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# Assessing Environmental and Social Dimensions of Water Issues Through Sustainability Indicators in Arid and Semiarid Zones

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## 1. Introduction

All humans need basic things or products for their material and physical well-being: air, water, food, shelter and others, all over the World, but in arid zones the prevailing condition is water scarcity. Besides the huge necessity of water for human consumption, agriculture and livestock demand large volumes of water. But sustainability for these activities is a highly fragile and complicated concept, difficult to be reached. Biomass production of a cash crop grown under drought will be lower than that grown under optimal soil moisture conditions; therefore in practical terms, it is not possible to obtain immunity against the effects of drought. In arid and semiarid zones, the environmental and agricultural issues depend on the availability of water and on its use efficiency, which is affected by high temperatures and elevated evapotranspiration rates. As a production dedicated activity, agriculture has changed dramatically especially since the end of the World War II. Food and fiber productivity were improved due to new technologies, mechanization, increased chemical use, specialization and government policies that favored maximizing production. These changes allowed fewer farmers with reduced labor demands to produce the majority of the food and fiber. But in this framework, one of the highest costs is the water extraction.

The objectives of this paper are to present a review about a method to assess the environmental and social dimensions of water issues through sustainability indicators in arid and semiarid zones, and to discuss the challenges for sustainability in terrestrial and agricultural ecosystems in a Mexican arid zone.

## 2. Hydrologic aspects of arid and semiarid zones

Several basic conditions can be distinguished between arid regions and other zones from a hydrological point of view:

1. A few, often intensive, rain events with a low amount of overall precipitation, which causes most of the small rivers or seasonal streams to be active only a few months or weeks every year, and sometimes only once every few years.
2. Loss of soil fertility and development of "desert crust" on the land surface.
3. Commonly, the aquifer is characterized by a thick aeration (vadose) zone, the zone between the water table and the land surface, resulting in a deep water table, and
4. Exacerbation of salinity-related problems, in both, groundwater and soils. When these factors are misunderstood, the lack of development and mismanagement of water cause environmental degradation and desertification (Sharma, 1998).

### 2.1 Low soil water retention, poor fertility and formation of desert crust

Vast areas of bare soils, low annual precipitation, and few high intensity rainfall events with high kinetic energy characterize arid zones. The parent material and the degree of weathering determines the level and availability of nutrients, and the type of clay and sandy minerals; these in turn largely determine cation exchange, base saturation, the adsorption, and sometimes fixation of Phosphorus, texture, permeability, moisture retention and the stability of soil aggregates. As a result of its chemical and physical properties, a soil may harden on drying, form a surface crust that restricts the entry of water and air and inhibits seedling emergence, develop a subsurface layer or pan that restricts root growth, be susceptible to erosion, become acid or alkaline on drying, or have a subsurface horizon that hardens irreversibly on exposure. Positive correlation between soil moisture in every layer and precipitation, and negative correlation between soil moisture and air temperature are common patterns (Zhuguo *et al.*, 2000). Such relationships are gaining more relevance in global change-related studies. In this sense, Seneviratne *et al.* (2006) reported that the impact of atmospheric circulation modifications might be indirect, by imposing changes in the seasonal cycle of soil moisture, which in turn can lead to modified soil-moisture-temperature coupling characteristics, although years ago, Calvet *et al.* (1998) pointed out that further studies are needed to investigate the soil water content retrieval by simple surface schemes using estimations of the surface soil moisture and temperature.

Soil constraints to plant growth may be summarized as:

- a. Inadequate moisture
- b. Deficiencies/imbbalances in nutrients
- c. Low cation exchange capacity
- d. Low base saturation
- e. Low water retention in some cases, but under specific conditions, water logging impeded drainage and poor aeration
- f. Poor fixation of phosphorus
- g. Low pH (acidity) with high pH (alkalinity)
- h. Salinity
- i. Impermeability
- j. Shallowness
- k. Textural problems (crusting, hardening, stoniness)

- l. Physical loss of soil,
- m. Hardening of subsurface horizon, and
- n. High temperature on the soil surface.

In arid soils, dryness and salinity, and their interaction under mismanaged irrigation, are the main causes of soil degradation. Effluent irrigation results in increased soil sodicity, because of the medium-to-high salinity and sodium concentration (Balks et al., 1998).

Bare soils exposed to rainfall are subjected to physical and chemical processes that change the hydraulic properties of the soil near the surface (Arie and Resnick, 1996). When the soil is dry, a hard layer is formed in the soil surface that is often called "desert crust", commonly enriched with calcite or silica. Desert crust decreases the infiltration rate of soils, thereby increasing runoff and soil erosion, reducing the availability of water through the root zone, and impeding seedling and plant growth (Figure 1.A). Other kind of crusts are formed in agricultural plots, irrigated with saline waters (Figure 1.B). Understanding the formation and properties of such crusts, as well as developing engineering methods to break it, are essential to control the runoff-infiltration (groundwater recharge) ratio and to maintain successful and sustainable agricultural activities. When desert crusts are a result of microbial activity, these kinds of crusts could help to protect the soil surface (Campbell et al., 2009). Besides, arid soils typically possess within a predominant sandy soil, a very low organic matter content with a consequent low fertility. In this sense, crop productivity under dryland conditions is largely limited by soil water availability. Soil organic matter (SOM) contents have been found to be a reliable index of crop productivity in semiarid regions because it positively affects soil water-holding capacity (Diaz-Zorita, et al., 1999).

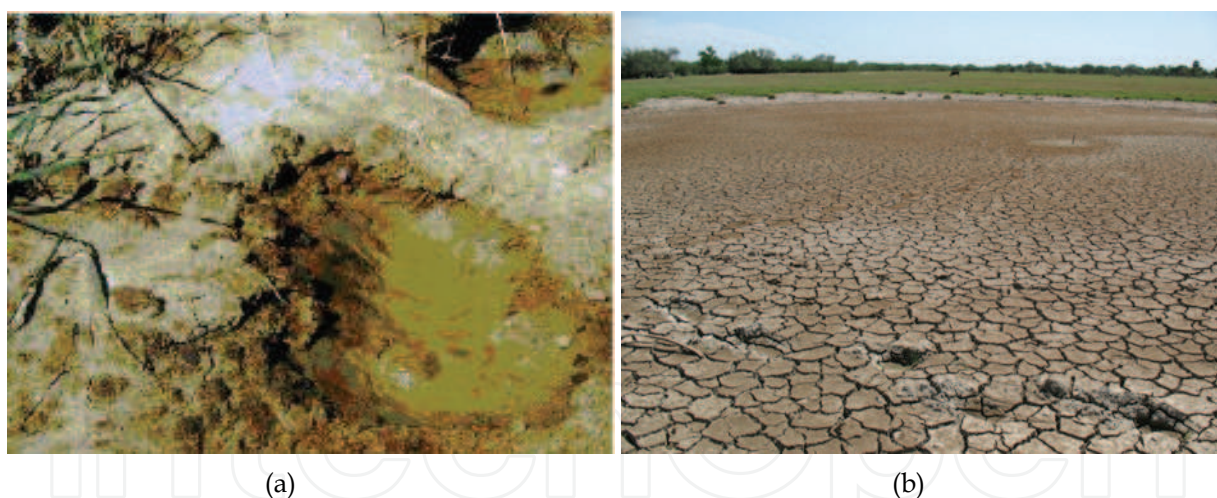


Fig. 1. Soil salinity symptoms and consequences. A: Photograph of soil fines and saline crusts; Wyoming, USA (<http://www.powderriverbasin.org/assets/>). B: Degraded unfertile soil because of salt accumulation in Chametla Baja California Sur, México

## 2.2 Vegetation and livestock control

Vegetation may be the most important control on water movement in arid soils. Because vegetation in arid regions is opportunistic, when the water application rate is increased, plant growth increases as it uses up the excess water. The opportunistic nature of desert vegetation is shown by a significantly higher concentration of vegetation in areas of increased water flow, such as in ephemeral streams and in fissured sediments or rock-beds.

Where the water supply is limited, plant activity decreases until the water-supply rate increases. The importance of vegetation on a local scale has been shown in several field studies elsewhere, including soil cover protection, maintaining the soil aggregation and other effects. As a negatively associated activity, the extensive production and maintenance of livestock generate overgrazing, loss of plant cover, soil exposure, loss of biodiversity and desertification, which turn to be economically irreversible.

### **2.3 Vadose zone studies**

A number of studies of the vadose zone in arid environments have been conducted elsewhere primarily for water resources evaluation. In the last two decades of the twentieth century, however, emphasis shifted from water resources to waste disposal and the transport of salts and other contaminants. Arid areas are being proposed for low-level and high-level radioactive waste disposal. Most of the studies related to the vadose zone in arid settings were conducted in the western United States, in regions that are designated as waste facilities. Some of these sites include Hanford Washington, Sandia New Mexico, Ward Valley California, Eagle Flat Texas, Nevada test site and Yucca Mountain Nevada (Scanlon et al., 1997). The increasing interest in the desert environment for waste facilities, in general, and radioactive waste, in particular, raises the need to understand the importance of preferential flow in the subsurface. One could assume that a thick vadose zone combined with low precipitation promotes the safest possible environment for waste disposal. However, fast flow via fractures, cracks, and macropores had been suggested as a major mechanism leading to contaminant transport much faster than anticipated by models that predicted transport based on average soil properties. For hydrologic studies, dual-porosity models exist (i.e. HYDRUS) (Simunek, 2008), but they are difficult to parameterize for this kind of soils.

### **Salt accumulation**

Salinization is a significant issue to consider in arid environments is the salinization of both soils and groundwater. The low precipitation combined with high evapotranspiration and often-slow flow rates through the subsurface, result in higher concentrations of salts. Human-induced salinization has a long history. A major source of salts accumulating in the upper vadose zone is irrigation water, which is essential for sustaining agriculture in arid lands. More than one-third of the developed agricultural lands in arid and semiarid regions reflect some degree of salt accumulation. High salinity in agricultural lands imposes stress on the growing crops that can lead to decreased yield and in some cases complete crop failure. This problem emphasizes the need for careful management of desert land and water balance.

### **2.4 Water management issues**

Despite the difficulties for plants, animals, and humans to live in desert regions, they are increasingly being utilized because of pressure from world population growth. This problem is expressed in the expansion of agricultural activities onto desert lands as well as by the formation and rapid growth of urban and industrial centers. These trends not only result in a growing demand for usable water, but also for the increased disposal of vast amounts of wastewater and solid wastes (e.g., radioactive wastes, hazardous wastes, and municipal solid wastes). In several cases, international conflicts have developed due to water rights in arid regions. Large rivers crossing desert regions are often the only potential



source for water that is essential for agriculture, industrial use, and drinking water. For example, the rights to use the water of large rivers in Africa (e.g., the Nile) and in the Middle East (e.g., the Euphrates and Jordan) remain one of the major issues that govern the relations and conflicts between the countries upstream, where most of the river water discharges, and the countries that use the river water downstream.

2.5 Desalinization strategies

The process to separate salts from saline waters or desalinization of either deep saline groundwater or seawater is a feasible alternative source for water in arid regions. However, the cost of desalinization remains higher than most other alternatives. A complex infrastructure is required, and the need for a close source of saline water makes this alternative impractical in many arid environments. The world's largest desalinization projects are in the Arabian Gulf (Saudi Arabia, United Arab Emirates, Kuwait), United States, and Japan, all which are wealthy countries with long seashores; lately, in Northwest Mexico some desalinating plants are being installed, with uncertainty about operational costs in the near future.

3. Methods

Sustainability indicators were reviewed and applied to an arid region; a study case was analyzed by means of the application of selected indicators and indexes in an overexploited aquifer. Results were interpreted within the framework of sustainability of water resources. A water usage balance study was analyzed for the La Paz Watershed, Baja California Sur, in a semiarid zone of Northwest Mexico, in order to determine environmental and social dimensions of water issues through sustainability indicators. In this zone, conventional crops are a major user of irrigation water, because of its water-demanding nature, due to an average of the five to seven irrigations needed per year. Within the La Paz watershed, four micro basins were evaluated for water deficit: El Cajoncito, La Huerta, La Palma and El Novillo.

Three variables were assessed in order to estimate the index of water scarcity Iwsc (water availability indicator), a composed integrated index which takes into the regional hydrological account, the natural groundwater recharge, the extraction and the resulting balance. In order to understand the relationship ‘availability-demand’, the index of water scarcity (Iwsc), which combines information about water abstractions and water availability, is assessed at first. For this purpose, the regional water availability index (Irwa) is a measure of water available for socio-economic development and agricultural production. It is the accessible water diverted from the runoff cycle in a country, region or drainage basin, expressed as volume per person per year, m<sup>3</sup>/p/y. The indicator Iwsc is defined by:

Iwsc = (W - S)/Q (1)

Where:

- Iwsc water scarcity index [-]
- W annual freshwater abstractions in Mm<sup>3</sup>, (M: millions)
- S desalinated water in Mm<sup>3</sup>
- Q the annual available water in Mm<sup>3</sup>

Q = R + α S Dup (2)

Where:

- R the internal water resources in the country in  $\text{Mm}^3$   
 Dup the amount of external water resources in  $\text{Mm}^3$   
 $\alpha$  ratio of the external water resources that can be used.

The factor  $\alpha$  is influenced by the quality of the transboundary water, by the consumption of water resources in the upstream region, and the accessibility of water.

Critical values of Iwsc identify various ranges for water scarcity and its parameters; the most common range for Q oscillates between 1000 and 1700  $\text{m}^3/\text{p}/\text{y}$ . A region is considered highly water stressed if Iwsc is higher than 0.4 (Alcamo et al., 2003), which is a reasonable although not definitive threshold value, because not all the renewable freshwater resources are used by human society. Data with shorter time scales will enable more detailed assessments considering the effects of seasonal variability in the hydrological cycles (Oki, 2006). These values are important because the World Bank and other aid organizations use them to prioritize and to direct aid to developing nations.

An indicator related to the 'efficiency of land cultivation' is the cultivation factor R.

The ratio of cultivated to non-cultivated land was defined by Ruthenberg (1976) as:

$$R = (C \times 100)/(C+F) \quad (3)$$

Where:

- R cultivation factor (years of cultivation as % total cycle)  
 C length of cropping period, years  
 F length of the fallow period, years

For the interpretation of R, Ruthenberg defined:

- $R < 30$  as shifting cultivation;  
 $R = 30$  to 70 as semi-permanent cultivation;  
 $R > 70$  as permanent cultivation.

## 4. Application of sustainability indicators in Baja California Sur, México

### 4.1 Study region

Baja California Sur is one of the driest Mexican States, with an annual average 140 mm of precipitation along its 72,000  $\text{km}^2$  extension. La Paz, the capital city, is located near the southern tip of the Baja California Peninsula (Figure 2). With a population approaching 200,000, it is the third largest city on this peninsula, after Tijuana and Mexicali. The La Paz region is dominated by desert and arid ecosystems, with a low availability of water resources. The annual mean temperature reaches  $24^\circ\text{C}$  with a yearly total rainfall of 180 mm, but with several dry months with null precipitation (Figure 3), with much of water coming in the form of hurricanes (CNA, 1999).

### Application of sustainability indicators

Information on quantity and quality of natural resources is essential for sustainable development. In particular, information on freshwater resources, their availability and use is becoming increasingly important with the emergence of regional water shortages and the need to improve water use efficiency.



Fig. 2. Geographic location of the Mexican State Baja California Sur and La Paz, the capital city. Northwest México

For the application of sustainability indicators to the diagnosis of La Paz watershed, data on water uses, the natural groundwater recharge and the extraction were obtained from the National Water Commission (CONAGUA) reports and other previous studies (Cruz-Falcón, 2007; CONAGUA, 2008). Weather data (temperature, evaporation and precipitation) used in this study for La Paz B.C.S. (México) were obtained from División Hidrométrica de Baja California Sur, of the Comisión Nacional del Agua (CONAGUA, 2008), who collects this information from the La Paz Weather Station, located at 24°09'N and 110°20'W, 3 km south La Paz City. Our analysis indicate that agriculture is the major water consuming activity, in both, Baja California Sur state and the whole Peninsula of Baja California (Table 1).

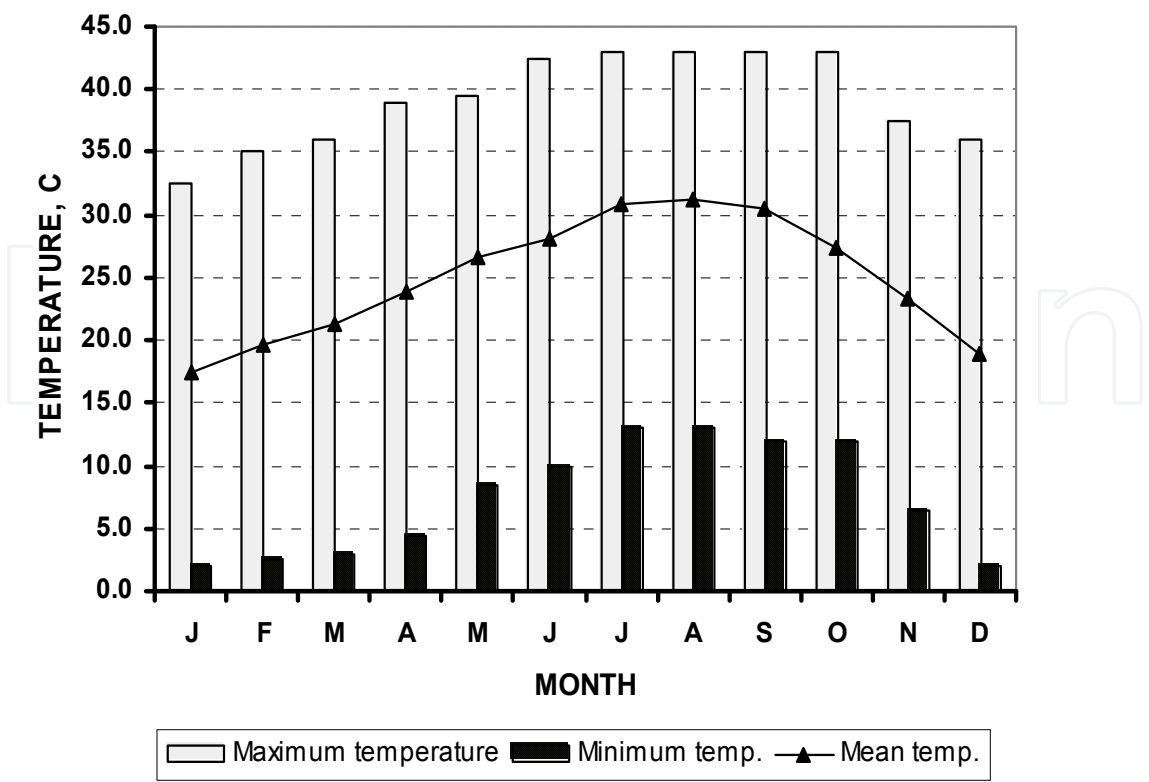
The natural groundwater recharge was estimated by the method according to the groundwater lever fluctuation method, which is an indirect method of deducing the recharge from the fluctuation of the water table. The rise in the water table during the rainy season is used to estimate the recharge, provided that there is a distinct rainy season with the remainder of the year being notoriously drier (Cruz Falcon, 2007).

Water use	Baja California	Baja California Sur	Peninsula (total)
Agriculture	1830227	6450	1836677
Domestic	74	1914	1988
Multiple (industries)	164	425	589
Livestock	809	2403	3212
Urban-public	146640	421	147061
Services (county)	28	129	157
Total	1977942	11742	1989684

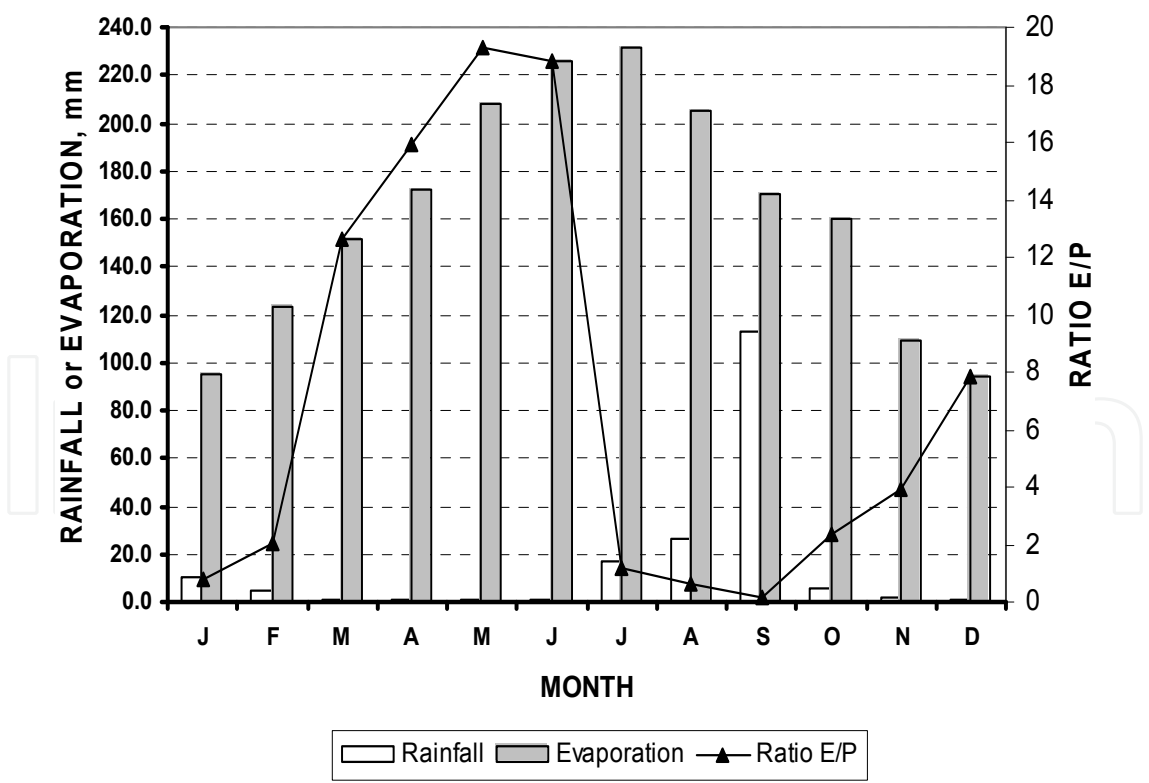
Source: Official data base from REDPA - National Water Commission of Mexico (CONAGUA, 2008).

Table 1. Synopsis of the water use in the Baja California Peninsula and related States, according to the consumptive use; unit: Millions m<sup>3</sup>/yr





(a)



(b)

Fig. 3. Pattern of climatic variables for La Paz weather station, (A): maximum, minimum and mean temperature; (B): rainfall, evaporation and ratio E/P

4.2 Results and discussion

Factors affecting agriculture in Baja California Sur were found to be water deficit (evaporation dramatically exceeds rainfall): 2,380 mm – 180 mm = 2,200 mm of hydrological deficit, water scarcity (evidenced by absence of surface water with groundwater depletion), high temperatures: Temp avg = 24.5, Temp max = 42 C; Salinity (natural and caused), low fertility of soils, and socio-economical factors (long distance form main markets, complex marketing policies, others).

The oriented-extensive ground water extractions have caused notorious water depletion in two out of three contiguous watersheds, at La Paz municipality (Table 2).

Name of Aquifer	Recharge (Mm <sup>3</sup> )	Extraction (Mm <sup>3</sup> )	Availability (Mm <sup>3</sup> )	Possible has with irrigation 100 cm depth
El Carrizal	16.0	8.60	7.40	861.00
La Paz	27.8	36.95	-9.15	3,200.00
Los Planes	8.5	9.57	-1.10	957.00

Table 2. Hydrological balances for three contiguous watersheds in Baja California Sur, Northwest Mexico

Calculation of the index of water scarcity for La Paz watershed and its four microbasins rendered high values, from 1.11 (microbasin La Palma), to 2.74 (microbasin El Novillo) (Figure 1, Table 3). Results suggest that El Novillo faces a critical condition as a result of high extraction rates, over passing the natural groundwater recharge, with a notorious deficit, estimated in -4,450,068.75 m<sup>3</sup>, which affects the water availability for urban growth and development.

Microbasin	Recharge	Extraction	Balance	Iwsc
	===== m³ =====			
El Cajoncito	2,233,967.75	3,689,549.00	-1,455,581.25	1.65
La Huerta	7,519,608.13	8,565,189.38	-1,045,581.25	1.14
La Palma	16,524,756.81	18,420,338.06	-1,895,581.25	1.11
El Novillo	2,559,500.39	7,009,569.14	-4,450,068.75	2.74

Table 3. Values of Iwsc calculated for four microbasins of La Paz B.C.S. watershed, Northwest Mexico

The concept of ‘sustainable development’ as well as ‘sustainable agriculture’ integrates three main goals: environmental health, economic profitability, and social and economic equity. A variety of philosophies, policies and practices have contributed to these goals. People with many different capacities, from farmers to consumers, have shared this vision. In the case of agriculture, one of the most water-demanding activity, an agroecosystem must be viewed as a source of ‘goods’ and a sink of ‘inputs’ (i.e. water). For this activity and for the others, ‘nature’ (the ecosystem) is the main source of all we consume, but the ecosystem also serves as a sink for all wastes. For production systems, the main resources basically are: water, plants, grains, animals, energy from the sun, wind, and other nonrenewable: oil (from fossil). Human activity is necessarily focused for extracting resources and producing waste to produce, transport to consumer, and dispose of materials. As agriculture and the other socioeconomic activities in arid and semiarid zones depend on water, which mainly is

obtained from an aquifer, it is crucial to analyze the concept of sustainability of an aquifer: Maintaining a balance between recharge and extraction, or seeking that average annual extraction does not exceed the annual recharge. Although extraction from some groundwater resources has been above the long-term sustainable yield, its use must be managed to the sustainable yield through the implementation of water sharing plans for groundwater (Scanlon, 1997). Current droughts have increased the demand on groundwater resources, causing localized stresses in parts of groundwater systems and overexploitation, with a high risk of water scarcity. A wide variety of ecosystems depend on groundwater for their continued survival. Significant changes in groundwater quality and quantity have the potential to degrade ecosystems and affect human uses of water.

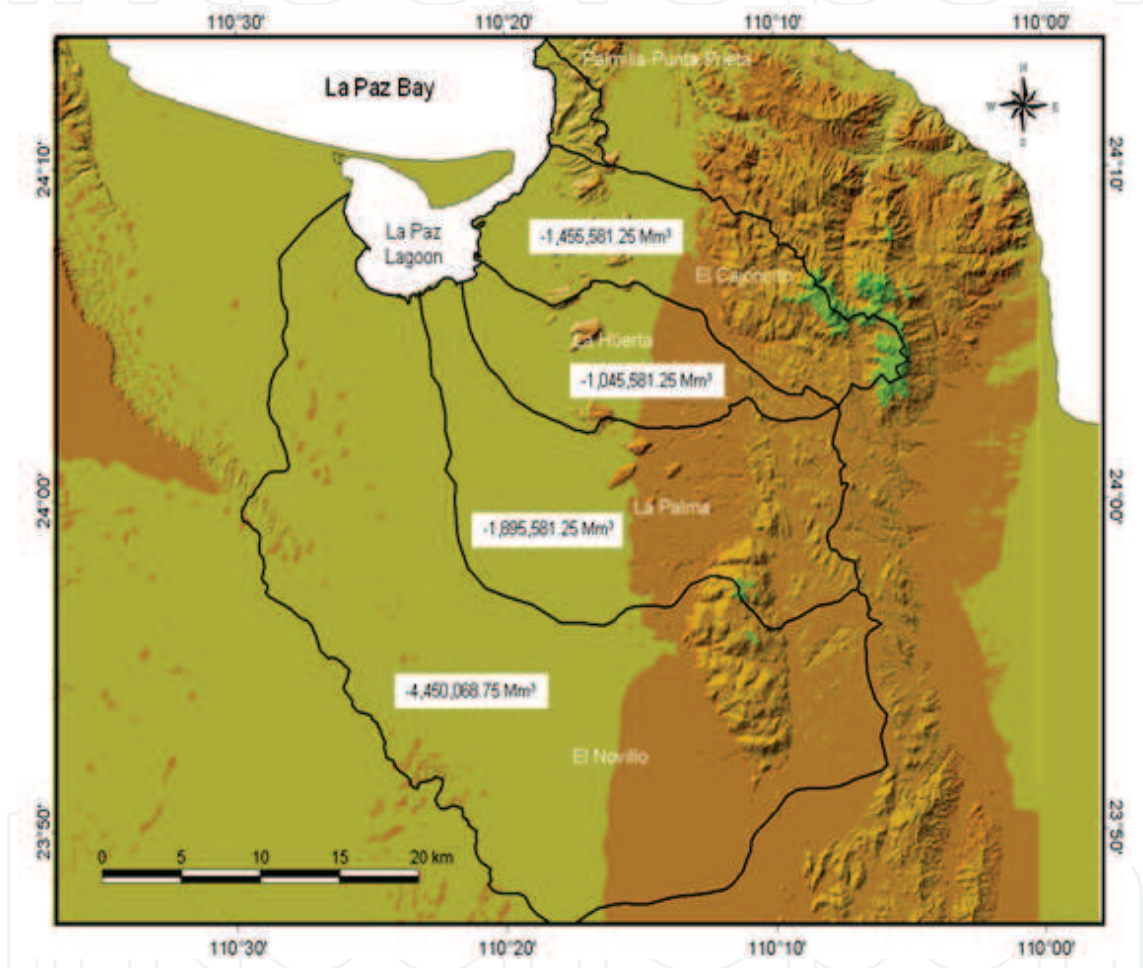


Fig. 4. Geographic and topographic configuration of four microbasins within La Paz BCS watershed, Northwest Mexico, with estimated water deficit, in millions (M) m<sup>3</sup>

Agriculture and livestock depend on water. Under natural conditions, water deficit is a common condition for agro-ecosystems and grazing-lands in arid zones. “Rainfall” is an important climatic parameter, but in arid and semiarid zones, its analysis scarcely explains the dryness intensity and the aridity pattern. At this stage in earth’s history, it is believed that mankind can make ‘productive efforts’ to decrease or diminish the water depletion, such as artificial groundwater recharge, small dams, artificial infiltration ponds, desalination, increasing the water use efficiency, mitigating or remediating losses, promotion of native agro-forestries for water retention, ad others. In a sort or medium term, the hydrological

cycle will be intensified in several zones, with more evaporation and more precipitation, but the extra precipitation will be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation, or major alterations in the timing of wet and dry seasons (Arnell, 1999). A challenge for scientists is to find appropriate models to diagnose the water deficit, which is the real parameter that impact livestock and agricultural ecosystems. Advanced extensive techniques are so varied and complex that only large areas are feasible and realistic. Most of adapted species to drought do not have yet a real important market, although there are possibilities to develop it. i.e.: *Salicornia bigelovii*, *Aloe vera*, *Opuntia spp.* An additional problem is the significant distance from suppliers and market.

## 5. Conclusions

The study reported here has applied a series of spatially-resolved data sets depicting the biogeophysical and socioeconomic properties of the South-Baja Californian communities in Northwest Mexico. We, as others, have found that Northwest Mexico is a dry zone. Associated with this dryness is a highly dynamic water cycle, providing a large degree of variability in terms of climate, runoff and discharge. A systems perspective is essential to understanding sustainability. The system is envisioned in its broadest sense, from the individual farm, to the local ecosystem, and to communities affected by this farming system, both locally and globally. An emphasis on the system allows a larger and more thorough view of the consequences of farming practices on human communities and the environment. The application and interpretation of sustainability indicators motivates, for the La Paz watershed case, the design and instrumentation of strategies in order to improve the water use efficiency, and to alleviate the water deficit of the aquifer.

A significant fraction of agricultural land and human population is located in the study region with low runoff hydrography at the center of the La Paz valley, with disperse small localities and villages at the high sections of the watershed, with high runoff and high variability. Hence, agricultural water demand defines the aggregate water use for the watershed. These characteristics of human-water interactions, in turn, provide challenges to the water infrastructure of the watershed, with evidences that the region may be experiencing curtailed use of water, relative to its high demands. Biogeophysical data sets, emerging rapidly from the local science community, can make important contributions to emerging water resource assessments.

On the base of available evidences, we conclude that both, bio-geophysical as well as socioeconomic indicators will be necessary to map the patterns and intensities of water scarcity. Interdisciplinary study is thus an important component of future research.

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There is an estimated 1.4 billion km<sup>3</sup> of water in the world but only approximately three percent (39 million km<sup>3</sup>) of it is available as fresh water. Moreover, most of this fresh water is found as ice in the arctic regions, deep groundwater or atmospheric water. Since water is the source of life and essential for all life on the planet, the use of this resource is a highly important issue. "Water management" is the general term used to describe all the activities that manage the optimum use of the world's water resources. However, only a few percent of the fresh water available can be subjected to water management. It is still an enormous amount, but what's unique about water is that unlike other resources, it is irreplaceable. This book provides a general overview of various topics within water management from all over the world. The topics range from politics, current models for water resource management of rivers and reservoirs to issues related to agriculture. Water quality problems, the development of water demand and water pricing are also addressed. The collection of contributions from outstanding scientists and experts provides detailed information about different topics and gives a general overview of the current issues in water management. The book covers a wide range of current issues, reflecting on current problems and demonstrating the complexity of water management.

### **How to reference**

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