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# Groundwater Flow Systems and Climate Change Adaptation in Mexico

## Introduction

Water management requires a precise understanding of how the hydrological cycle works. Explained simply, it begins with the evaporation of the largest expanse of water (seas and oceans); the wind blows this vapor in the form of clouds to all the continents, where it falls. After falling, part of the rainwater and snow drains off in the form of streams and rivers, while the rest seeps into the subsoil or evaporates.

The water is reincorporated into the atmosphere through evapo-transpiration. The part that seeps into the subsoil is the largest volume of freshwater, since, of all

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the water on the planet, 94 percent is in the seas and oceans; only 4 percent is groundwater; and 2 percent makes up the polar ice caps and glaciers; while rivers, lakes, lagoons, reservoirs, and the water contained in living things represent less than 0.01 percent of the total.

This resource fulfills different functions in the world's ecosystems. Groundwater is of particular interest because it is the main source of fresh water for many land ecosystems and for humanity, despite the fact that we cannot see it. All its movement and storage takes place in the subsoil, where it is studied through geological, geophysical, hydraulic, chemical, and isotopic techniques, and with the support of numerical flow and transport models.[1]

Groundwater moves and is stored in the porous spaces of gravel and sand, in sedimentary granular deposits, and between the cracks in rocks, which can measure thousands of square kilometers and be hundreds of meters thick. Groundwater is not stagnant; it moves due to its interaction with the other components of the cycle and to the properties of the geological formation. This allows it to move distances ranging from 1 centimeter to 8 meters a day, and in karst regions like Yucatán and Florida, even further.

## Times in the Water Cycle

The time that water remains in each stage of the cycle varies, making it difficult to quantify exactly. However, the average time that it remains in seas and oceans is 4 000 years; groundwater can remain in that stage from weeks to more than 10 000 years; in the form of ice and glaciers, from weeks to more than 1 000 years; and in the atmosphere, rivers, lakes, and living beings, it can remain from a few weeks to ten years.[2]

## Groundwater Flow Systems

The concept of groundwater flow systems (GFS) has evolved in international scientific production from the 1940s to today.[3] Given its importance in the integration and quantification of all the elements in the water cycle, it has been gradually incorporated into strategies for surface and groundwater management and regulation throughout the world. Countries like Canada, the United States, and Japan, among others, are adopting GFS in water management and conservation. In Mexico, efforts have been made since the 1980s to understand these systems, since 97 percent of the country's water is under the ground.

GFS were conceived to be able to understand the interaction of the stages of the water cycle, in particular what happens to the groundwater that circulates and is stored in huge geological containers, staying there different lengths of time, as mentioned above. This characteristic of the GFS has very important implications in water management and adaptation to climate change.

GFS are gravity-based: they begin their journey in high, mountainous, forest areas and travel through the subsoil toward lower areas. The movement of groundwater in aquifers makes up three main zones: local, intermediate, and regional.[4] These flow systems are connected to river, lake, wetland, and mainly natural spring ecosystems, where their journey ends. In the local flow system, the journeys are short and the groundwater stays there for anywhere from weeks to a few years; it is cold, close to the average environment temperature, and contains few chemical elements absorbed from the rocks it encountered on its way. In the intermediate case, the journey through the subsoil is longer and can take hundreds of years. Finally, in the regional case, the residence time is thousands of years; the water is thermal and contains a higher number of dissolved chemical elements, although this depends on the types of rock it has gone through on its way and the order in which it encounters them.[5] Under natural conditions, the geological containers are full and all the elements of the water cycle interact as the result of up to thousands of years of equilibrium, just like the associated ecosystems that developed over similar periods of time.

Understanding and quantifying all these interactions is fundamental for comprehensive water management, and, in addition, the natural limits imposed by geology must be respected, unlike territorial or administrative limits. That is why the criteria for this kind of study must be standardized.

## The Importance of Groundwater in Mexico

Approximately 75 percent of Mexico's central and northern regions are desert and semi-desert, where annual

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rainfall does not exceed 500 liters per square meter, while in the Southeast, estimates put it at 5 000 liters per square meter. This is why in northern and central Mexico groundwater is practically the sole source of water available for human consumption and domestic, agricultural, and industrial use. It has also been estimated that nearly 75 million Mexicans depend almost exclusively on groundwater for our different needs. Approximately 80 to 85 percent of the water extracted from Mexico's aquifers is used for agricultural production, and, in general, its management is inappropriate, causing different environmental impacts, foremost among them the depletion and contamination of groundwater.

Unfortunately, water management in Mexico has been very deficient. The institution responsible for it in Mexico is the National Water Commission (Conagua), which has based its decision-making regarding groundwater-related matters on what they call the annual balance, which takes into account renewal or annual recharge of groundwater, and on administrative —not geological— divisions of what they call aquifers. These principles are incorrect and have created a huge crisis.[6] By ignoring the interaction of all the components of the cycle and particularly that of groundwater with surface water and ecosystems, this has given rise to irreversible human regional environmental damage involving regional contamination of groundwater with huge effects on the population. This is the case of Northern Mexico's Lagunera Region.[7]

## Aquifer Exploitation And Groundwater Renewal

Taking the foregoing into account, we can understand that when wells are drilled in a granular or fractured medium (called an aquifer) and groundwater is extracted, the water obtained is of different ages. When more water is extracted than the amount that enters naturally (known as recharging), the aquifer will begin to empty, above all if what is extracted is the oldest water and its renovation is not immediate and it cannot be recovered in a short period. That is why it is important to have knowledge of the areas where extraction is the most appropriate, so the negative impacts can be reduced.

One example of this is a regional system covering eight municipalities in the state of Guanajuato. It includes a 7 000-square-kilometer basin where almost 2 500 wells have been dug; of these, 2 000 are used for agriculture, with almost 70 percent waste. In this case, among other things, the age of the groundwater was measured, and the finding was that the young water (formed in the last 60 or 70 years) had already been utilized, and that that what was being extracted is mainly water 10 000 to 35 000 years old. That is, it comes from the last ice age. The concentration of arsenic and fluoride dissolved in it is 10 times the maximum suggested by international and national norms for human consumption, giving rise to thousands of cases of patients ill from fluorosis and renal insufficiency.[8] Based on this, scientists estimated that 1 500 wells should never have been dug, since the demand surpasses the amount of water stored and the capacity for renewing the aquifer. This demonstrates the importance of understanding the dynamic of groundwater and its interaction with the other components of the hydrological cycle; if we do not take this into account, we can cause an imbalance to such a degree that the renewal of this valuable element of the subsoil will not occur fast enough to fulfill human requirements. Something similar happens with other aquifers in Mexico's Central Highlands and North.

Part of the solution is to use appropriate agricultural techniques. One of the central issues in the groundwater flow systems (GFS) study, for example, is the interaction of the water cycle and the dynamic of water in the non-saturated area, or vadose zone, through the top layer of the soil. This interaction is determined in part by climate conditions, surface water, and the characteristics of the surface granular material. The analysis and prediction of the behavior of this interaction is controlled mainly by

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the characteristics of the soil, such as its texture, stratigraphy, hydraulic properties, humidity content, and organic material, including different aspects of the migration of solutes.

Recently, the study of water cycle behavior in the non-saturated zone has focused on predicting the effects of climate change and its impact on groundwater, the production of food, and the permanence of ecosystems. Understanding and applying a series of conservation techniques in the top 50 centimeters of soil would allow for a rapid increase in the humidity content throughout the soil profile, since it makes possible the immediate penetration and storage of rainwater with minimum evaporation and zero runoff. This shows that it is feasible to favor the infiltration of enough rainwater to produce basic crops and seasonal fodder and reduce the negative impacts of climate change. This can be applied to irrigated crops, which would make it possible to gradually decrease the extraction of groundwater by more than 50 percent, something fundamental in aquifer management.

Carbon capture using these techniques is another factor associated with adaptation to climate change. It reduces the damage caused by drought due to the amount of water stored in the subsoil, which would allow for the production of perennial, seasonal crops and fodder for animals. These results suggest changing policies for supporting Mexico's countryside to promote management through appropriate conservation techniques and stimulating the increase of organic material in the soil structure, as well as the incorporation of rainwater.[9]

## Conclusions

Mexico needs to include in its water management and climate change adaptation tasks an appropriate quantification of the water cycle and an understanding of how it works, particularly with regard to groundwater, which represents 97 percent of the country's water. Groundwater is part of the water cycle and optimum knowledge of it would make more tailor-made planning for national development possible, as well as the implementation of appropriate solutions to current problems. The inclusion of groundwater flow systems (as put forward by Tóth and other scholars) is urgently needed for understanding and managing water in order to establish legislation and national regulations. Also, understanding and applying a series of conservation techniques in the top centimeters of the soil would make possible the immediate incorporation and storage of rainwater, with minimal evaporation and zero runoff, benefitting the production of basic crops and fodder and decreasing damage due to climate change. VM

## Notes

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