Provisional chapter

# Hydrological Stress and Climate Change Impact in Arid Regions with Agricultural Valleys in Northern Mexico

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Additional information is available at the end of the chapter

**Abstract**

In recent decades due to the negligence of groundwater management, the resources are degrading rapidly and have resulted in soil water stress. Owing to the role of climate change, now most of the environmental variables undergo variations in their dynamics and magnitude, and above all, arid zones suffer the greatest loss due to evapotranspiration and soil water stress. In order to understand the nutritional future of the most important agricultural regions in Mexico, this scientific contribution aims to analyze the trend of soil water stress in the Northern Mexico. The work emphasizes on the relationship between the energetic movement of groundwater and soil water stress which also includes the process of crop absorption that is affected by the changes in soil surface temperature and the geography of the region. The results reveal a positive trend that gradually leads to soil water stress and intensities associated with conditions of interdependence of unique variables in each valley. Global withdrawals of ground water tripled in the last 50 years with unequal volumes in arid zone that will definitely lead to instabilities, where sustainable management will be the basis of conservation to adapt to the new facies of climate change.

**Keywords:** groundwater, climate change, water stress, risk and agricultural valleys

## 1. Introduction

Worldwide, in many countries, the concerns of the productive sector on issues related to global warming and the consequences that current climate change could cause, especially the effects due to the changes in the average surface temperature of the world, will be discussed in this chapter. Soil and environmental temperature can significantly affect economic activities that are mainly related to the agricultural sector where soil is the main source of supply for food sustainability which is at risk due to water stress. The situation strongly affects the developing countries because of scarce economic resources that make their population vulnerable and poor resilience when it comes to facing the phenomena related to climate change. Decades ago, simple observations permitted mankind to realize the changes experienced by the environment, preferably by the increase in the frequency of occurrence of extreme weather events and environmental changes. Likewise, global environmental events associated with global warming caused the initiation of relevant investigations that would implement different methodologies to evaluate the vulnerability of climate change and henceforth to bring in awareness among the people. The book "Training methodology to assess vulnerability to climate change" is a typical example of this action. Undoubtedly, the frequency of occurrence and extreme meteorological phenomena of the past, present, and future and the fundamental cause is largely due to the increases and/or decreases in the regime of precipitation and potential evapotranspiration resulting in droughts and heavy rainfall regimes. Several research papers have documented the disparities and influences of climate change, whereas this work presents the thematic behavior of the temporal variation of soil water stress in the agricultural zones of North Mexico. In the present investigation, climate modifying factors in reduced spaces are analyzed in an integrated manner which could permit the scientific community to focus on general concepts such as heat islands and heat waves [1, 2] as in the past, which is actually related to augmented temperature rise [3].

There are many documented evidences regarding the economic losses caused by extreme meteorological events due to climate change, for example, Colombia witnessed 1970–2000 landslides and floods from 1970 to 2000 that caused heavy economic losses up to US $ 2.227 million that the National Planning Department (NPD) of that country was only 2.66% of the National Gross Domestic Product (GDP) for the year 2000 [4]. Perilous phenomenon in Mexico that could cause economic losses in the future, such as those caused in other regions of the country, is the excessive accumulation of cloud systems around the great mountains in the south of the country, preferably over the southern mountain ranges of Oaxaca and Chiapas, and also in the Northwest on the eastern and western Sierra Madre Oriental and Occidental. Several satellite images have also represented an increase in the spatial and temporal distribution of cloud systems (mostly clusters) that can reach up to size of a cyclone. The cloud accumulations before the presence of sufficient humid air initiate their route toward their distinct stages resulting in precipitation. However, irregular precipitations due to climate change can be considered to be the vital reasons that could increase the ambient and soil surface temperatures.

Specifically, in the mountain ranges of Sierra Madre Occidental and Oriental, the cloud clusters begin to group and tend to grow vertically to reach their mature state during the afternoons and later they begin to propagate throughout the region, but when crossing the great mountain ranges of the Sierra Madre, they form storms with intense lightning and up to the possible presence of hail. During the propagation, the clusters are conglomerated in large cloud systems of extensive oval shapes that can be observed by infrared satellite images. Likewise, the similar type of occurrences on August 23, 2010 caused heavy rains in the Papaloapan River Basin situated in the southeast part of Veracruz State, Mexico was observed, which eventually resulted in the accumulation of large oval cumulus systems during the same time period causing electrical storms that by the end of August ensued large floods in the Tlacopalcan community of the same state. Given the damage caused, there is no doubt about the importance of continuous monitoring of meteorological phenomena by means of available resources, and that the evolution and trajectory of the meteorological events must be tracked, in order to anticipate possible damage and take right decisions immediately. However, current meteorological studies do not reach such magnitudes of tracking, but with state-of-the-art technology developed in Mexico, satellite imageries and high-end monitoring techniques can provide early alerts and prevent risks from fires, severe storms, hurricanes, and also infrared satellite images can track the trajectory of a tropical storm in real time [5]. It is important to highlight that there are many scenarios in Mexico where the historical levels of diverse phenomena related to extreme meteorological events are surpassed; and most of them occur in regions which have experienced the rainiest periods in their histories leading to massive floods in the agricultural areas affecting the economy. Otherwise, the phenomenon can also occur in regions with absence of precipitation face drought scenarios such as those found in the northwest of the country facing Gulf of California. Regardless of the conditions caused by climate change, increase in the frequency of extreme meteorological activities always affects the economy and GDP of a country as climatic variability in great proportions distresses different productive sectors. Several studies at the regional level indicate that agriculture and rural development are severely affected, especially during the presence of the El Niño and La Niña phases; that increase or decrease in the climatic anomalies in large proportions bring floods, landslides in cultivated lands, proliferation of diverse pests, expansion of diseases, changes in the vegetative cycles of crops that are commonly enabled to the repeated ways of practicing agriculture, the seasonality of crops and production. Agriculture largely depends on the rainfall regime, soil surface and ambient temperature, and the soil conditions.

Therefore, it is logical to think that in places where climate change effects are observed, it can be inferred by the presence of environmental damages, so this would be the areas where the responses of soil due to climate change have to be defined, considering that soil, air, and temperature are in equilibrium. The large coastal plains of Northwest Mexico located along the Gulf of California encompassing the states of Sonora, Sinaloa, and Nayarit are the regions in which changes have been observed and reported for a long time due to the increased occurrences of extreme meteorological events. In the present work, the abovementioned regions are considered to be regions where geography intervenes to the formation of meteorological events. So, in this work, it is assumed that the environmental interventions due to climate change are directly proportional to the local geographical conditions that aid the formation of extreme meteorological events described above. That is the reason why we selected a coastal region of the state of Sinaloa to raise the objective of determining the change in water stress with respect to time [$\Delta Eh(x, t)$] in the soil of the valley of Guasave better known as "The agricultural heart of Mexico." The region is predominantly agricultural in which the subsoil has undergone agricultural pressure continuously since the 1960s due to the growing technologies and ideals set by the "Green Revolution."

In order to achieve the objective, data available from CONAGUA and the Environmental Engineering research group of CIIDIR-IPN-Sinaloa were analyzed and processed; in relation to the intrinsic variables of the agricultural land possibly affected by extreme meteorological events. The temporal space variation of $\Delta Eh(x, t)$ was measured based on the criteria of Medrano et al. [6] and conditioned to the methodological approaches of Sánchez [7]. The results can significantly measure over effects that could cause changes in the internal structure of the soil subjected to local climatic changes that could significantly affect the ways in which various crops exploit the $H_2O$ resource for its development in the area possessing climatic conditions ranging from arid to semi/arid.

The investigation is justified by the mere fact of the latent presence of the meteorological phenomenon that currently occurs in both Sierra Madre Occidental and Oriental that causing rare meteorological events and forcing to carry out agriculture unceasingly under high risk.

## 2. Methodology

Among the three states of the Northwest Mexico (Sonora, Sinaloa, and Nayarit), a coastal agricultural region of Sinaloa State, Guasave, was selected for the present study. Located in the Northwest part of Sinaloa State, the region elucidates a long history of agricultural practices even from the period of "Green Revolution" (**Figure 1**). Due to its agricultural history, high productivity, and high-end technology, the area represents the incursion of large foreign currency into the Mexican economy, which have been the fundamental bases to be called "The agricultural heart of Mexico." The region consists of soils with diverse granulometric extents originated by the geological processes derived from different episodes that date from the Late Oligocene, the Middle Miocene (25–15 million years ago), and late Pliocene (<5 million years ago) and the current Quaternary [8]. The region also characterizes intermountain relief and coastal valleys.

The variation in the present-day relief started approximately in the altitudinal elevation of 1800 m, in the eastern limit of the Sierra Madre Occidental (natural barrier that protected Mexico against the dangerous tropical hurricane Patricia in mid-October 2015, formed by a tropical disturbance south of the Gulf of Tehuantepec). A transition towards the high plateau is characterized by a steep decline governed by an abrupt slope tending toward the Gulf of California and the Pacific Ocean until reaching the coasts at a regular altitude varying between 14 and 40 m above sea level. Specifically, to the North of the Sierra Madre Occidental, geological processes have resulted in an average altitude of 1400 m above mean sea level [9]. Henceforth, the area is made up of extensive agricultural coastal plains, and precisely the valley of Guasave constitutes slow and continuous flows of River Sinaloa streams of Ocoroni, Cabrera, and San Rafael; where the last three streams discharge into the Gulf of California. According to recent studies on the interpretation of geophysical data of geo-electric type [10], as a hydrogeological unit, the system is sometimes treated as a free aquifer that is commonly exploited and represents the regional geology which could be observed in varying depths where the hydraulic works are drilled [11].

Due to the changes in the environmental temperature, the increase and/or decrease of the precipitation regime, the presence of global warming and the consequences of climate change, some of the considerations of the criteria of Medrano et al. [6] were taken into account in order


**Figure 1.** Coastal agricultural valley of Guasave, Sinaloa, Northwest Mexico.

to justify this investigation related to the ways in which a soil is stimulated Δ*Eh (x, t)*. Given the presence and absence of the precipitation regime, it is considered that an environmental scenario can be altered under the behavior of the main factors that modify the climatic conditions in a reduced and closed space, and such a scenario was constructed in this investigation taking into account that the local geography is the fundamental cause that intervenes the modification of the main climatic factors. The important evidence that integrates these main climatic factors is to consider that it is a continuous system that fills everything within a closed space, that is, each of the variables measured at each point of the continuous system is the result of the volumetric response of the matter before the intensity of each variable that occurs within a closed space and continuous, in order to modify the factors that govern climate change and resulting in dissimilar soil conditions Δ*Eh (x, t)*.

Since each continuous system fills every space it occupies, the magnitude of the variables that described Δ*Eh (x, t)* is the total response of effects on the matter or mass measured. Therefore, the accurate measurements of different variables that intervene in the modification of climate change and soil conditions were evaluated in the present study. The processes to characterize (physiological response of crops to water flow, capacity, and volume of each soil to store water and climatic conditions), were selected according to the criteria of Medrano et al. [6]

and various continuous variables were measured. Understanding the different physiological processes that govern water flow in plants allows us to estimate the efficiency of plants to manage water surplus and shortages. The density and depth of each plant species determines the water hold capacity of soil with respect to the total available water. However, the climatic conditions regulate the actions in which the plants need water and are strongly defined by the evaporation of the soil and in the same way by the atmospheric demand of how a soil requires water. The arguments by which the above criteria were selected was due to the fact that their variables can converge in an interdependent way and describe most of the processes that plants require during their development and growth, but also because they take into account a set of variables that intervene in the description of the physical state of the soil and which allows to act as indicators to estimate the behavior of $\Delta Eh\ (x, t)$.

The following is a brief description of the variables that intervene in the previous criteria and justifies the reason why they were taken into account in the definition of $\Delta Eh\ (x, t)$.

In the first criterion, the variables that intervene in the physical, chemical, and physiological processes inside and outside the plants are addressed and correspond to the variables that integrally give an ideal representation of the mechanisms that govern the water fluids. Therefore, it was considered that these variables define the availability of water resources, the humidity of both the soil and the environment. The variables considered were the depth at which the groundwater table is located in the aquifer as this distance is defined according to the internal and porous structure of the subsoil by 80% in the presence of the surface moisture of the soil and the moisture of the environment.

Regardless of the fact that a change in the precipitation regime is the one that can largely define the presence and/or absence of both surface and groundwater resources, this process does not result in a significant change in the internal structure of the subsoil at great depths and influences the physicochemical properties that would occur only in the structure of the superficial parts of the soil. Henceforth, within the aquifer, there are no significant changes in the ways in which advection processes can occur simply because no changes occur in the internal structure that defines the properties in which the advection occurs, to mention a few; storage coefficient, porosity, transitivity, hydraulic conductivity, among others; which will be discussed in the following criteria. Nevertheless, the foregoing, significant changes may occur due to the intensity and long periods of rain affecting the surface soils and within the aquifer, the changes would occur in relation to the magnitude of the intensity of the flows and quantities of existing fluids during the transportation processes in the porous medium. Therefore, it was taken into account that the magnitude of the following variables is those that contribute greatly to the existence of water flows and directly related to the temporal space variation of the depth of the static level of a region.

In the second criterion, the soil scenarios in which the crops are grown are also directly related with the internal structure of the soil and/or with the potential of each soil to exercise agriculture. Texture is one of the main variables that define the granulometric variation of each soil, degree of characterizing its structure type from thin to thick; that allow plants with the facility to extend their roots to the length of the subsurface horizons and are associated with the potentiality of crop development. Other variables that develop a crop into plant and aid in water storage are porosity ($\phi$), hydraulic permeability ($K$), and transitivity ($T$) of the water resource through the porous medium that defines in a great way the opportunities of development of the crop and the amount of water required by the soil based on the availability of water, that could be altered by the presence of $\Delta Eh\ (x,\ t)$. Continuous water flow received by a plant is determined by T and ϕ of the subterranean environment, which according to Villanueva and Iglesias [12] T must be in a range of 500–1000 $m^2$/day. So, this research was based on the fact that the variables that define the development opportunities of a crop in terms of what is required to a high availability and/or absence of the water resource in the porous medium and in the plant would be the variation in the abovementioned parameters. Several field works were carried out in the area to define the variation of surface geology and to set up a monitoring network of 42 wells where the monthly sampling of water at different depths and soil for every 2 m was performed. Laboratory measurements were carried out to evaluate the porosity, transitivity, and hydraulic permeability in the saturated and unsaturated zone of the free and confined aquifer.

The third criterion was selected because it indirectly contemplates for its occurrence which includes the effects of the amount of radiation, humidity (absolute and relative), environmental temperature, and wind speed, which can be altered due to global warming, changes in the rainfall, and climate regime of a region. Regarding the modification produced by climate change, the criteria of Sánchez [7] were taken into account to select the factors that have enormous consequences on any climatic parameter and that depend on geography and that the literature considers them as the main regional climate modifiers. The modifying factors in a closed system that favor climate change were observed to be absolute height (*ah*), relative height (*rh*) or location, latitude (*Lat*), longitude (*Long*), exposure (*Ex*), and local continentality (*Ct*). The consideration by which we took into account these factors that can lead to climate change within a closed system was due to the fact that as a whole are the factors that depend on the local geography and can produce climatic mutations in a reduced space. Whereas in an open system, mutations are caused by the general circulation of the atmosphere (GCA) and they are generally very small and reduced to the degree which almost become nonexistent in such a short distance. Reduced climate change effects, unlike those that occur on a large scale, are favored by the conditions of the GCA, geographical factors, the shape of continents, and the action of the oceans. Therefore, the present investigation constitutes a basis to consider climate change as the sum of the set of microclimates influenced by closed spaces that function independently according to the local conditions and to the behavior of the main climate modifying factors already mentioned. Such climate modifiers are those that regulate the presence of water in a region, and according to the granulometric constitution of the soil, they would be those that as a whole affect the variations of the phreatic depth of the aquifer that regulates the presence or absence of environmental and soil humidity. Therefore, this work focused precisely on the exhaustive measurement of the phreatic depth in order to comprehensively describe the behavior of $\Delta Eh\ (x,\ t)$ considering other factors of vital importance of the soil, such as $Tx$ and ϕ. The global climate change can be considered as a real representation of the climatic behavior at greater scales or by means of the summation or integral that makes a more complete estimate about the changes that occur globally. To understand this approach, it is important to establish that the main profound changes experienced by climate variables in a relatively closed area such as the Guasave Valley have a behavior that responds differently according to their geographical factors and directly influences the thermal and fluviometric conditions. In this study, $\Delta Eh\ (x,\ t)$ is considered as a relative system as absence and/or extreme excess of water in the soil can be considered already engrossed in the process of $\Delta Eh\ (x,\ t)$ and its behavior cannot be estimated through a simple statistical correlation or factor thresholds, but rather with the use of a complex statistical analysis, in which all the variables intervene and the interdependence and percentage contribution, with which the influence of each variable of the Medrano et al. [6] criteria can be described in an accurate way. The factors or variables are also influenced by the geographical effects according to a representative function (ψ (x,t)) of the integrated behavior of the system $\Delta Eh\ (x,\ t)$ in which the temporal space variation is the summation of the behavior of each variable as defined by the equation $Eh(x, t) = \oint_{to}^{tn} \psi\ (x, t)\ dx$, which integrates the changes occurred due to climate change in a closed system, where *to* and *tn* represent the change in time in the matter and that have effects on each variable to understand the intensive properties caused by climate change and as a whole can be considered as an extensive property as a function of time through each function ψ (x,t). The integral equation of the functions ψ (x, t) presents extensive properties in the matter that in this case is the soil and that in an integrated way the set of variables are those that define the response of $\Delta Eh\ (x,\ t)$ and the contribution of each of these is described mainly by the weight of each of the variables inside and outside the system. Furthermore, if the property of the material can be extensive in time, if and only if it is governed by the behavior of the previous equation, it can be said that the effects caused by climate change respond to two properties in the matter that is associated to "the intensive property given by the variables and the extensive property given by the effects of climate change." In this case, according to the principle of continuity, the intensive properties are the variables resulting from continuous interaction of climate change with the matter resulting in different conditions of $\Delta Eh\ (x,\ t)$, whereas extensive properties refer only to the effects that take place in the set of all the variables before the intrinsic properties of the soil and they result in the total presence of $\Delta Eh\ (x,\ t)$. Thus, the relationship presented is an integral function that defines an intensive property and establishes a one-to-one correspondence between extensive and intensive properties. In particular, if the values of the integral function are vector, then the corresponding extensive function will also be vector. It should be noted that there are different ways to define an intensive property and, in our case, we have defined it as the property that has the effects of climate change per unit volume.

From the physical point of view, the basic hypothesis to formulate this investigation was "The balance of the extensive properties in the theory of the systems of the continuous flows and of the variables that interact with the matter, as a whole converge to define an integrated manner both in closed and open systems the effects produced by climate change" whose numerical analysis will be established through the type of system (closed and/or open) and its mass balance can be obtained through the premise "any variation of the extensive property caused by the changes in matter due to climate change is the result of what is generated or destroyed within the body or mass and of what enters or leaves through its borders." Given that the effects caused by climate change depend on the main geographic factors that regulate the climate of each region, precipitation, and environmental temperature, their respective magnitudes were concentrated in a database to position the variables according to the three criteria of Medrano et al. [6] and according to the territorial extension. To perform the measurements of the variables involved in the description of $\Delta Eh\ (x,\ t)$, a monitoring network of 660 wells was established. Because of the costly, laborious, and/or simple that it was to obtain the sample and how difficult and/or easy to access, from the general network in a random way, 42 wells were selected, which were taken monthly at every 2 m of depth. Water and soil samples were transferred to the laboratory to measure the physical and granulometric characteristics, respectively. Following the techniques of Bouyocus and paraffin, the values of Tx and ϕ, respectively, were determined. In the network of 42 wells using the simplified Theis method, pumping tests were carried out to estimate the magnitudes of T, S and K, while in the network of 660 wells, we used an electrical probe to measure the phreatic depth and at the same time the height of the curb of each hydraulic work was also determined. With the measurements of phreatic depth and height of the curb, the hydraulic load (H) was obtained in each well and using Darcy's Law, the regional hydraulic gradient (∇.H) was obtained from well to well; and thus, through the interpolation of data by means of a Kriging, maps were prepared that indicate the preferential direction of the groundwater flow from the recharge zones to the discharge zones.

During the field trips, the locations of the wells in both the networks were estimated using differential GPS. The temporal variation of the solar radiation was also measured using a pyrometer. Although a good number of variables were measured to understand the dynamics of $\Delta Eh\ (x,\ t)$, the statistical analysis was focused on the description of the behavior of the phreatic depth of aquifers, since it was considered as one the most important variable responsible for the volumetric exchanges of $H_2O$ between the aquifer and the surface; besides the absence and/or presence of this in the porous structure of the soil, in the plants as well as in the environment. Therefore, the proximity or phreatic distance was considered directly proportional to the moisture potential of plants. To describe the behavior of the zone of saturation, statistical measurements of central tendency, noncentral position, and dispersion were used [13]. The measures of central tendency used were Mean ($\overline{X}$), Median ($M_e$), Kurtosis ($K_s$), and the dispersion of range of variation ($X_{min,}\ X_{max}$), Standard deviation ($\sigma_0$), and Variance ($\sigma^2$). The statistical measures carried out using the software STATISTICA (version 7.0) and the interpolations to obtain the equipotential curves of the variables were done using SURFER (version 10.0), where the latter formed to be the fundamental basis for the preparation of the final maps attached to the regional urban trace. Final details were elaborated using the program Corel Draw X6.

## 3. Results and discussion

To meet the first criterion of Medrano et al. [6] for the presence and/or absence of surface humidity in the soil and in the environment, indistinctly of precipitation, the results of the spatial variation of the phreatic depth are discussed. The phreatic depth variation from the measures of central tendency presented an irregular spatial behavior along the valley with respect to the average value obtained from the dataset in the network constituted by 660 wells from the coast to the mountain areas. The central tendency measurements marked somewhat similar values for $\overline{\overline{X}}$ and $M_e$ equivalent to 5.88 and 5.61 m; measures of central tendency did not provide an adequate description of the set of measurements that defined the spatial distribution of phreatic depth in the Valley, and could not give an exact description of the variation of this parameter; however, because the phreatic depth values turned out to be superficial, it can be regarded as a potential indicator of the evidence of $Eh(x, t)$ type saturation in most of the soils of the study area. The values of $X_{min,}$ $X_{max}$ were 0.94 and 16.17 m, respectively, whereas the variability or dispersion of the variance was observed to be $\sigma^2$ = 10.34 m and $\sigma_0$ = 3.21 m with $E\,\sigma_0$ =0.03, which was relatively low.

The values of $\sigma_0$ were accepted to be less than the values for $\overline{\overline{X}}$ and $M_e$, situation observed by the symmetry of the phreatic distribution along the valley with the magnitude of 2.54 presented the distribution of $Ks$. $\sigma_0$ showed a less value, so in general terms, the data collected were considered adequate for the information process. The spatial variation of the phreatic depth is presented in **Figure 3** and the lesser values of the phreatic depth ranged from 1 to 5 m with parallel alignments to the coast line and in the preferential direction of NW-SE revealing the protuberances of the Sierra Madre Occidental. These conditions of low depth represent the presence of a high environmental humidity; however, it is also indicative of high saturation states in the internal structure of the soil and in turn the presence of $\Delta Eh(x, t)$, in which the soils by proximity to the sea in the presence of an intrusion phenomenon are no longer apt for practicing agriculture. In turn, the spatial configuration of the phreatic zone allows us to observe soils in transition to the presence of $\Delta Eh(x, t)$ and that could be considered as a future risk. Nonetheless, the foregoing, before the most important factors that modify the climatic conditions of a closed environment, it is important to take into account the superficial granulometric variation of the soil that may constitute its full conservation or its ease of destruction, and which is defined respectively by the magnitudes of $Tx$ and $\phi$; also indicate the potential of the soil to retain $H_2O$, so they are both directly related to the field capacity of the soil that is an indicator of the amount of water moisture that the soil requires after being completely saturated, may be it has been wetted and drained with respect to the topographic slope until again the water potential stabilizes its action that lasts from 1 to 2 days (24–48 h).

There are evidences that at the depth at which the phreatic zone is located, a very specific humidity condition will be defined in the environment that is directly proportional to its depth, i.e., there is a linear and direct relationship with soil moisture. Due to the above conditions, increases and decreases in the water table of a zone like those observed in **Figure 2** can represent a direct relation to the period of time without precipitation, where $Tx$ and $\phi$ play an important role in the filtration/runoff interaction, being greater and faster the response the shorter is the period. Similarly, considering the logic to a hydrological response of the soil of a valley in the presence of rainfall, it is expected that the phreatic zone will vary in large scale depending on the time in which the rain occurs with respect to the previous period, and this hydrological response of the soil has increased to the extent that there are increases in phreatic zone, or decreases before the decrease; therefore, the speed of the believed hydrological response will depend on the forms of how $Tx$ and $\phi$ permit it.

In **Figure 3(A)**, the spatial distribution 660 wells where the measurements of the depth of the water table (*m*), hydraulic conductivity (*K*, m/s), transmissivity (*T*, $m^2$/s), curb height (*hb*, msnm), hydraulic load (*H*, dimensionless), and hydraulic gradient ($\nabla$.H) are presented. The

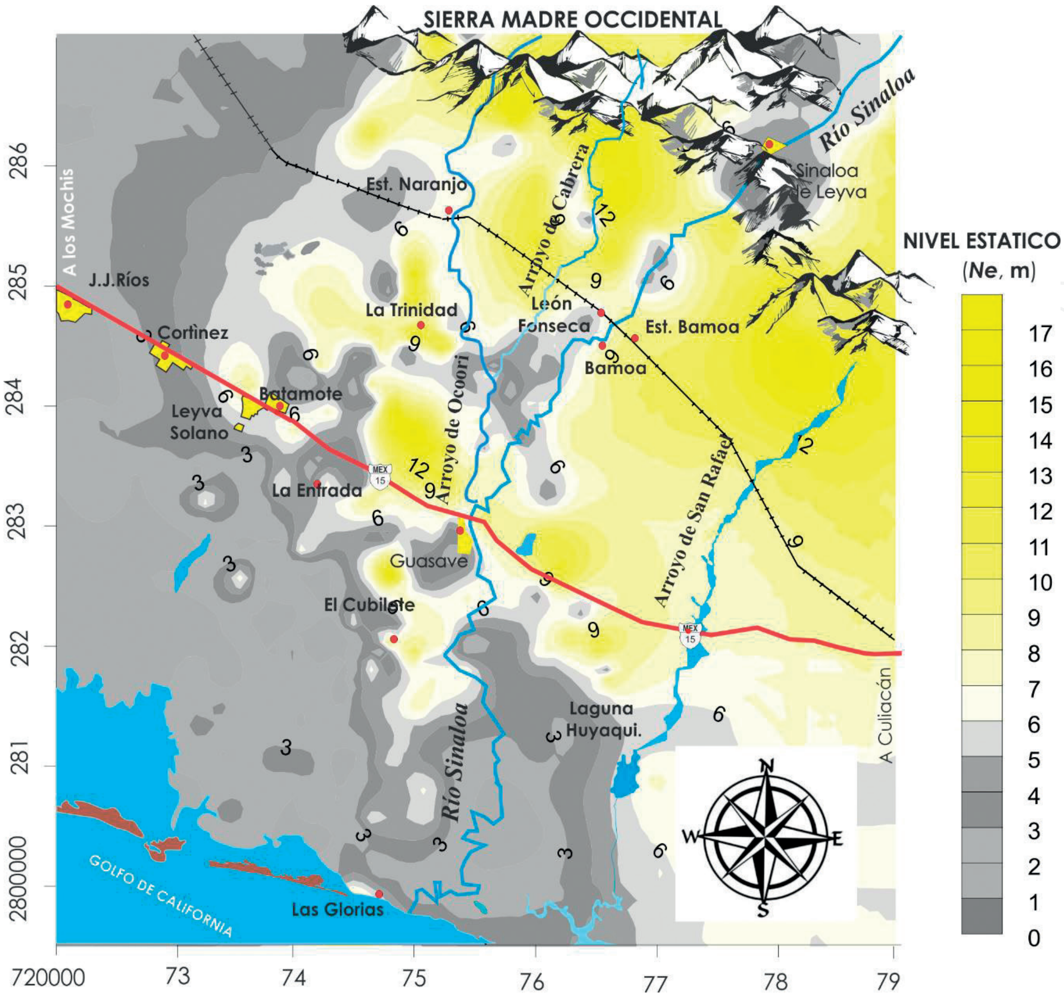


**Figure 2.** Spatial variation of the depth of the static level (*Phreatic depth*, m), configured for 2018 using 660 available wells for both human consumption and agricultural use (wells and deep agricultural wells) from the coastal zone of the Sierra Madre Occidental.

last three parameters were important in the determination of the piezometric map indicating the preferential direction of the waters in the subsoil. In part B, of the same **Figure 3**, the monitoring network of 42 wells selected from the general network is shown, under the consideration that there is an ease in the road and gaps to achieve access to the wells and facilitate the transfer of samples to the laboratory to perform the determination of the texture parameters (*Tx*, dimensionless) and porosity (ϕ, %) of the soil. Parts C and D of **Figure 3** present the map of the spatial distribution of the parameters *Tx* and $\phi$ measured in the laboratory. The last two maps are the result of the "Kriging" type interpolation made in the SURFER 10.0 computer program.

The reason why a wide network of 660 wells was selected was due to the fact that it was considered to have a greater control in the phreatic depth of the aquifer due to the fact that most of the water is concentrated throughout the year, and it is with respect to the phreatic depth. This network constitutes a constant and important source of water volumes that intervene in the content of the environmental and soil humidity, as well as large volumes of water for the ETP processes occurring between the plant and the soil.

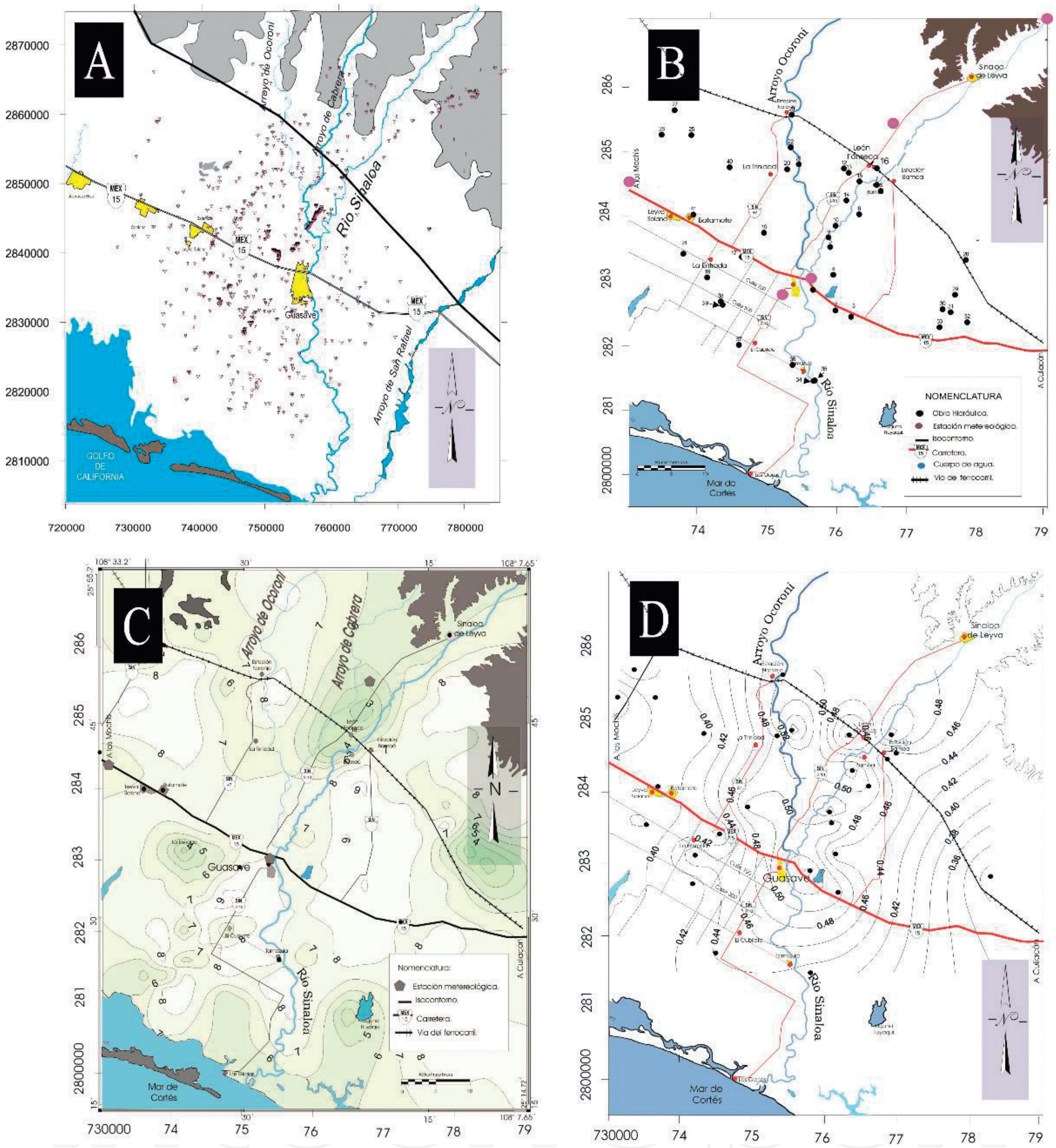


**Figure 3.** (A) General monitoring network of 660 wells selected randomly for the study (B) 42 wells selected for the measurements of textural parameters and porosity of the soil; (C and D) show the behavior of the spatial variation through the equipotential curves of textural parameters and porosity.

**Figure 3(C)** and **(D)** represents the spatial behavior of the equipotential curves for the values of $Tx$ and $\phi$, both obtained in the laboratory with their respective techniques. Since most of the crops in the valley are concentrated in the central areas of the valley, in the search of the best representation for $Tx$ and $\phi$, it was decided to have the majority of the wells distributed in random form in the central area as presented in **Figure 3(B)**. **Figure 3** presents the spatial variation of $Tx$ for which a scale was established, ranging from 1 to 11, which allowed to analyze the granulometric variation that goes from the most compact, through the soils of intermediate type until reaching the lowest content of cement: (1) clay, (2) sandy clay, (3) silty clay, (4) clayey-sandy mudstone, (5) clayey mudstone, (6) clayey-silt mudstone, (7) sandy mudstone, (8) mudstone, (9) silty mudstone, (10) silt, and (11) sand. If it is taken into account that the soils have the highest concentration of cement between their grains, they are soils that have a tendency toward low values of K, T, and S, so this type of soil will be revealed in the drought seasons.

According to the values of $\varphi$ (**Figure 3(D)**), a heterogeneity will be exhibited due to the high values of K allowing the soil to reach scenarios of $\Delta Eh(x,t)$ of high water saturation or low values of $\varphi$ with low $K$ values that tend to be completely dry. Therefore, correlations between intensive and expansive processes in the gradual scenarios of $\Delta Eh(x,t)$ can be represented through the following multiple and interdependent correlations [$tx$ $vs.K$ $vs.\Phi$ $vs.T$ $vs$ $S$]. It is also important to mention that the porous medium and its changes with respect to its internal structure are made in a slow way and are minimal changes that may occur over long periods of time; however, in the presence of extreme meteorological events, soils present erratic portrayals.

Despite the slowness with which the internal structure of the soil occurs, a scenario of drought or saturation of its internal structure is highly conditioned to the availability of water resources, and the aforementioned multiple interdependent correlation would be dominated exclusively by a scenario of drought or saturation, with all the intrinsic parameters of the soil to be defined $\Delta Eh(x,t)$ under the availability of water resources. In the map of $Tx$, in **Figure 2(C)**, an alignment in the direction NE-SW parallel to the flow of river sediments with the tendency of belonging to sandy soils can be observed, also the similar scenario is repeated in the area located to the NW and in some areas of the coastal zone. The clayey soils are observed to be distributed concentrically along the valley, which indicates isolated basin lines where the water is concentrated to drain quickly toward the tributaries of the area, not allowing the soils a strong interaction with the water resource which also puts them at risk of being dry. The region is partially covered by alluvial materials and fluvial deposits of the Quaternary, which occupy the subsoil of the entire region with variable thicknesses, heterogeneous in terms of lithology, degree of cementation, and hydraulic characteristics.

**Figure 4** represents the water availability ($mm^3$) in the valley. The statistical measurements in the distribution for the central tendency of the data describing the availability of $H_2O$ showed values for $x^-$ = 1337.92 $mm^3$ and $M_e$ = 1095.91 $mm^3$, with very significant variations among each other; so, this type of measures of central tendency revealed the first approximation that the values of the distribution do not meet with a dominant or preferential tendency toward the minimum or maximum values of the whole distribution and propitious to reach in a gradual way the different scenarios of $\Delta Eh(x,t)$. Water availability measurements are an indicator of the existence of a marked variation in the availability of the $H_2O$ resource within the aquifer, which controls the presence of moisture in the soil and environment. The observations were complemented by the statistical dispersion and noncentral measurements, $X_{min}$ = 109.12 $mm^3$; $X_{max}$ = 3194.33 $mm^3$; $\sigma^2$ = 599082.97 $mm^3$; $\sigma_0$ = 774 $mm^3$ (defined by $E\sigma_0$ = 8.2), and $Ks$ = 2.5. The manifestation of $\sigma^2$ and high $\sigma_0$ above 50% in the values of $x^-$ and $M_e$ define a different availability of the water resource from one place to another, in such a way that the soil can have different values of absolute and relative humidity in the states of $\Delta Eh(x,t)$.

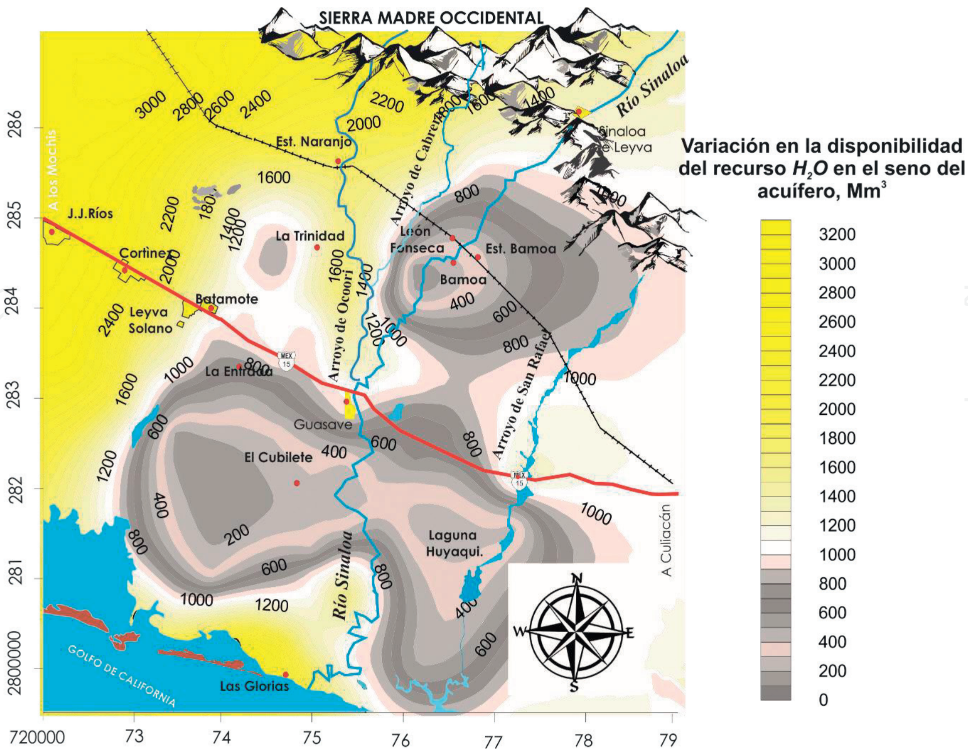


**Figure 4.** Spatial variation of the available water resource in the aquifer of Sinaloa river valley.

**Figure 4** presents the North and Northwest part of recharge of the area, as well as the discharge area that is mostly located toward the most important water tributaries; the recharge was observed to be 1600 $mm^3$ and reaches a volume of up to 3200 $mm^3$.

The marked variation in the water availability of the central area of the valley is most probably to the sedimentary terrain of the region. High volumetric imbalance in the storage coefficient can be related to the high demand for groundwater that has always existed in the region due to extensive agriculture practices, livestock, and trade business. It should be noted that these soils, due to their varied granulometric composition, are the soils that are preferred in agricultural activities because they allow diversity in the types of crops of commercial interest whose productivity provides guarantees of having diverse products throughout the year.

Differences in the agricultural activity governed by different types of soils throughout history have been favored by a superficial sedimentary geology in which the water tributaries play an important role in the formation of its granulometric efficiency. In the present study, soils are mostly characterized by a silty-sandy mudstone and silty-clay mudstone, making them suitable for agricultural activities as they permit water content in the pores that have no tendencies toward positive values and extreme negatives of being able to store $H_2O$ in its structure and are suitable for any type of crop growth. The variations that exist in the availability are relatively of small gradient (approximately 200–300 $mm^3$ for every 2–3 km), defining the area as high risk tending to the presence of $\Delta Eh(x, t)$ primarily subjected to water availability; however, in a previous year, a scenario with high intensities of precipitation had been presented.

## 4. Conclusion

The current increase in temperature and changes in weather conditions had significant impact on the rainfall. The absence/increase of rainfall has possibly been resulted in flooding and/or drought. The soil in these regions has faced different "stress states" depending on the rainfall. So, it is always important to know its current response to the new precipitation regimes, in order to identify the porous internal structure and the current potential to store the water resources. Usually, the development of crops is based on the presence of maximum or minimum $H_2O$ retention scenarios and/or absence of the relative and absolute humidity. One of the methods by which they form extreme meteorological events as mentioned in the introductory part, it is directly associated with the formation of cumulus clouds. Occurrence of meteorological events increases when the clouds reach mature stage that causes high cumulus densities to accumulate in the atmosphere by setting the surrounding areas at risk with the continuous manifestation of high rainfall and droughts. It occurs mainly in the presence of humidity in the environment. Continuous accumulation phenomena of cumulus clouds and the saturation of the ground that caused increases in the conditions of $\Delta Eh(x, t)$ depend on the soil moisture condition, the behavior of the water table, surface and subsurface processes of the soil, and the environment. Thus, it is important to know the conditions in which it can develop the magnitude of $\Delta Eh(x, t)$ and are produced to a certain extent by the conditions of antrum factors depending on the activities of each region. The soil protection programs would preferably be aimed at protecting its internal structure through nondeforestation of green areas. Another way is to avoid the production of gases favoring the greenhouse effect, which in turn attributes further changes in global temperature. Understanding the given essentiality of soil in the world, humans must adapt and adjust with respect to climatic stimuli in order to moderate the damages happening in the environment. In addition, it is worthy to identify the beneficial opportunities and possible resources to circumvent the new changes. On the other hand, the current flora and fauna is the result of a continuous evolution by an adaptation to the different environmental conditions, i.e., changes in the temperature on the face of the Earth. We suspect that these new meteorological processes like the one presented here would lead to environmental changes affecting plants. As plants are mostly in contact with soil, water, and air, they are easily amenable for adaptations to environmental temperatures and the availability of the water resources. The governance in tolerance and the way of developing adaptability will allow the plants to define their permanence or disappearance as a species. Apparently, in a given land, fundamental factors like, the dynamics of changes undergone by a land through its history in the different stages of its evolution, and in some of the occasions, external conditions from other planet have been considered to identify the sources causing changes. On this occasion, the evolution dynamics can be conditioned to the high and/or low availability of the water resource and to the environmental conditions in which the soil develops the phenomenon $\Delta Eh(x, t)$. Currently, many scenarios are changing in relation to the ambient temperature which has forced the plants to develop new tolerance limits and live in the presence or absence of $H_2O$.

An increase or decrease in the ambient temperature, in different regions, will allow the existence of new living conditions experienced by the scenarios that will be conditioned by the presence and/or absence of the superficial or underground $H_2O$ depending on the phreatic depth and the water retention capacity of different types of soil. Henceforth, it is recommended in the places where the ambient temperate decreases or increases, studying the availability of water resources from a point of view where the variables are related by the geographical effects allow the development of climatic conditions that are different for both global and closed environment, so the representative function of the change $\psi\,(x, t)$ according to each variable will tend to behave differently from the effects caused by the geographical factors but there will always be a function in each environment (representative of the integrated behavior of the system $\Delta Eh(x, t)$, in which the general spatial temporal variation of the global climate change can be represented by the summation of the behavior of each variable defined in the $\Delta Eh(x, t) = \oint_{to}^{tn} \psi\ (x, t)\, dx$). It is concluded based on the argument of the equation that integrates $\psi\,(x, t)$ as a whole through its environmental phenomena having energetic properties, so they can produce changes in the extensive properties of matter, which in this case is the soil; and one of those changes in the set of variables that define the response of the soil to $Eh(x, t)$. The energetic process attributed to the changes in matter is found or conditioned mainly by the weight that each variable has inside and outside the soil system subjected to the continuity principle of the intensive property that interacts and formulates climate change with effects before the subject leading to different status of $\Delta Eh(x, t)$ referred exclusively to the result caused by the extensive properties of matter between the effects produced by all the variables in relation to the intrinsic properties of the soil, which would be a response to anisotropy, heterogeneity, and interdependence on the forms in which $\Delta Eh(x, t)$ appears in the different soil types. Therefore, given the moisture content of the soil surface and the environment, since both are conditioned to the phreatic depth, a change in land use may affect the magnitude and seasonality of the storm flows and the seasonality of the plants and crops, making them difficult to evaluate due to the high variability in the response of the watersheds to the events of precipitation and the state of soil moisture, especially when evaluating with respect to the previous event, as Bruijnzeel [14] attributes that the observations in the variations of the humanity have observed in the different places of the world that have basins experiencing extreme precipitation events. Real quantitative predictions cannot be made for any area particularly since many of these subjected to climate variability [15, 16]. Therefore, there is a need to implement specific monitoring programs for hydrological variables focused on the identification and quantification of processes, in order to determine the effects on the flow dynamics in relation to the coverage and conditions of the basin or its state of alteration. So the availability of water resources in different parts of the earth is defined through the hydrological cycle conditions of $H_2O$, and the magnitudes of different precipitation and evapotranspiration vectors that, together with other factors, will define the ideal amount retained in the subsoil thus favoring the development and adaptation of the flora and fauna that characterizes each place. The decrease in water availability results in aridity and when the pluviometric manifestation occurs in large volumes that exceed the saturation threshold of the soil, flooding occurs. At present, concepts of drought and a weather condition in the absence of rain can be tolerated by all plants. Water deficit refers to the water content of a tissue or cell in a plant below the highest water content that can resist, and is exhibited in the state of greatest hydration [17]. The complexity in the analysis of this type of phenomena is attributed to the forms that originate them, as well as the lack of detailed quantitative information on the changes in the infiltration capacity of the different soil types and the fertile profiles of hydraulic conductivity with respect to the soil depth, moisture retention capacity, and the depth of development of plant roots, in front of climate change risks, the presence of systematic sampling campaigns is demanded in order to perform numerical models of associated extreme flow rates in hydrological basins.

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