects and manifestations, such as rain, snow, dew, evapotranspiration, runoff is well known. However, water in its underground phase constitutes 97% of the liquid fresh water on the planet, it is the main type of water in the environment and the source of the perennial water bodies that are observed on the Earth's surface. The perennial volume, or base flow, of a river, lake or lagoon comes from the emergent groundwater that provides water on a permanent basis, regardless of the local rainfall regime, and is linked to the regional water flow system, which may begin hundreds of kilometres away.

Tóth's theory of regional groundwater flow systems (Tóth 1970, 1971, 1999, 2009, 2016) allows to verify the unicity of water and how the groundwater phase binds so many of the elements of the environment. Groundwater is ever present, and the only natural mechanism that transports and interconnects matter and energy to and from the Earth's surface, defining local and regional environments, linking the geofoms, soil, vegetation and even the climate of any environment.

The Tothian theory (Tóth 2000) explains how groundwater circulates in flows that are determined by the regional geological context and identifies natural features that are produced by groundwater, though they may be modified later by environmental conditions. Through the analysis of permanent surface water, soil type, vegetation, geomorphology and climate, these surface indicators of groundwater flow systems can be identified (Tóth 1999).

The underground part of the water cycle begins with infiltration in recharge zones, and flows towards discharge zones, where the water emerges to the surface (Tóth 2009). In Fig. 9.1, which is based on Tóth's theory (Tóth 1962, 1963, 1999), the zones of the groundwater flow systems that can exist in a certain environment (*recharge*, *throughflow* and *discharge*) and the hierarchy of the flows (*local*, *intermediate* and *regional*) are shown. There is no scale in this diagram, as it depends on the geological context; the depth, length and magnitude of the velocity of groundwater flows,

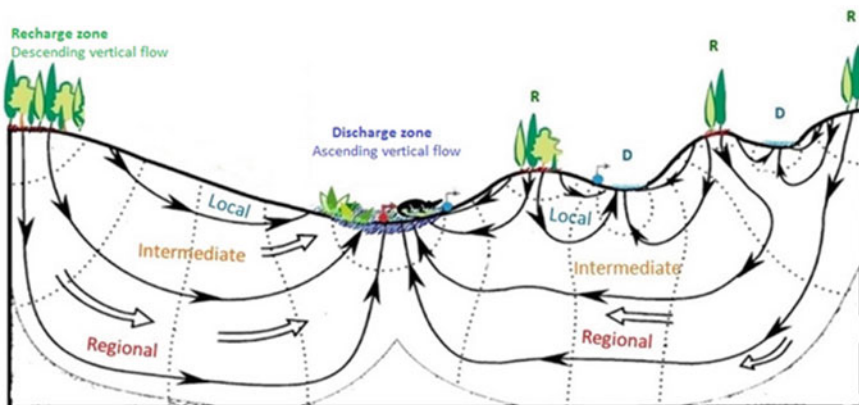


Fig. 9.1 General diagram of groundwater flow systems (modified from Tóth 1999)

determined by the geology of the area, as well as the degree of interaction between water and rocks, and the local-regional environmental dynamics induced by human intervention.

Tóth’s theory of regional groundwater flows explains how the water that circulates, forms and supports the biosphere reserve of the Marismas Nacionales is just one entity, with different phases, all interrelated. However, at present, there is no understanding of the complete hydrological dynamics of this important area. Located on the Mexican Pacific coast (Fig. 9.2), the Marismas Nacionales are an area of outstanding natural wealth, which has unique landforms and valuable ecosystems. Twelve rivers pass through the area, the dynamics of which produce a complex coastal hydrological system containing a large extension of mangroves and other estuarine wetlands, which develop along a plain of frontal dunes that extend inland for more than 15 km.

Within the biosphere, the reserve of the Marismas Nacionales is the largest extension (133,850 ha) of mangroves on the Mexican Pacific coast, as well as a considerable area of rainforest and coastal dry forest, (CONANP 2013). The region was formed by complex hydro-sedimentary dynamics, tidal, riverine and underground. The preservation of the area depends on maintaining these fluxes. Land-use changes have accelerated since the middle of the twentieth century, pressurising the ecosystems via

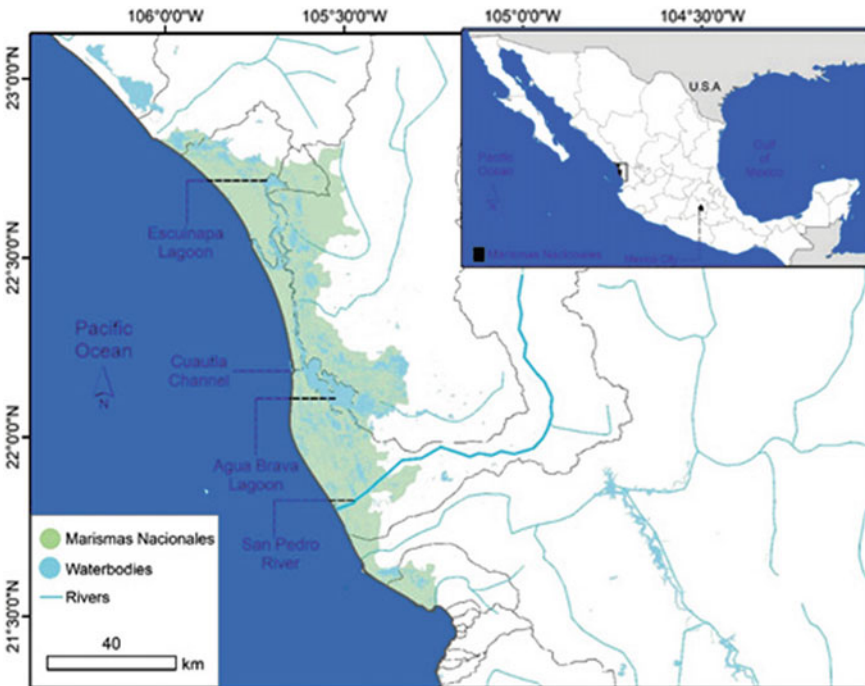


Fig. 9.2 Location of the Marismas Nacionales

the overexploitation of natural resources, such as timber and fisheries, the substitution of natural ecosystems for crops and aquaculture ponds and the construction of infrastructure that interrupts the flows of water and sediment.

The first step in understanding the role that groundwater plays in the conservation of the Marismas Nacionales was the characterization of the zones of the groundwater flow systems in the region. The importance of the marsh and its degree of vulnerability are presented. Then, hydrogeological analyses were carried out on the hydrographic and piezometric features, the soil cover, the vegetation and the topofoms of the reserve.

9.2 Degree of Conservation of the Marismas Nacionales

The biosphere reserve of the Marismas Nacionales is composed of several floodable ecosystems that developed due to the accumulation of sediment in the confluence of the alluvial plains of twelve rivers, that is, the Navarrete, Sauta, El Palillo, Grande de Santiago, San Pedro-Mezquital, Bejuco, Rosamorada, San Francisco, Acaponeta, Las Cañas, Escuinapa and Baluarte streams.

In the past, the alluvial plains were covered by rainforest, but advancing agriculture has reduced this natural vegetation. The coastal wetlands are one of the most valuable formations in the area because of the ecosystem services they provide. These wetlands can be divided into herbaceous and arboreal (mangroves). The herbaceous wetlands cover over 175,000 ha and are in a relatively good state of conservation. However, at the edges of the marshes advancing agriculture and aquaculture are replacing and fragmenting this ecosystem. The extension of mangrove in the reserve has fallen by 50% due to land-use changes and the interruption of hydro-sedimentary fluxes.

Throughout the Marismas Nacionales, there is a generalized loss of naturalness, which is greater inland, where the alluvial plains are seriously altered, and decreasing towards the coast, while the deltaic fronts are less degraded, although there are some patches on the coastal plain which have been altered as well. This loss of naturalness is sometimes referred to as degradation, the response of the environment to all the complex mechanisms occurring in the landscape (Simensen et al. 2018). Anthropoc interventions and consequences that generate degradation in the Marismas Nacionales include the building of artificial barriers that obstruct the normal flow of matter and energy in the ecosystems. Bare soil, excavations, deforested areas (including secondary vegetation), burned areas, crops, live fences, are indicators of human interventions that are producing long term changes in the land use of specific parts of the reserve.

In most of the degraded areas, the alterations have been caused by agriculture. The greatest alterations have been induced by aquaculture, where shrimp ponds (artificial water bodies) modify the natural flow of matter and energy between the delta and the lagoon area. In the deltaic and ridge areas, where there is less agricultural activity,

there is less alteration, especially in the flood and hypersaline areas. In the lagoons and channels between the dune ridges, known as dune slacks, the main economic activity of the local population is fishing. Traditional fishing is less likely to transform the landscape than aquaculture or agriculture. Since the 1940's intensive aquaculture has been established in some flood-prone areas, transforming the landscape at an alarming rate (Lithgow et al. 2019).

The severe deterioration of the mangrove areas in the Marismas Nacionales was attributed only to the Cuautla Channel (Flores-Verdugo et al. 2014). However, the deterioration beyond the area influenced by the channel indicates diverse hydro-sedimentary imbalances. Undoubtedly, the Cuautla Channel produces one of the main hydro-sedimentary imbalances in the region, but other projects, such as the Aguamilpa Hydroelectric Dam and concurrent socio-economic activities, have also contributed to the degradation of the mangroves (Blanco et al. 2014). Figure 9.4 shows the original course of the channel and the 1976 coastline position.

The alteration of the ecosystems in the Marismas Nacionales affects their ability to maintain ecological processes and a diverse community of organisms, and thereby has a direct impact on the ecosystem services they provide.

Perturbation of the wetlands could induce losses of high ecological values by reducing the rich biodiversity of the area. The socio-economic impact of these perturbations will affect the acute dependency of the local population on the mangrove-associated fisheries. It could also affect the health and resilience of interconnected ecosystems.

An approximation of the economic value of the ecosystem services in the Marismas Nacionales by Mendoza et al. (2012) considered the average value per hectare per ecosystem in US dollars, updated in 2018. It was found that the coastal lagoons and the mangrove area are the most valuable in terms of ecosystem services (US\$ 26,000 ha⁻¹. year⁻¹). The coastal beaches and foredunes were estimated to have an approximate value of US\$ 18,000 ha⁻¹. year⁻¹, when taking into account protection services against extreme hydrometeorological events (e.g. hurricanes), and recreation services.

9.3 Hydrographic Structure

The hydrological structure of the Marismas Nacionales has diverse geometries and dynamics, but is a single system connected to the ocean. To date, only the hydrological structure of the surface has been characterized. To understand how the hydrological system is interconnected with the ocean, it is necessary to complete the picture by characterizing and incorporating the underground phase.

The surface hydrological network is made up of 2,480 km, which include the main rivers as well as the artificial channels within the reserve (Fig. 9.4). This exceptionally high number is because there are over 200 natural channels between the relict dune

ridges, and many large artificial channels. Most of the artificial interventions in the natural drainage network are related to agricultural irrigation, and many are connected to the natural streams, often modifying the natural patterns of runoff in the area. The mild slopes of the coastal plain and the delta cause stagnation of the water flows. The considerable dissection of the terrain by the hydrological network and the low topography of the coastal plain make the area especially vulnerable to rising sea levels (Fig. 9.4). Water bodies occupy a total area of 170 km²; the vast majority being permanent (168 km²).

In a large part of the study area there are ridges of about 15–100 m in length, lying roughly parallel to the coast on the 14 km wide coastal plain. The average height of the ridges is 1 m, and the highest is 2 m. The dune ridges are perpendicular to the San Pedro river, inducing the natural formation of lagoons between the ridges.

For example, naturally, the connection between the Agua Brava and Toluca lagoons with the sea tends to erode the ridges, however this process has been intensified by projects designed to facilitate navigation from the lagoons to the ocean, such as the Cuautla Channel (Figs. 9.3 and 9.4).

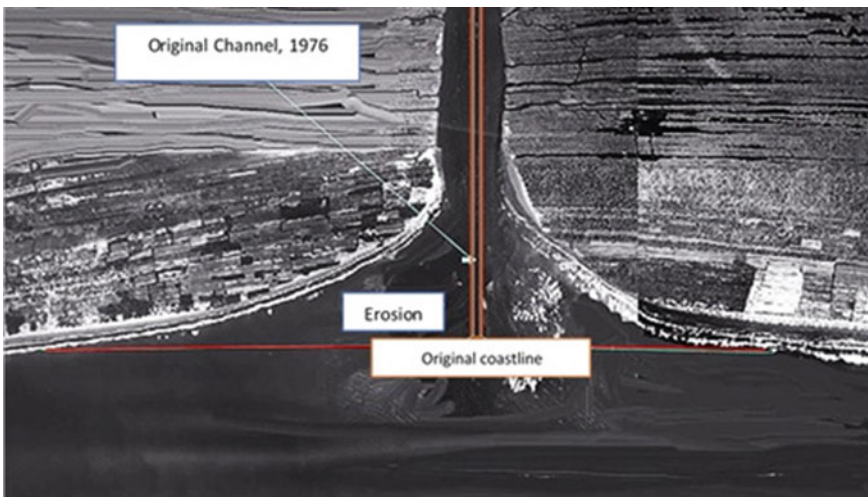


Fig. 9.3 The Cuautla channel, showing the width of the original channel and the coastline recession since 1976 (adapted from Flores-Verdugo et al. 2014)

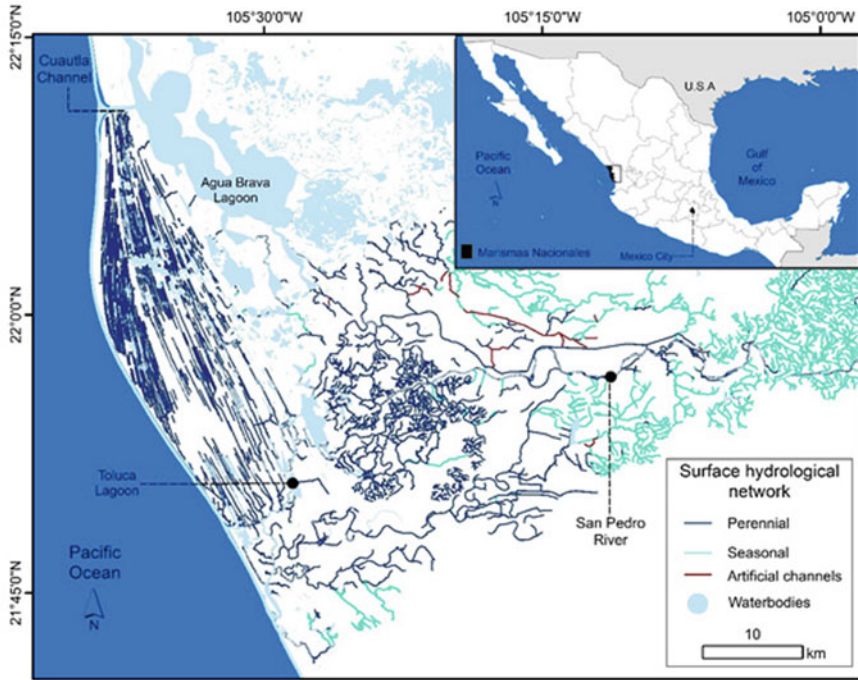


Fig. 9.4 The surface hydrological network of the Marismas Nacionales

9.4 Systemic Hydrological Interconnections

Currently, no complete explanation of the hydrodynamics of the Marismas Nacionales has been carried out; only data on surface hydrology is available.

The permanent, simultaneous in situ interactions between groundwater and the environment determine the distribution of the products of that interaction. It is now recognized that groundwater flow systems are the most important general geological agent in a great number and variety of natural processes and phenomena (Tóth 2016). Identifying surface indicators is the first step in understanding the complete dynamics of the groundwater in the Marismas Nacionales, as these bear witness to the interactions of the underground flows.

To understand the underground path of water, it is easier to start at the end of a groundwater flow, where the underground water emerges onto the surface, the point or zone of discharge. There are four main features of a *discharge zone* (Tóth 1971): (i) positive potential slope, (ii) relatively low position, (iii) allochthonous physical-chemical composition of the water and (iv) allochthonous temperature of the water.

The aspect and intensity of these features depends on the hydrogeological context: air temperature, slope of the relief, physico-chemical composition of the rocks,

permeability of the rocks, vegetation, land use, etc. Natural features of groundwater discharge may be seen either directly on the surface, or in a diffuse manner, and include seas, lakes, lagoons, springs, geysers, floodplains, swamps, quicksands, salt flats, landslides and mudslides, swamps, depressions, excess soil moisture, hydrophilic vegetation and halophyte vegetation. The permanent presence of water, waterlogging, mud and flooding and a shallow static water level depth are the first and main surface indicators that a site is in a groundwater discharge zone.

In the *recharge zone* the water table can vary greatly throughout the year and it is usually at a considerable depth. According to the size of the study area, there may be no signs of permanent surface water in relation to local or regional conditions. Throughflow zones are those between the discharge and recharge zones of groundwater flow systems. The main feature of a throughflow zone is that horizontal flows dominate due the water's mechanical energy mostly does not vary, while in discharge zones vertical upward flows dominate, and in the recharge zones, the main flows are downward and vertical (Tóth and Hayashi 2010).

9.4.1 Surface Indicators of Groundwater

Based on Tóth's theory, a systematic, non-linear analysis was carried out of features on the surface related to groundwater flow systems. The following order of features shows their respective importance:

- (i) Natural perennial water on the surface, including springs
- (ii) Groundwater depth
- (iii) Soils
- (iv) Vegetation and land use
- (v) Topofoms

For each indicator the oldest datasets available were used at scales of 1:250 000 (continental relief, hydrography, depth of piezometric level, edaphic coverage, hydrology, potential wetlands, land use and vegetation) and 1:1 000 000 (climate and topofoms). This official geographic information was used (CONABIO 2013; CONAGUA 2016, 2019; INEGI 1980, 1991, 1992, 1993, 1995, 2000, 2001, 2005, 2006, 2008, 2009, 2010, 2012). For the analysis of the attributes of the original maps INEGI, their respective cartographic interpretation guides and data dictionaries were used (INEGI 2001a, 2009a, 2010a, 2014, 2014a, 2016). The criteria of the World Soil Resources Reference Base (IUSS-FAO 2007) and the Keys to Soil Taxonomy (Soil Survey Staff 2014) were used to analyse soil edaphic properties.

The analyses were made for the polygon known as the Priority Area of the Marismas Nacionales ("Región Terrestre Prioritaria Marismas Nacionales") (Arriaga et al. 2000), which includes the RAMSAR wetland site 732. Priority Areas are those with rich ecosystem diversity and a viable potential for conservation measures, as designated by the CONABIO (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad), WWF (World Wildlife Fund), USAID (United States Agency for

International Development), TNC (The Nature Conservancy), INECOL (Instituto Nacional de Ecología A.C.) and FMCN (Fondo Mexicano para la Conservación de la Naturaleza).

Each surface indicator was reclassified in terms of the characteristics of the zones of the groundwater flow systems. This hydrogeological reclassification is shown in five new maps.

(i) Naturally occurring perennial water on the surface. The information for this surface indicator was taken from maps with spatial information regarding surface water. Features that are directly associated with discharge zones are lakes, lagoons, marsh, swamp, perennial rivers, springs, muddy terrains, wetlands and floodplains. From all the available, official, spatial information regarding surface perennial water a new map was created showing that 88% of the surface area of the Priority Area has perennial water. Applying a 1 km margin around the points and polygons of perennial water found in a topoform associated with discharge the new map identifies locations of potential discharge processes.

This map is presented in Fig. 9.5. The discharge zones of groundwater flow systems are shown by blue shading. Springs are the clearest, most direct indication of the processes of groundwater discharge. A spring is where water emerges directly from the ground, and occurs where there is enough hydraulic conductivity in the rocks and the groundwater table is shallow. Where they occur in a geoform related to discharge, this confirms that the area is one of discharge. Where they occur in topoforms not related to discharge, they are assumed to be points of discharge.

The presence of thermal springs in, or near, confirms that the discharge zones can have regional flow system characteristics.

In the Priority Area the main perennial rivers are the San Pedro, Grande de Santiago, Bejuco and Rosamorada streams, whose respective base flows are the proportion of stream discharge sustained by groundwater discharge. All perennial rivers travel through sections of discharge, throughflow and recharge. Where rivers are in discharge topoforms, this shows that the systemic process of discharge is dominant.

(ii) Groundwater depth. The geo-referenced register of the piezometric depth, which indicates the groundwater depth at a given point, is important in analysing the surface indicators as a whole. The following classification is suggested:

- a. Thermal water with static water level ≤ 3 m in discharge topoform
- b. Thermal water with static water level between > 3 m and ≤ 11 m in discharge topoform
- c. Thermal water with static water level between > 3 m and ≤ 11 m not in discharge topoform
- d. No thermal water with static water level ≤ 3 m in discharge topoform
- e. No thermal water with static water level between > 3 m and ≤ 11 m in discharge topoform
- f. No thermal water with static water level between > 3 m and ≤ 11 m not in discharge topoform
- g. Static water level > 11 m

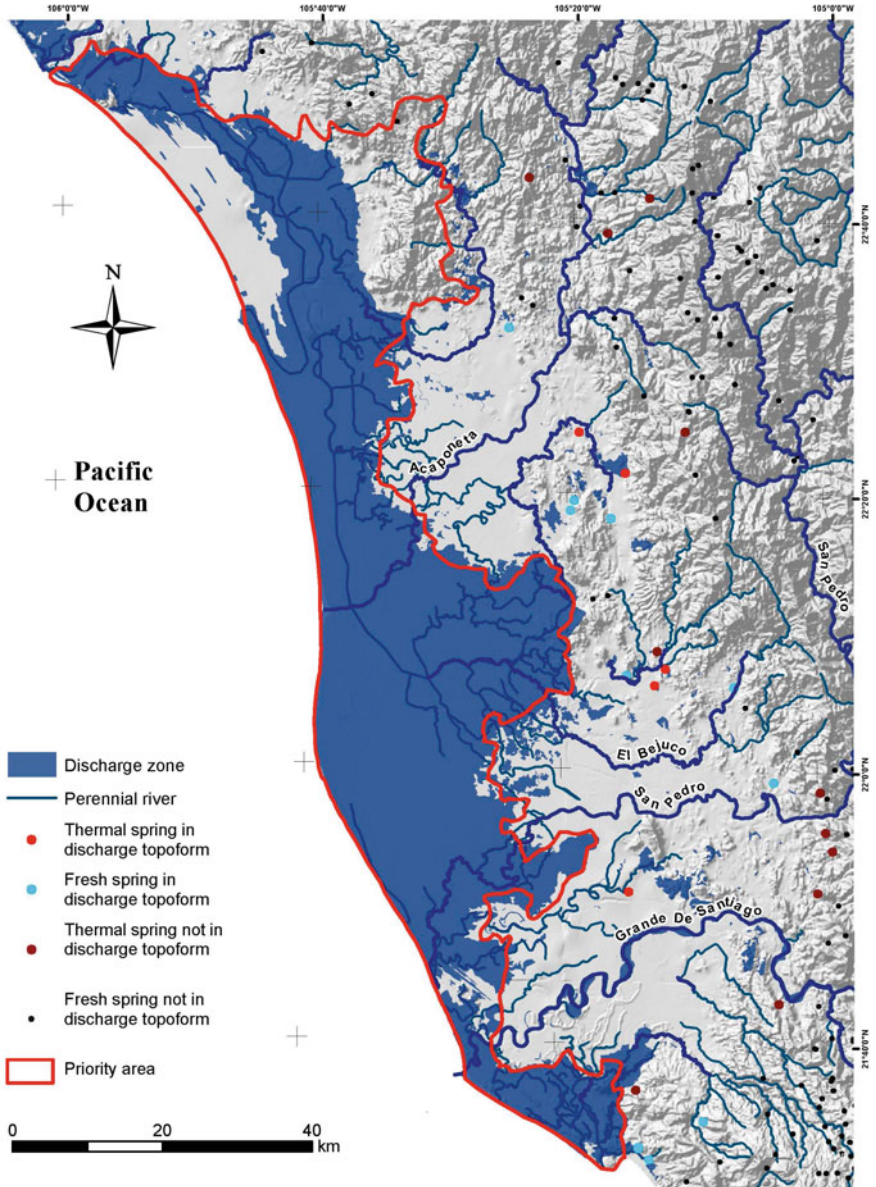


Fig. 9.5 Permanent surface water as an indicator of hydrogeological dynamic

A groundwater depth of less than, or equal to 3 m is a direct indicator of a point or zone of discharge where water emerges, as it is the average limit for evapotranspiration to occur in the subsurface. The range 2–11 m is the interval in which natural temporal groundwater fluctuations have been observed.

There are more points with a shallow depth in discharge zones than in recharge or throughflow zones. A static depth of > 11 m in a regional topofrom associated with recharge is a surface indicator of a potential recharge zone of groundwater flow systems. Figure 9.6 shows the publicly registered groundwater depths classified.

The discharge points found close to the coastline at ≤ 3 m show that the groundwater dynamics do not stop at the coast, there are maritime discharge zones (Moore 2010). Submarine groundwater discharge (SGD) provides at least 50% of the fresh groundwater received by the sea (Povinec et al. 2007; Post et al. 2013).

(iii) Soils. The third surface indicator of groundwater in the Marismas Nacionales is the edaphic coverage, which is present in 86% of the area studied (Arriaga et al., 2000). The soil types described in the maps available were analysed using the Reference Soil Groups and principal and supplementary qualifiers (IUSS-FAO 2007; Soil Survey Staff 2014). The Marismas Nacionales have 11 types of soils (INEGI 1991, 2014) which were analysed and grouped into 3 categories:

- a. Soils associated with discharge zones: Fluvisol, Histosol, Lixisol, Solonchak and Vertisol
- b. Soils associated with recharge zones: Leptosol, Luvisol and Regosol
- c. Soils found in indistinct zones: Arenosol, Cambisol and Phaeozem

In the official Mexican spatial information of soil coverage, the groups are described with main qualifiers of the soil. Those associated with discharge processes are endogleyic, epigleyc, ferric, fluvic, gleyc, hypersodic, hyposalic, hyposodic, rheic, salic and vertic (INEGI 1991, 2014). The rest of the edaphic characteristics may occur as a result of both recharge and discharge processes, so they were assigned as indistinct. Figure 9.7 shows the soil classifications resulting from the analysis of soil attributes that show the processes of groundwater flow in each polygon of the soil cover of the priority area and its surroundings: 70% of the edaphic cover is related to discharge processes (*discharge zone*), 14% to *discharge-throughflow zone*, 7% to *throughflow zones* and 5% to *throughflow-recharge zone*. The 4% of the edaphic cover is defined as being of *indistinct* relation and 1% of the soils are typical of *recharge zones*. Outside the main area, two other classifications are observed *major discharge with minor recharge surface*, indicates that 60% of the polygon is discharge soil, and 20-40% is a soil with conditions associated with groundwater recharge; and *major recharge with minor discharge surface* category is an edaphic polygon with $\geq 60\%$ covered by a soil type associated to recharge zones and that 20-40% of the polygon has a typical groundwater discharge soil.

(iv) Vegetation. The maps of Vegetation and Land Use (INEGI 1980, 1993, 2009a, 2014a, 2016) were used to produce Fig. 9.9. This shows the edaphic coverage of the Marismas Nacionales: 14% of the soil cover is classified as water bodies and 68% vegetated by 9 types of vegetation (INEGI, 1980, 1993) associated with:

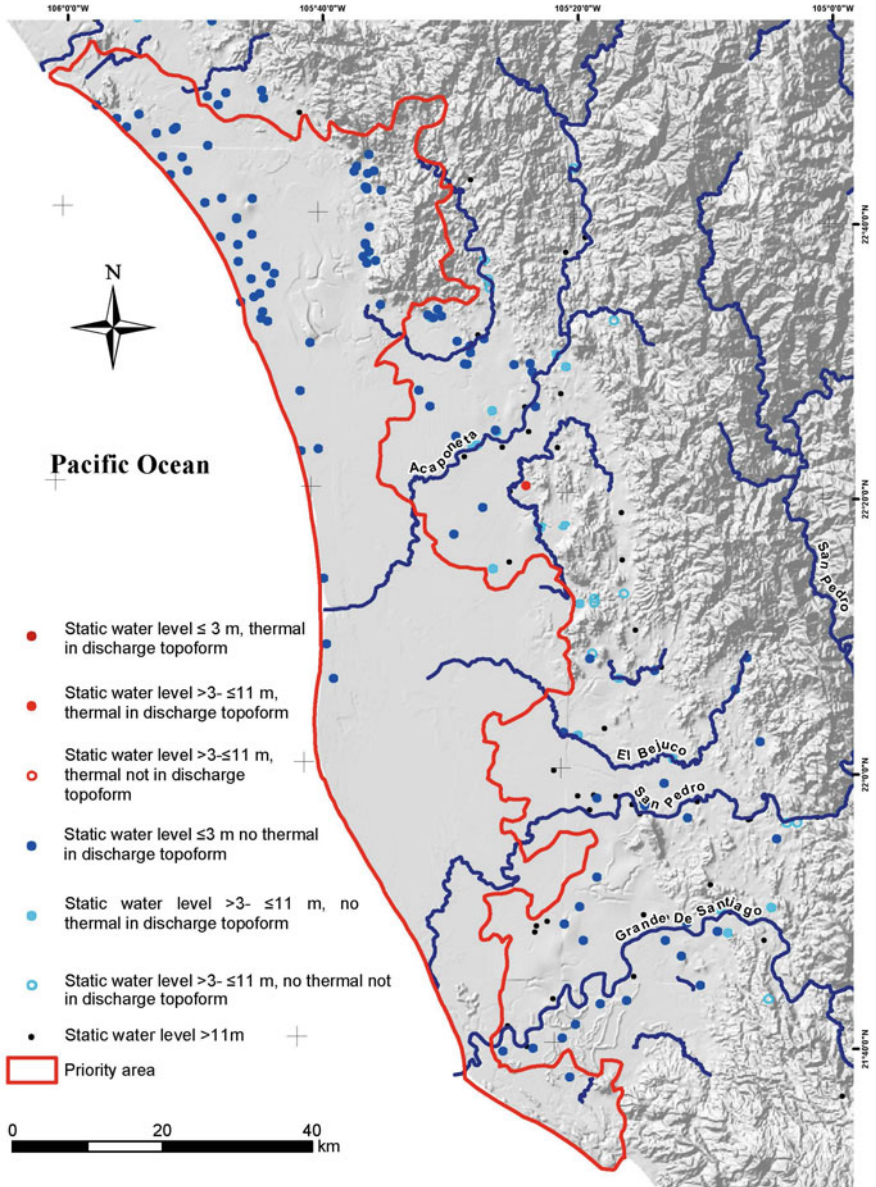


Fig. 9.6 Groundwater depth

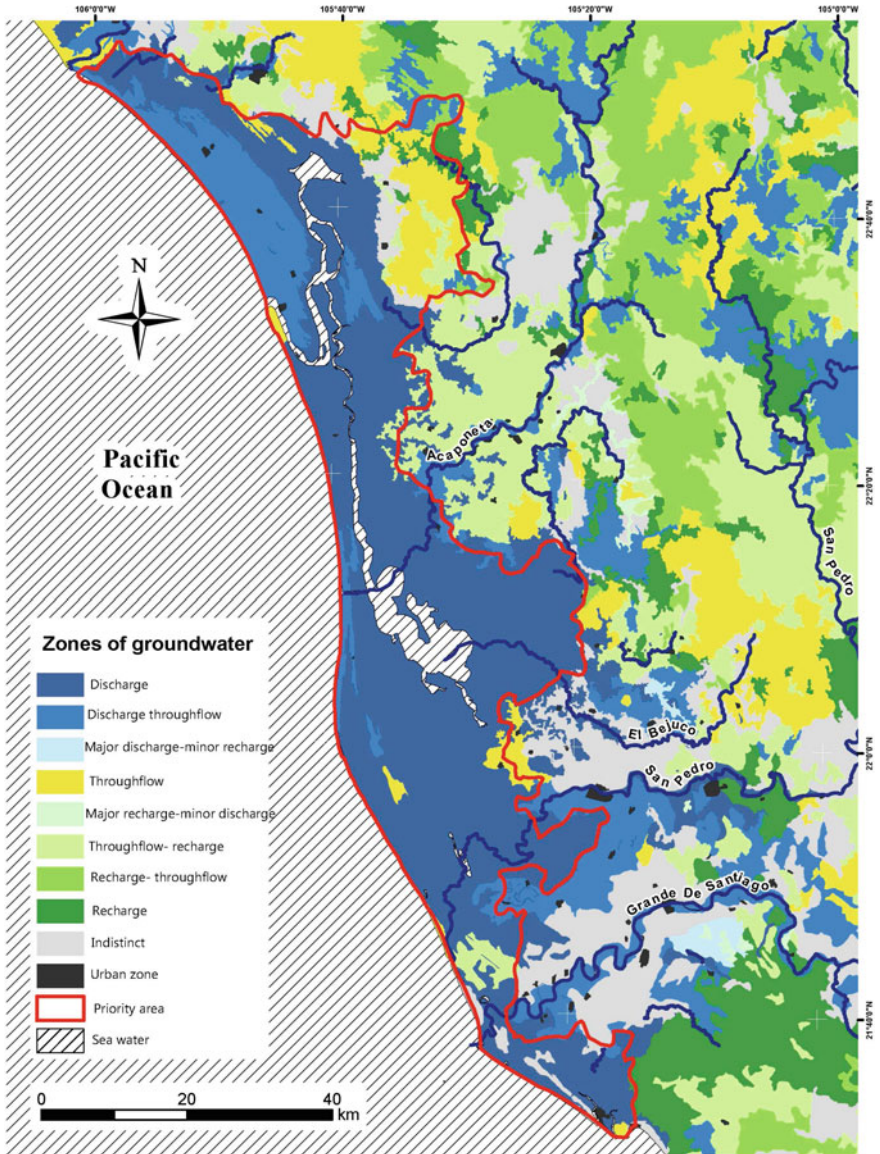


Fig. 9.7 Soils as a hydrogeological surface indicator

- a. Discharge zones: halophilic vegetation, mangroves, coastal dune vegetation and palm grove
- b. Discharge - throughflow zones: halophilic grassland and spiny lowland forest
- c. Throughflow - recharge zones: low deciduous rain forest
- d. Recharge zones: medium sub deciduous rain forest

Of all the “natural” cover, 74% is associated with *discharge zones*, types of vegetation which need a supply of groundwater at a shallow depth, 14% is associated with *recharge* or *throughflow* zones.

Given the changes in land use, it is wise to use the oldest land use data available in order to make a characterization based on natural or original vegetation cover. In the 1980s, 18% of the study area had been transformed, 15.7% for seasonal agriculture, 0.85% for irrigated agriculture and 1.45% for cultivated pastures.

Tóth’s theory of conceptual criteria on soils and vegetation should be considered as a first reference and a more detailed systemic analysis should be carried out. Furthermore, it should be remembered that groundwater flows are multi-dimensional (Fig. 9.1). In this perspective, the soil and vegetation types with the highest degree of certainty are those related to the discharge and recharge environments (Fig.9.8).

(v) Topoforms. The relief features characterized regarding the groundwater flow systems, using a scale of 1:1 000 000 were:

- a. In discharge zones, coastal plains with swamps, coastal salt plains, coastal plains with salt lagoons and deltaic plains; 71.6%
- b. In discharge swamping zones, floodable plains with barriers, 5.3%
- c. In discharge - throughflow zones, coastal plains with highlands, 2.6%
- d. In throughflow - recharge zones, highlands with plains, 3.1%
- e. In recharge zones, mountains, highlands and hills with valleys, 14.7%

The term *swamping discharge* zone was used as in the dictionary from the meta-data used, the “flooded” characteristic is indistinct for both tidal and/or continental flooding processes (INEGI 2001).

Figure 9.9 shows the topoforms which are surface indicators of the distinct zones of groundwater flow systems in the study area.

9.4.2 *Surface Variables in the Definition of Hydrological Zones*

Each of the individual surface indicators provides preliminary information about the zones of the groundwater flow systems. As previously mentioned, groundwater is the natural agent with the greatest capacity to integrate the greatest amount of natural and environmental components, from the water depths to the atmosphere. For this natural reason of the systemic dynamics of water is that the surface indicators are analysed in conjunction.

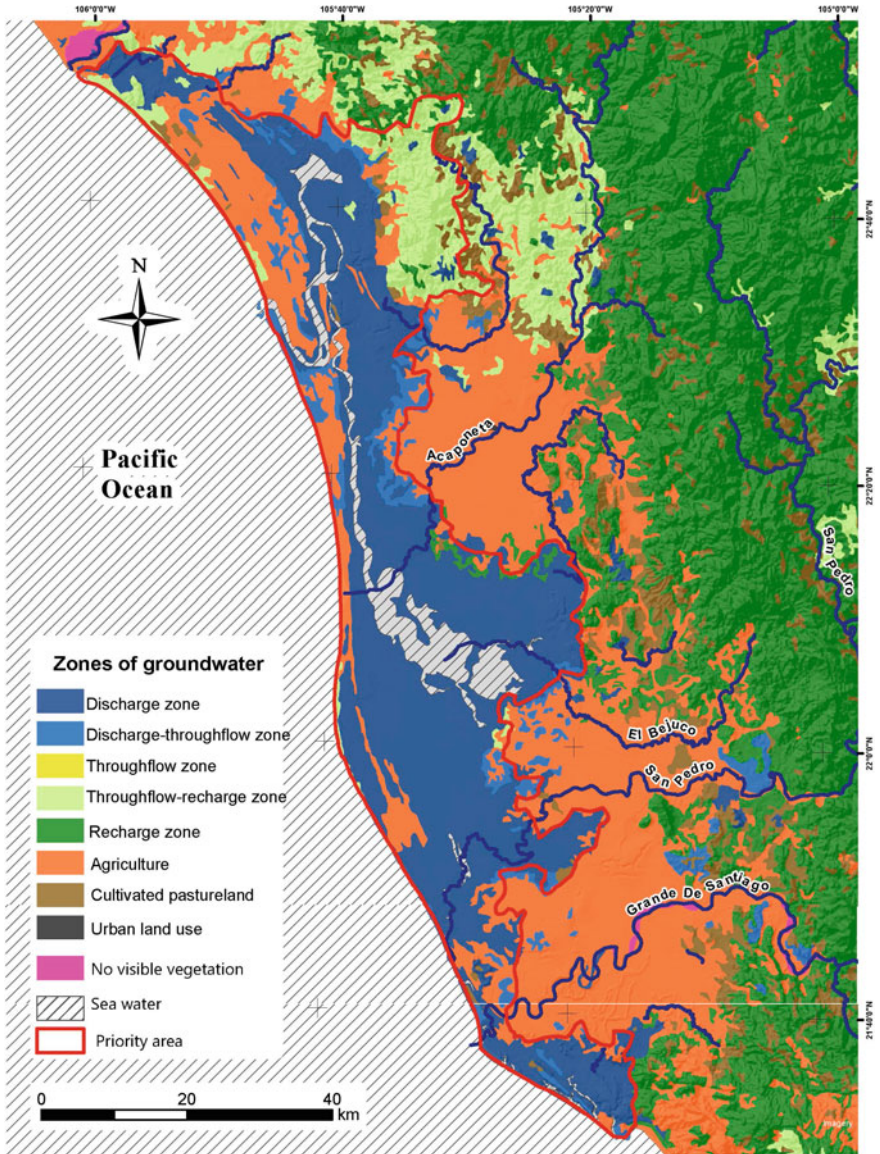


Fig. 9.8 Vegetation as a hydrogeological indicator at the water surface

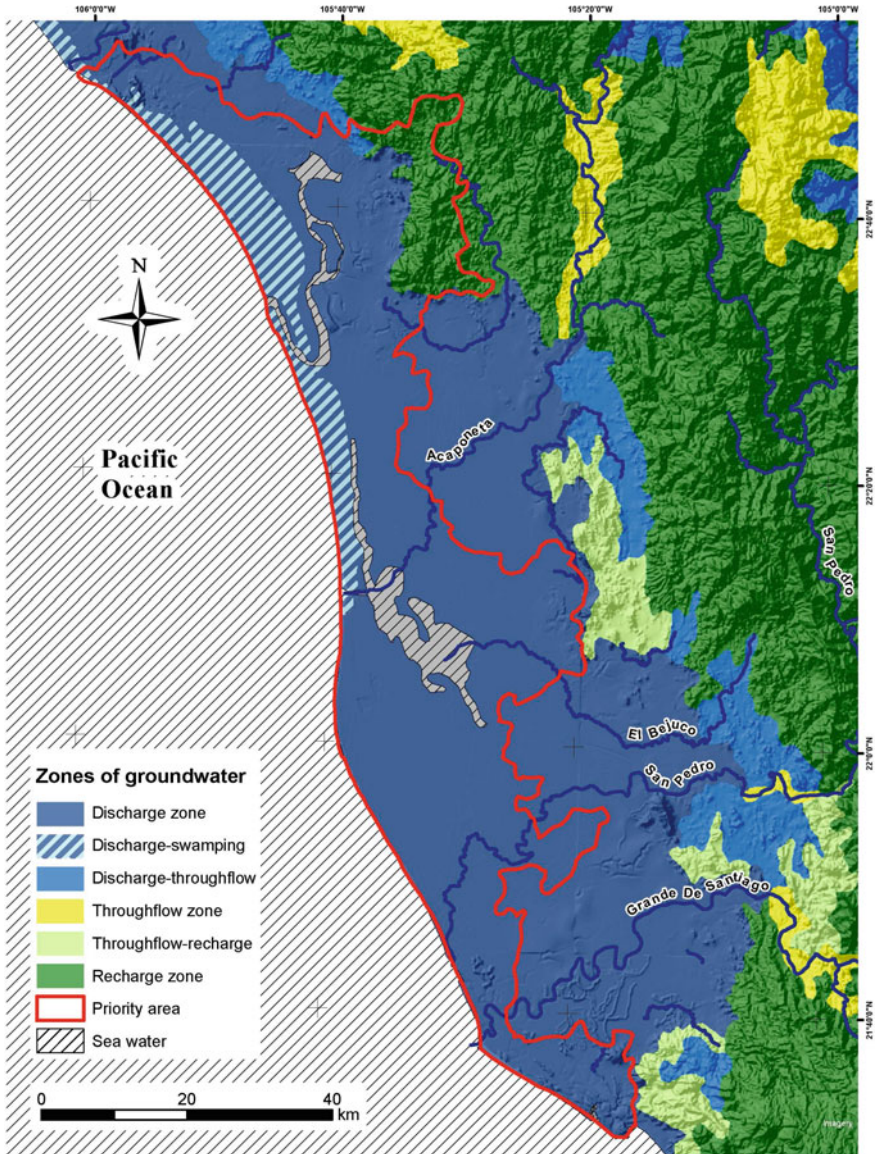


Fig. 9.9 Topoforms as a hydrogeological indicator at the water surface

The attributes of each map were combined into a single feature class inheriting all the attributes of the intersecting features. A comprehensive analysis of all conditions defined for each of the surface indicators was conducted for a final association of groundwater flow assigned to each feature. The areas that had previously been associated with discharge in the “Permanent surface water as an indicator of hydrogeological dynamic” (Fig. 9.5) and “Soils as an indicator of hydrogeological dynamic” (Fig. 9.7) maps were directly associated with discharge; the remaining combinations of unique conditions were systematically analysed separately, defining the zones of the groundwater flow systems, from which the final “Superficial evidence of the presence of groundwater flow systems” map was obtained (Fig. 9.10). This process has limitations as it combines different thematic datasets with different spatial resolution and accuracy and should be interpreted with caution and only in a general context approach.

Approximately ninety per cent (90.33%) of the Priority Area contains surface indicators associated with processes of *discharge* from groundwater flow systems. The features reported in the remaining ~ 10% of this area are associated with *discharge – throughflow*, 2.79%; *throughflow*, 1.51%; *throughflow - recharge*, 4.79% and *recharge* zone with, 0.58%.

In the discharge areas shown in Fig. 9.10, water is permanently present, either at the surface or at a shallow depth. However, the only way to confirm the presence of shallow groundwater at a point in these discharge areas is by using local and up to date records. This is so for two reasons: (i) the origin and temporality of the data for each of the surface indicators, as indicated in the methodology, and (ii) the constant dynamics of the groundwater flow systems, mainly due to human activity, direct or indirect.

At present, groundwater discharge and recharge are mainly affected by water extraction through drilling and wells, soil evapotranspiration and agricultural activity, loss/alteration of natural vegetation, alteration of the natural channels of perennial runoff, soil waterproofing and soil compaction-collapse. Climate change will also affect the volumes and patterns of precipitation, and therefore affect the groundwater flow systems.

Around 90% of the Priority Area studied has been classified as a zone of *discharge*, and of that 88% has perennial water on the surface. In other words, 90% of the spatial polygons of the spatial attributes of all the surface indicators evaluated were directly associated with the discharge *zone*. The complex hydrographical network has produced the ecosystems and topofoms that are found here; it is important to establish the associations which exist between these and the surface indicators of groundwater discharge. Table 9.1 shows the surface of the Priority Area associated with the discharge zone and the degree of correspondence of each indicator in the surface individually associated with the discharge process of groundwater flow systems.

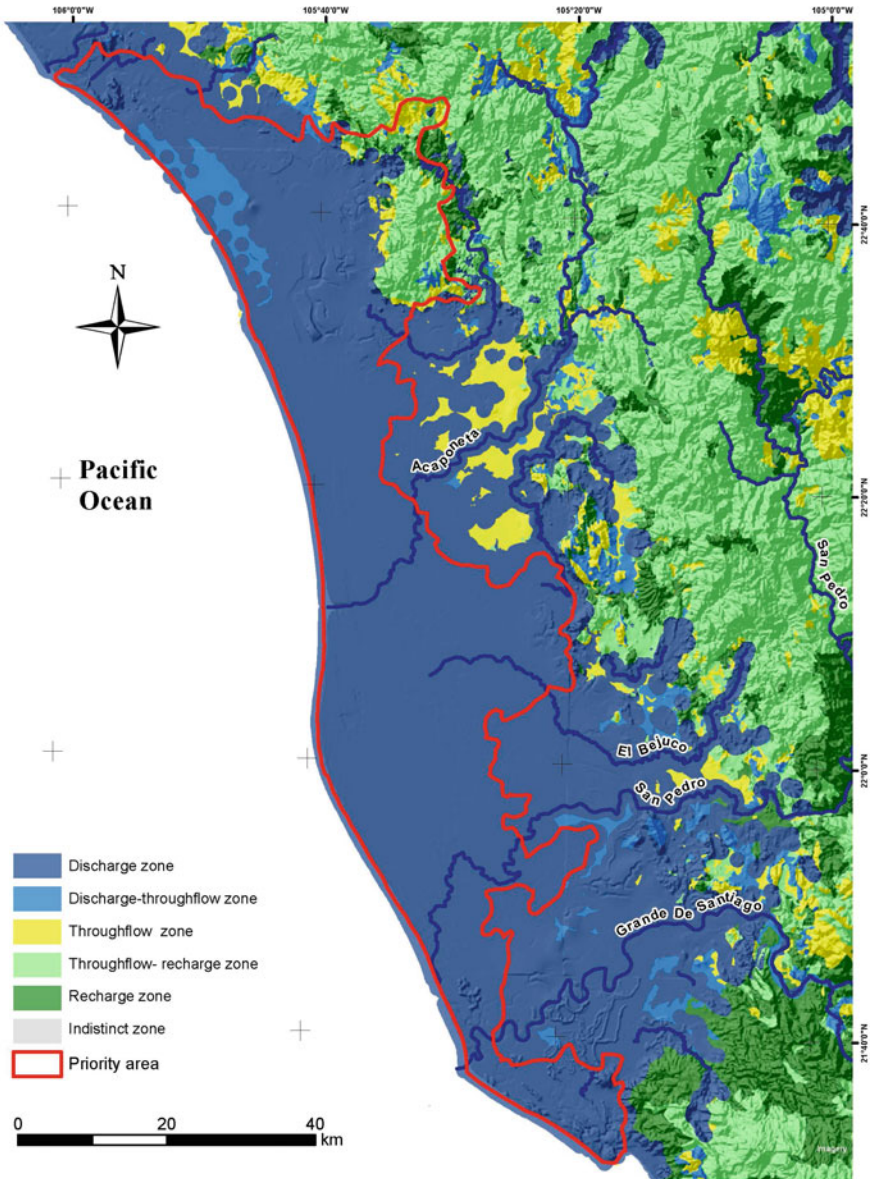


Fig. 9.10 Superficial evidence of the presence of groundwater flow systems

Table 9.1 Surface indicators and association degree in the discharge zones

Final association zone	Surface indicator						Marismas Nacionales (%)
	Surface water	Soil	Vegetation	Groundwater depth	Topoforms		
Discharge	Discharge	Discharge					60.00
	Discharge	Discharge-throughflow					7.80
	Discharge	Discharge/Discharge-throughflow					68.00
	Discharge		Discharge				57.00
	Discharge	Discharge	Discharge				47.50
	Discharge	Discharge	Discharge		Discharge		46.50
					Discharge		4.56
					Discharge		2.00
					Discharge	Discharge/Discharge-throughflow	4.43
	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge/Discharge-throughflow	0.17

It is worth noting that in 47% of the Priority Area, the edaphic coverage and the vegetation are associated on the maps with the discharge of groundwater flow systems in parallel with the presence of perennial water on the surface or the subsurface. This means, the cartographic features for each surface indicator are characteristic of processes of discharge from groundwater flow systems. While 46.5% of the area associated with the discharge zone registers that all the surface indicators, except “Groudwater depth”, are individually classified as discharge zone. This is caused by the scarce record of piezometric depth that exists in the study area, as in the rest of Mexico. It is important to consider the dates when the maps were elaborated. That is, the years and dates of field registration and/or satellite images for each of the maps used are not from the same date. This may mean that in a zone that has been mapped a Solonchak type soil (typical soil of the discharge processes) in the dry season, it can be registered as flooding zone in other maps.

In relation to the recharge zones, Fig. 9.10 shows that 5.37% of the priority area presents manifestations associated with recharge processes (4.79% throughflow - recharge, and recharge zone 0.58%). The importance of the zones does not lie in their territorial extension, but in their location with respect to the environment of interest. In the case of the priority area of the Marismas Nacionales, the zones associated with recharge processes indicate that the recharge that occurs in them supplies the priority area as well as environments outside the polygon. And that evidently, the recharge processes that mostly feed the study area happen outside the established polygon.

It is worth remembering that in smaller recharge/throughflow zones, discharge processes also occur, and in discharge zones processes of recharge/throughflow may also occur locally.

9.5 Environment—Groundwater Interactions

After developing the spatial analysis of the surface indicators, it must be integrated to the existing knowledge about the ecosystem and environmental functioning of the Marismas Nacionales (Blanco et al. 2014; Flores-Verdugo et al. 2014; Lithgow et al. 2019; Silva et al. 2019), allowing to solve questions about the functioning and the ecosystem interconnection through the water dynamics. In addition, however, there will surely be clearer, and perhaps more challenging, questions as the content of this study is assimilated.

To understand natural and environmental systems it is important to start from the origins, development and behaviour of each of the components analysed. By characterizing the zones of groundwater flow systems in the study area, questions about the causes and mechanisms of environmental impacts related to groundwater begin to surface. Many of these have direct effects on the ecosystems in the area, and, therefore, on the ecosystem services they provide.

- In almost all the study areas there is evidence of the processes and features typical of groundwater flow system discharge zones. The recharge zones of this water are

beyond the polygon studied; most of the water which supports the ecosystems of the Priority Area of the Marismas Nacionales originates outside the conservation area. Is it possible to conserve the Marismas Nacionales without conserving the zones of recharge and throughflow that feed it?

- The evidence of discharge zones off the coast indicates that the marine ecosystems are dependent on the discharge of groundwater from inland.
- The ecosystems found in the Priority Area depend directly and heavily on groundwater.
- The ecosystems of the Marismas Nacionales are under great pressure from agriculture and aquaculture activities. The effects of these activities are related to inappropriate farm management practices, such as periodic flooding and draining, lack of water treatment, lack of control and monitoring groundwater well operation, as well as water extraction from springs and rivers.
- Even with the naked eye, it is easy to see the degree of change and pollution generated by agriculture and aquaculture. However, the main cause of changes related to all uses of water, is the extraction of underground water via pumping wells, both within and beyond the polygon.
- Pollution of and via groundwater affects all the interdependent ecosystems, both on land and off the coast. For example, phosphates, and other pollutants infiltrate into streams and groundwater inducing mangrove mortality in the surrounding areas and downstream. Despite the lack of samples of polluted groundwater, a significant increase in superphosphates and other pond fertilizers has been detected downstream during harvest season.
- Given the high number of channels between the low ridge dune systems, this coastline is very vulnerable to an increase in sea level. Therefore, in order to maintain the cohesive forces between the sediment particles on the coast, it is vital to maintain groundwater flow systems, since the present equilibrium is due to the presence of water from direct or diffused discharge.
- In the best case scenario, where it is possible to reduce or eliminate the processes causing water pollution within the conservation area, the question arises: Can we guarantee that the groundwater flow systems which discharge in the polygon are not agents of pollution originating beyond the polygon, in zones of recharge?
- Apart from global factors, the Marismas Nacionales sustainability is highly vulnerable to local changes in sedimentary dynamics because the system relies on sediment inputs from inland and sediment transport by waves. The permanent contribution of the sediments from inland occurs through the rivers and their respective baseflow, i.e. through the discharge of groundwater.

Consequently, land or coastal infrastructure and human activities alters and may eventually eliminate hydrogeological interconnections in the area. Therefore, the effect of hydrological and biological processes on the energy and matter fluxes need to be understood. An accurate diagnosis of these relationships is critical in designing conservation and restoration strategies of the system.

9.6 Final Considerations

From the environmental information available, new maps were developed linking environmental features with groundwater flow systems, using Toth's theory. The present work achieves the first contribution or utility of the spatial analysis of surface indicators of groundwater flow systems: making groundwater visible. Phase or condition of water that is so difficult for people to see and understand, apparently.

This work offers new information concerning the natural dynamics of the Marismas Nacionales, based on the application of modern hydrogeological theories to existing databases. The reinterpretation and spatial integration of the main biophysical components on the surface shows the interconnections between groundwater flow systems and the ecosystems within the Marismas Nacionales. This has a direct bearing on the ecosystem services they can provide.

This work should continue, in order to identify the recharge and throughflow zones and their links to the discharge zones. In this way it is possible to know exactly where the continental water recharge that supports the Marismas Nacionales occurs by the groundwater flow systems with discharge zones located inside the conservation polygon.

While from the outset it was obvious that the Marismas Nacionales can be considered a groundwater discharge zone, it is necessary to define the hierarchy of groundwater flow systems, in order to understand the natural dynamics of an ecosystem or specific environment. By defining the recharge and throughflow zones it becomes clearer that a given feature worthy of conservation depends not only on its immediate surroundings. For example, the mangroves of the Marismas Nacionales are recognized as a RAMSAR site and depend on the groundwater supplied to them from beyond the polygon in which they are found.

On the other hand, from the evidence presented by this work the Marismas Nacionales is an area that has potential to produce clean electric energy by salinity gradient technology, since it registers a relevant coastal freshwater discharge zone with a gentle topographic slope.

By understanding the relationship between natural and anthropogenic factors in the dynamics of change in the region, the consequences of actions such as natural or artificial groundwater extraction can be evaluated in specific areas.

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