Groundwater flow regime under natural conditions as inferred from past evidence and contemporary field observations in a semi-arid basin: Cuenca de la Independencia, Guanajuato, México

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Abstract

This study was carried out in the Cuenca de la Independencia, a semi-arid basin in Central Mexico. The objective is to describe the main features of a groundwater flow regime under natural conditions, based on groundwater discharge manifestations. Information obtained from paleoecological, paleontological, archaeological and historical data suggests that, prior to heavy development (starting in the 1950s), the hydrogeologic regime was characterized by a larger groundwater availability in a more humid and colder climate. Manifestations associated to groundwater discharges are springs, lagoons, wetlands, saline soils, chalcedony deposits, phreatophytes, thermalism, and artesianism. The different types of manifestations and their position in the basin indicate the influence of groundwater flow systems hierarchically nested, forming concentric zones at ground level. The groundwater flow regime corresponds to a

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classical gravity-induced flow system with generation of local, intermediate and regional patterns. Integrating several types of data to establish the flow geometry and its dynamics has proven a useful tool to increase understanding of the original groundwater regimes. This approach can also be applied in other over-exploited semi-arid basins.

Keywords: Groundwater flow regime; Paleohydrogeology; Regional groundwater flow system; Central Mexico; Semi-arid basin; Guanajuato

1. Introduction

In Mexico, arid and semi-arid climates cover more than half of the territory being located mainly in the Altiplano Mexicano (Mexican Highlands) in the central and northern part of the country. The annual rainfall in these areas is 20% of the national total. The population is about 77 million producing 84% of the gross national product (CNA, 2002). The physiographic conditions, the population distribution, and the development of the economic activity generate contrasting regions of hydraulic resource availability. Groundwater is the main (often only) water resource in semi-arid basins. In about a 100 Mexican basins, the excessive groundwater extraction during the last three decades has caused important alterations in the hydrogeological balance. These alterations are made obvious by: (a) the fast lowering of the water level; (b) the continuous reduction of spring and river discharges; (c) a significant deterioration of the ecosystems that depend on the shallow phreatic level; (d) remarkable changes in the hydrochemical quality that affect agricultural activity and human consumption; and (e) increasing intensity and extent of the subsidence phenomenon. This has brought about complex environmental, economic and social problems (CNA, 2002). The state of Guanajuato has historically been known for its outstanding agricultural production, but at the same time as the second largest groundwater consumer at national level (~2723 Mm³ year⁻¹). Additionally, it is the state that faces the most serious problems derived from over-exploitation (SAGAR, 1999).

The Cuenca de la Independencia (CI) is located in the most arid region in the state of Guanajuato (UNAM-CODER, 2000) (Fig. 1). The first deep wells were drilled during the 1930s, and since then the number has increased to more than 2500 wells, mainly used for irrigation purposes (CEASG, 1999). In the last 30 years, the groundwater extraction rates have greatly surpassed the average recharge volume, causing important alterations in the hydrogeologic regime. At present, the pre-development conditions of groundwater flow can only be inferred through the groundwater manifestations mentioned above. The description can be used to improve the understanding of flow dynamics in the basin. This enables to analyse hydrogeologic information and historical piezometric data, as well as to explain the occurrence of similar phenomena in other semi-arid basins. Furthermore, conceptualization of groundwater flow through the basin (conceptual model development) mainly determines the interpretative and predictive capabilities of numerical models (Anderson and Woessner, 1992).
The purpose of this research is to describe the main features of a hydrogeologic regime under natural conditions. This was done by analysing distribution and characteristics of relict manifestations associated to groundwater discharges. These manifestations are springs, wetlands, phreatophytes, saline soils, and mineral deposits, as well as the existence of thermalism and artesianism phenomena. The results not only demonstrate the utility of various investigative approaches in evaluating the dynamic nature of groundwater flow systems in a regional context, but also provide insight into some of the factors that control groundwater over-exploitation effects on ecosystem deterioration.

2. Study area

2.1. Basin description

The CI covers a total area of 6840 km² and is located in the northeastern portion of the state of Guanajuato (Fig. 1). The basin is composed of a plain with an elevation that ranges from 1900 to 2100 masl (meters above sea level), surrounded by mountains reaching 2850 masl. It has a major axis of 135 km in NNW-SSE direction and a minor axis of 76 km oriented NNE-SSW.

Three climate types predominate in the area with variations in temperature and winter precipitation. Climatic differentiations are caused by humid air coming from the Pacific Ocean and the area orography. In the S and SW of the Sierra de Guanajuato prevails a warm climate; in the Sierra de Guanajuato and Sierra de San...
José Iturbide a subhumid condition is observed; and in the lower parts of the north and west of CI the climate is dry. Meteorological information obtained from 60 stations, with an average of 30-year registration (INIFAP, 1998), indicates a mean precipitation of 576 mm year\(^{-1}\). The highest rainfall registered is in the Sierra de Guanajuato (>800 mm year\(^{-1}\)) and the lowest (<300 mm year\(^{-1}\)) in the northeast of the basin area. Additionally, the annual mean temperature is 16°C (range = 9–25°C), with a mean potential evaporation of 1828 mm year\(^{-1}\). The average infiltration rate is 25 mm year\(^{-1}\) according to chloride mass balance results reported by Mahlknecht et al. (2004).

Predominating soils are phaeozems and vertisols covering approximately 80% of the surface. Luvic phaeozems are present from the central part down to the southern border of the basin. Haplic phaeozems are dominant in the north and southeast. There are pine-oak forests in the mountains, grasslands and desertic shrubs down in the plain. Lately, natural vegetation has largely been removed from the plains for farmland activities.

The CI is located in the southern part of the physiographic province of Mesa Central specifically in the Llanuras y Sierras del Norte de Guanajuato subprovince. The main geomorphologic features are mountain of tectonic-volcanic origin dominated by erosional processes. The plateau origin is tectonic-alluvial and fluvialacustrine, depending mostly on accumulation processes (Fig. 2). It is a system of valleys interconnected by stretchings, hills, and small gullies.

2.2. Geology

Three geological provinces intersect at the CI, the Sierra Madre Occidental (SMOc), Sierra Madre Oriental (SMOr), and the Transmexican Volcanic Belt
The oldest rocks in the area are of volcanic, plutonic and vulcanosedimentary origin of late Jurassic and early Cretaceous ages. In late Cretaceous a thick sequence of limestones, sandstones, and marls was deposited (SMOr). The sequences are exposed in the east (Sierra de Mineral de Pozos) and southeast (Sierra de los Cuarzos) of the basin. During late Cretaceous and early Tertiary (middle Miocene), voluminous volcanism of intermediate to silicic composition (SMOc) took place in the north and west of the CI (Sierra del Cubo and Sierra de Guanajuato). However, late Tertiary is characterized by the eruption of important volume of andesitic, rhyolitic, and basaltic rocks (TMVB). In the south and southeast of the CI, three big stratovolcanoes were emplaced and caused the definitive hydrogeologic closing of the basin. The episodic tensonal events occurred during Tertiary provoked differentiated sinking of tectonic blocks. The depressions formed were simultaneously filled with volcanoclastic sediments under a terrigenous and fluvial lacustrine environment. At the foot of the mountains, the sequence is composed of breccias and partially consolidated conglomerates, with blocks and gravels in a matrix of medium to coarse sands. The plain consists of gravels, sands, silts, clays and volcanic ashes. The thickness varies some meters at the foot of the mountains and 100–460 m in the center of the basin. The evolution of the basin and a detailed geologic description is presented by Alanis-Ruiz (2002).

2.3. Hydrology and hydrogeology

The eastern border of the CI represents a continental divide, where the runoffs are split up toward the Gulf of Mexico (Panuco River) and into the Pacific Ocean (Lerma and Santiago rivers). The Laja River is the most important stream and the only of perennial type. The average runoff recorded at the basin outlet is 258 Mm$^3$ year$^{-1}$ (CNA, 1997). The drainage network is mainly of dendritic type.

The hydrogeology consists of three hydrostratigraphic units: (a) basal unit of low permeability that performs as an aquiclude; composed of sedimentary, volcanosedimentary and plutonic rocks of late Jurassic and early Cretaceous; (b) fractured aquifer made up of marine sedimentary sequences of the late Cretaceous and all the later volcanic emplacements; and (c) porous aquifer composed of clastic sediments filling the tectonic depressions and forming a vast plain. The hydraulic conductivity mean value for both aquifers is 2.01 and 4.21 m d$^{-1}$, respectively. Total groundwater recharge calculated in 1991 by water balance approach is estimated in 170 Mm$^3$ year$^{-1}$ (CNA, 1992).

3. Materials and methods

Sedimentary basin research during last four decades has shown that, under gravity force influence, water flows through a geologic medium in spatially defined patterns (Ground Water Flow Systems, GWFS). Three flow system types are recognized: (a) local, when recharge and discharge areas are contiguous; (b) intermediate, when
there is one topographic elevation, or more, between recharge and discharge areas; and (c) regional, when the recharge area is located at the border of the basin and discharge area is situated in the lowest part. GWFS generate diverse types of surface manifestations: hydrological, hydraulic, chemical, mineralogical, biological (vegetation), edaphological, geomorphological, etc. (Ingebritsen and Sanford, 1998; Tóth, 1999). Groundwater flow characteristics are unique in each basin and the manifestations and phenomena produced are diverse in their forms and intensities. Thus, there is no specific methodology for general applicability to analyse and describe hydrogeologic regimes. Methods to investigate the hydrogeologic environment most commonly used (GWFS domain delineation and characterization) include field observations, historical records, hydrogeochemistry, isotopic analysis, numerical modeling and remote sensing techniques (Durazo and Farvolden, 1989; Salama et al., 1994; Edmunds et al., 1999; Batelaan et al., 2003).

The methodology applied in this research involved three stages. First, a compilation, generation and analysis of basic information was carried out. These activities included gathering information from historic hydrogeological data and from thematic maps of the state of Guanajuato (SRH, 1970; SPP, 1980). Information on springs was initially obtained from a set of geographic maps and inventories provided by local, state, and national water supply management authorities (SRH, 1970; INEGI, 1981; SARH, 1981; CEASG, 1999). The analysis of digital elevation models provided drainage network through automated generation and basin delimitation from slope analysis. Also, runoff and accumulation areas were located using the methods described by Martz and Garbrecht (1992). The Landsat-7 TM satellite images and aerial photographs (1:70,000 scale) were used to identify geomorphic and geologic features, ancient drainage networks, saline soil coverage along with ancient lagoons and bogs. The remote sensing methodology used to locate recharge and discharge areas is reported by Salama et al. (1994). The information was incorporated into a geographical information system (GIS) to facilitate its handling. Secondly, an analysis of historical data and evidence search about specific aspects related to groundwater discharge manifestations was done (SRH, 1970). The activities taken into account were the examination of historical archives and information exchange with specialists of other disciplines in order to document manifestation sites. The localities documented include fossiliferous areas, vestiges of early human settlements and ancient waterworks like hand-dug wells, irrigation channels and aqueducts. The third stage consisted of fieldwork in order to make an inventory of groundwater discharge manifestations. This comprised direct observation, detailed description and georeferenced location with a handheld global positioning system. This stage was facilitated by the area toponymy, because many places are allusive to these manifestations.

4. Results and discussion

In a general way, the role of groundwater flow in a regional context has been recognized as a geologic agent, acting continuously during hundreds or thousands of
years, producing surface manifestations (Tóth, 1999). However, these inferences have been obtained from observations in basins with cold and humid climates, where groundwater availability is larger than in arid and semi-arid regions (Edmunds et al., 1999). Taking into account that the climate is one of the factors on which the number, magnitude and diversity of the manifestations depend, it would be logical to deduce that evidence and manifestations in semi-arid regions were less remarkable or impressive than in the most humid climatic regimes. The climatic variability and the tendencies in the global climate change are also recognized, along with their timescales which are over hundred and thousands of years (O’Hara et al., 1994; Eckhardt and Ulbrich, 2003). However, the noticeable increase in the groundwater abstraction rates started in the 1950s and the effects on the ecosystem deterioration were accelerated since the 1970s (SRH, 1970; SARH, 1981; CNA, 1992; CEASG, 1999).

Under this working hypothesis, initially old evidence was first investigated in order to confirm the existence of a humid climate with ecosystems different from the present. Paleoclimatic conditions suggesting humid and savanna-type environments in the CI was supported by the fossil record and the existence of paleomeanders forming a complicated drainage network as revealed by satellite images and aerial photographs (Carranza-Castañeda and Ferrusquía-Villafranca, 1978). Also, archaeological evidence points out that abundant water availability was determinant for the settlement of an indigenous group in the CI more than two millennia ago (Nieto-Gamiño and Brown, 2001).

With the arrival of the Spaniards and later conquest of El Bajío (Lowlands), during the XV and XVI centuries, surface water and springs were decisive to determine the commended land extensions or given in graces to the settlers (Wright, 1998). In the case of the CI, groundwater discharges were not only considered for land allotment, but rather they influenced directly on the foundation place of some villages. For example, the original foundation of San Miguel village took place in the proximity of a spring called Yzquinapan, that means ‘water of dogs’ in Náhuatl language.

The oldest known map of the western portion of the basin is shown in Fig. 3. This pictorial document, dated in 1580, is commonly referred to as ‘Pintura de San Miguel y San Felipe’. The document was part of the Relaciones Geográficas de la Nueva España and probably related to the ‘Chichimeca Códice’, whose text was strayed (Nieto-Gamiño, pers. comm.; Wright, 1998). The map was manufactured on a mixture of paper and maguey. At present, the original document is in the Sala de Consejo de la Real Academia de Historia de Madrid. Undoubtedly, the document mentioned above is the most important testimony describing the geographical, economic, social and environmental aspects of the region at the time. The river and springs are shown as strategic resources in the incipient colonization and regional development. San Miguel and San Felipe represented the most important population centers (Fig. 3 (1–2)). These sites played a decisive role in the colonization of northern New Spain, whose expansion was accelerated by the discovery of silver veins in Zacatecas (1546). A route running parallel to the Laja River was readily established (Fig. 3 (3)). This road from Zacatecas to Mexico City was known as ‘Ruta de la Plata’ (Silver Road) (Fig. 3 (4)). There were numerous springs in San
Fig. 3. Map of the western portion of CI, known as ‘Pintura de San Miguel y San Felipe’ (1580). (1) San Miguel, (2) San Felipe, (3) Laja River, (4) ‘Ruta de la Plata’, (5) springs, (6) pine/oak forests, (7) Altepec or ‘Cerro de Agua’, (8) Water mill or batan. Original map measures 82 × 61 cm.
Felipe valley locally referred to as ‘ojos de agua’ (water eyes) (Fig. 3 (5)). Also, forests occupied the surrounding mountains (Fig. 3 (6)). The springs at the foot of the mountains (Fig. 3 (7)) were denominated ‘Altépec’ that means ‘water hill’ in Náhuatl language. In 1552, a water mill or ‘batan’ was built by friars (Fig. 3 (8)), and was initially used for grain milling (Wright, 1998).

At the end of the XVI century, the hacienda (homestead) property system substitutes the commendations and graces as land ownership and water control system in New Spain (von Wobeser, 1989). During more than three centuries, from the end of the XVI to the beginning of XX century, several haciendas were settled in the CI for a diverse range of activities. The haciendas were responsible for developing hydraulic infrastructure, building irrigation channel systems as well as hand-dug wells. From the hydraulic point of view, these old wells represent the first direct and quantitative evidence of groundwater level conditions before severe exploitation. A total of 80 ancient wells were documented in the area. The depth ranges from a couple of meters to 40 m, with an average of 25 m. Today most of these wells have dried up. The depth well is an indication of the ancient groundwater level condition if we consider that, once the water level was reached, it was not possible to dig more than a few decimeters. The obtained phreatic level information derived from these wells can be used for numeric flow model calibration under steady-state conditions, and it is useful for setting up initial conditions for transient flow numeric simulations (Navarro de León et al., in preparation).

4.1. Biological and hydraulic manifestations

The prevailing savanna environments during the XVI century in the CI and El Bajío were documented by Butzer and Butzer (1997). The Laguna Seca and San Luis de la Paz valleys had abundant wetlands and ponds representing groundwater discharge. Also, Díaz de Gamarra, in his 1777 description of La Villa de San Miguel El Grande y su Alcaldía Mayor, mentions the presence of plants growing near springs. These phreatophytes are known as guau (Parthenocissus quinquefolia) and rejaldar (Thevetia thevetioides) (AMSMA, 1994). Nevertheless, the most typical phreatophyte is the ahuehuete (Taxodium mucronatum), commonly known in the region as ‘sabino’ or ‘cypress’. The historical archives of the CI cities mention ahuehuetes growing in spring and stream borders (Butzer and Butzer, 1997). However, in the 1970s, these phreatophytes dried up due to water level lowering caused by the intensive groundwater pumping (CEASG, 1999).

The spring documentation provided information about the number, characteristics and distribution of groundwater discharge. The springs were categorized in perennial and seasonal, current and extinct, with thermal and cold discharges, discharging inward and outward the basin. A total of 201 springs were identified, 113 of them discharge inside the basin. At present, the number of active springs has diminished notably, with only 44 having permanent discharges; 91 are active during the rain season; 66 have dried off during the last years. The relation of height and distance for each spring to the nearest divide is shown in Fig. 4. A major density of springs is observed between 2050 and 2150 masl heights. This is due to a change in
the slope and hydraulic properties, when water passes through the fractured-porous aquifer limit. Furthermore, the horizontal distribution differences are evident, suggesting that discharges are controlled by GWFS geometry. Practically, 90% of the springs are supplied by local flow systems. The mountain springs (35%) have fluctuations in their discharges, depending on the precipitation regime. The springs in the plain (65%) generally show a smaller annual variation in their discharge rates, although these rates have diminished since the porous aquifer was exploited intensively. Spring discharge rates has been reported by SRH (1970), SARH (1981), CNA (1992) and CEASG (1999). The morphological characteristics of the surrounding mountains are a decisive factor for the spring distribution (Fig. 5). In the Sierra de Guanajuato, the springs are equally distributed on both sides of the divide. By contrast, the springs are absent inside the northeast divide, where all springs discharge toward the Panuco River. This situation reverses up in the north where almost all springs discharge inside the basin.

4.2. Mineralogical and edaphological manifestations

Saline soils cover important extensions in north and northeast Atotonilco. There are also saline soils in the San Jose Iturbide–Doctor Mora and Laguna Seca valleys covering small areas. The salt deposited in soils is mainly composed of sodium carbonate and correlates with the groundwater geochemical evolution in the CI
Groundwater in recharge areas, where local flow systems dominate, are calcic-bicarbonate type. In contrast, a sodic-bicarbonate domain is observed in discharge areas where the three flow systems converge. The Atotonilco area contains a chalcedony deposit as a result of groundwater discharge with high silica content. The silica origin can be explained because of the silicate mineral dissolution present in volcanic rocks. The accumulation of chalcedony confirms the hydrogeochemical modeling results that characterize the groundwater in this area as chalcedony-oversaturated (Mahlknecht et al., 2004). Several decades ago the Atotonilco and San Miguel groundwater discharges, as well as the Laja River flow, were abundant compared with the present conditions. It was almost unnecessary to drill deep wells for irrigation or water supply. However, when they were drilled, some wells presented the artesianism phenomenon, even in the mid-1970s.

4.3. Natural hydrogeologic conceptual model

The types of manifestations and their positions inside the basin suggest the presence of three areas with defined characteristics (Fig. 5):

Area I. This area is located at the foot of the mountains, in a mean distance of 5 km from the basin border, including the granular and fractured aquifer limit. Four places are characterized by cold springs and phreatophytes:
the San Diego community south of San Jose Iturbide; the oriental section of the San Luis de La Paz municipality; the northeast of San Felipe city and the Puerto de Nieto community in San Miguel de Allende. Saline soils at the center of San Jose Iturbide–Doctor Mora valley, are a result of a local flow system discharge.

**Area II.** This area covers most of the central plain, which includes the Central Graben and Laguna Seca valley. In the northern part of the latter, there is an area with manifestations such as lagoons, wetlands, saline soils and phreatophytes. Today only saline soils are observed.

**Area III.** It is situated at the center of the basin between Dolores Hidalgo and San Miguel, having an area of approximately 400 km², representing the most important area of manifestations. In this region, the ground was prone to floods, with widespread bogs and phreatophytes. The saline soils covered important extensions alternating with chalcedony deposits. The groundwater is thermal with temperatures close to 40 °C. The artesianism was a common phenomenon in most of the wells. The spring discharges were abundant, but they have recently dried out. Some wetlands have disappeared and artesianism has decreased.

The manifestation areas correspond to the influence of three flow patterns or systems. Area I, near the basin border, with cold springs of variable discharges throughout the year, is controlled by local flow systems. The presence of lagoons, wetlands and saline soils in area II, suggests a constant groundwater supply coming from a deep intermediate flow system. Finally, thermal springs, artesianism, salt deposits and chalcedony accumulation in area III, are produced by discharge of deeper groundwater with high temperatures and mineral contents. These manifestations are typical of a regional groundwater flow system. In area II, a local flow contribution is possible, whereas in area III the participation of local and intermediate flow depends on the system’s geometry.

A conceptual model is proposed based on geomorphologic and hydrogeologic basin characteristics, as well as on groundwater flow evidence and surface manifestations. The movement of groundwater in the CI is a classical gravity-induced flow system. Recharge takes place in the mountainous areas and groundwater flows to discharge in diverse regions of the basin, depending on the geologic and topographic situation. A section delimited by the points $ABCD$ is shown in Figs. 5 and 6. The Sierra de Guanajuato (between points $AB$) represents the groundwater divide and recharge areas are also located there. Groundwater flows through three systems: one local flow that discharges near point $A$ and deeper intermediate and regional systems continuing toward the southwest to the El Bajío region. Toward the interior of the basin, water recharged from the Sierra de Guanajuato generates triple flow systems that discharge in the region indicated by point $B$ and toward the basin outlet. In the oriental part (point $D$), a continental groundwater divide is located separating flows toward the Panuco River and inside the basin. The water recharged in the proximities of this divide, discharges through a local system in San Jose Iturbide–Doctor Mora valley. In the Laguna Seca valley,
another system of local type system is generated. The water from both valleys discharges in the center of the basin (point B) through an intermediate system and flow continues toward the south, in the same direction as the superficial flow. Point B is the region of convergence for the three flow systems. These interpretations are supported by modeling studies (Navarro de León et al., in preparation) that quantify many aspects of the groundwater regime described only qualitatively in this paper.

The conceptual model proposed with GWFS domain, describing surface concentric patterns, has important implications for groundwater resource management and protection. The GWFS are dynamic entities operating in diverse space and time-scales, having an order and distribution that correspond to these scale domains. The local flow systems are the most dynamic and react more rapidly to changes induced by recharge or extraction. For this reason, they are regarded as seasonal resources, while the other systems are considered secular resources (Tóth, 2000).

5. Conclusion

Evidence and groundwater flow manifestation analyses have provided information about the hydrogeologic regime under natural conditions in the CI. The paleoclimatic, paleontologic, archaeological and historic evidence indicate that in the past there were conditions of larger water availability. Savanna-type environments prevailed...
in the basin with abundance of surficial water and groundwater. The excellent ecological conditions allowed human groups to settle down in the lowest areas of the basin more than 2000 years ago. Groundwater discharge sites also played an important role in the foundation of the first colonial cities in the region almost 500 years ago. The groundwater shallow levels in the plain facilitated the rudimentary perforation of wells which supplied water for the haciendas during the centuries XVI–XIX.

The manifestations associated to groundwater discharge are springs, lagoons, wetlands, bogs, saline soils, chalcedony deposits, artesianism, thermalism and phreatophytes. The types of manifestations and their positions in the basin suggest the existence of concentric areas influenced by three GWFS: (a) area I, located in the mountains and within the plain limits with cold springs and phreatophytes; (b) area II, located in the central plain, where lagoons, bogs, saline soils and phreatophytes were abundant; and (c) area III, located from the basin center to the basin outlet, in addition to the manifestations previously mentioned, where chalcedony deposits along with thermalism and artesianism phenomena are located. In these three areas, the GWFS contributes with dominance of local, intermediate and regional order, respectively.

The hydrogeologic regime in the CI is characteristic of a classical flow system controlled by gravity force. Groundwater recharge takes place near the mountainous areas and discharge in diverse basin regions, depending on the geologic and topographic situation. Manifestations of groundwater discharge indicate that the GWFS convergence coincides with the basin center and continues in the same direction as the surface flow to the basin outlet in the south.

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References


