Water resource management in hydrological basins: the case of Mexico

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Abstract

Integrated water resource management (IWRM) has been recently incorporated to the Mexican national water policies through the National Waters Law. The objective of this document is to identify the area of opportunity for the development of mathematical models that would facilitate the instrumentation of IWRM at a national level. The legal, institutional and normative frameworks were analyzed for this purpose, as were the social participation mechanisms foreseen since the modification of the National Waters Law in the year 2004. It is concluded that in Mexico there exist the legal, institutional, normative and social participation conditions necessary for the management of water resources. They must be used to define a general work frame for the development, construction and instrumentation of mathematical basin models. In addition, there is a series of local water distribution procedures known by the water users that are compatible with the current norms addressing the determination of water availability. This constitutes a niche for research, since it is possible to develop a general model for the analysis of water distribution or river/dam system operation that is acceptable to the users without compromising science. Similar processes are being performed in other countries as in Mexico, and so the results of this study can be very useful.

Keywords

Basin management, hydrologic modelling, surface water use, water management, water resources use planning.

Introduction

The occurrence of surface water in a hydrological basin depends mainly on its climatic condition and hydrological behavior. However, the real availability of the resource for human use is finite and is conditioned to the existence of hydraulic infrastructure for the control, storage and use of the presented flows (WWC-CNA, 2006). The spatial and temporal distribution of water availability is also influenced by the operation of existent infrastructure. Thus, there is a strong relationship between the hydrological behavior of a basin and the human activities that use water in it.

The continuous growth of population and of the economic activities that use water, increase the demand for water resources and generate social pressure on those that administer it. The problem becomes a crisis in an unpredictable way, when there are difficulties satisfying the growing demand, especially in times of scarcity.

The economic activities inside a basin can be strengthened or restricted in function of water availability. However, the population growth that causes an increase in demand will unlikely stop in the short or medium term, and because of this it is necessary to manage the demand more efficiently.
This problem is more severe in arid and semi-arid regions, given the natural scarcity of water resources. The problem could be lessened in these regions through the establishment of water use policies that consider the integrated state of affairs, and guarantee the availability of water in the long term, in sufficient quality and quantity, at the same time considering the conservation of the environment. The establishment of these policies requires the participation of all the sectors that use this resource, until satisfactory agreements are reached through dialogue and negotiation (Lanini *et al*., 2004).
Because of the world water crisis, and as a result of the different international conferences on water and the environment, in the last few years several countries have incorporated the concept of "Integrated Water Resource Management" (IWRM) in their water management plans (GWP, 2006). Mexico is not the exception, as the National Waters Law (NWL) was modified in 2004 in order to provide the legal and institutional framework necessary to instrument the integrated management of national water resources. This modification also established mechanisms for social participation in decision making (Carabias, *et al*., 2005).
Mathematical models are tools capable of analyzing through simulation, what the hydrological response of a basin would be in the face of changing conditions, including different water use schemes (Silberstein, 2006).
The objective of this document is to identify the research needs in the area of mathematical basin modelling, whose fulfilment would facilitate the instrumentation of IWRM in Mexico.

Institutional structure for the water resources use planning in Mexico.

The Federal National Water Law (2004) establishes that it is responsibility of the National Water Commission (NWC) to conduct the integrated management of national water resources, including their administration, regulation, control and protection. This provides a unique legal and institutional frame for the administration and management of water in a national context in Mexico. However, once a right or concession for the use of water resources is given, the use of the volume of water protected by this right is subject to local criteria or regulations.
Mexico is divided into 13 hydrological-administrative regions, which are themselves subdivided into hydrological basins. In order to administer water resources, "Basin Councils" were defined in these territorial divisions. Basin Councils are collegiate organs of mixed-sector membership, and they constitute an instrument for coordination and concertation between the three levels of government, the representatives of water users, and non-governmental organizations (NGOs) (CNA, 2003).
There are 25 Basin Councils in Mexico (CNA, 2006), with different levels of reach in their functions, according to the specific problem that they face in their region. In those basins that have a greater competition for water resources, environmental risk in water bodies, or other related problems, internal work groups have been formed within the Basin Councils. These groups have the purpose of reaching rule-making agreements, or water distribution agreements when it is not possible to reach the former, that make it possible to solve the problem in question.

The role of water users in decision-making

Today, decision-making in the management of water resources falls not only of governmental institutions; it is the water users themselves that have increasing participation and responsibility in this process (CNA, 2006). Basin Councils have specific functions, detailed in the National Waters Law, meant to achieve a better administration and preservation of the basin's water resources.
Users and NGOs have 50% of the participation in Basin Councils; state and municipal governments have 35%, and the federal government has the remaining 15% (CNA, 2004). This shows the importance of the participation of users and local governments in decision-making.

Mathematical basin models as planning tools.

With the participation opportunity offered by Mexican Basin Councils, local governments and users have become involved in the definition of water resource management strategies. In the process of searching for consensus regarding water use policies, mathematical modeling has been sought as a tool for the analysis of water distribution alternatives and as the foundation for the reached agreements (IMTA and CNA, 2005). However, until now there no exists homogeneous criterion for the development of these models in Mexico, which has led to significant methodological and conceptual differences when they have been applied to the study of different basins. This has also caused diverse questions about which would be the most proper structure for these models, in order to reach the desired objectives. These questions are an obstacle that can even significantly slow down the planning process. Collado (1990) warned 17 years ago that what was hindering the development of Mexican hydrology was the urgency to solve the problems that had not been foreseen in time and form. This situation has not changed much to this day. The acceptance by the members of Basin Councils to use a certain basin model as a tool for decision making is of great importance. This can promote pro-positive participation or the systematic rejection of available alternatives. Mathematical models by themselves do not solve the problems in a basin (BDMF, 2000); they are merely tools that make it easier to find one or more feasible alternatives, and only with the participation of those interested in the matter is it possible to find consensual solutions that can be operatively instrumented.

The surface water distribution process in Mexico

Those that have authorization or concession for the use of water in Mexico have been assigned a supply source, which for the main developments demanding surface water in a basin are storage dams. Rivers are another source of surface water supply, most common in zones of medium or little development. The importance of having supply sources like storage dams lies in the fact that they constitute more secure water sources that make it possible to develop hydraulic infrastructure projects (WWC-CNA, 2006). Thus, the water that is stored in a dam (coming from flows that happened all throughout the ending year) sustains the activity of the starting year.

In accordance with the NWL (CNA, 2006), water for public supply has first priority (including water for domestic use, urban public use, and use by services, commerce and part of industry). Because of this, out of the available volume the fraction required for this use is reserved first and the remainder is distributed among the other activities that demand water. The self-supplied industry (with the exception of hydroelectric plants), as well as the public use, cannot depend on an erratic water supply, and because of this only a minimum volume of surface water is used for these activities in regions with water scarcity. Less than 1.7% of surface water is destined to industry in the regions of Río Bravo, Northeast, North Pacific, South Pacific, Central Southern Basins and Lerma-Santiago-Pacific (CNA, 2004a). In these cases, the industrial sector can temporally buy the water volume it requires from the agricultural sector, or have an alternate source of groundwater. Since hydroelectric activity is not a consumptive use of water (it returns 100% of the water it consumes), it is subject to the extraction programming of agricultural activity.

In practice, CNA (2000) annually assigns the volume of water for agricultural in function of the volumes naturally available in storage dams at the beginning of the agricultural year (usually October 1st). Usually, the volume to be extracted is determined by an analysis of dam storage functioning. The theoretical bases of the dam storage functioning are widely described by Aparicio (1987). The use of the assigned volume is sustained through the programming of its temporal and spatial application in an irrigation plan. The irrigation plan considers, among other information, the extension of land for crops to be established, the type of crops to be started, and the irrigation water depth to be applied. In other words, in order to distribute the available water one does not perform a forecast of precipitation or soil humidity; these factors are implicitly contained in each crop's irrigation water depth.

The climatic variability of a specific zone is considered in the determination of the volume that must be extracted from a dam for the irrigation of the different crops that can be established in it (Aparicio, 1987). The annual authorized volume of water to which a water user has a right reflects the effect of effective rainfall on the calculation of irrigation water depth; thus, an agricultural irrigation district in a zone with greater mean annual rainfall has a concessioned volume smaller than that of a district in a zone of less rainfall.

Inapplicability of the hydrological models to perform water distribution analysis

Hydrological models have shown application difficulties when one seeks to analyze the effect of implementing various policies for the operation of hydraulic infrastructure and the management of water resources in a basin. This happens because these models fundamentally attempt to represent the process by which rain is transformed into runoff (the basin's physical response), while the operational processes of hydraulic infrastructure, as well as the water distribution, water demand patterns and availability of water are frequently included in a general form (Barthel *et al.*, 2005). The greatest capacity of these models lies in reproducing a basin's natural flows; when dealing with basins that have significant use of their water resources, however, the application of these models becomes difficult and at times not very practical because of the altered state of the basins' natural conditions.

Some models like EPIC (Williams, 1995), SWRRB (Arnold and Williams, 1995), LERMA (IMTA and CNA, 2005) and the irrigation component of GLEAMS and CREAMS (Knisel and Williams, 1995), determine the volume to be distributed for agricultural activity by making estimates of water demand through modules that quantify soil humidity, consumptive crop use, effective rainfall and other

parameters in real-time simulation. However, in practice soil humidity and effective rainfall are not directly quantified for the distribution of water in agricultural zones because these parameters constitute “uncertain” water; that is, they depend on the annual climatic conditions of the current agricultural year and it is not possible to determine precisely when and how it will rain or how this will affect soil humidity.
Different developed hydrological models exist in literature (Singh, 1995; TNRCC, 1998; Singh and Woolhiser, 2002; Borah and Bera, 2003) that have demonstrated being excellent tools to face the hydrology problems for which they were designed; however, it is notoriously difficult to use them in the solution of the problem of water distribution in basins.
If there is any inconsistency between the way in which water is really distributed in a hydrological basin and the way it is represented in a model, not only can its application to solve the problems in question be limited, but its acceptance by those that participate in decision making (such as surface water users) is reduced. Without social acceptance, the use policies or regulations that might be implemented will not be seen as legitimate (Falkenmark *et al*., 2004).

The National Waters Law and the Integrated Water Resources Management

The NWL and thus the Mexican national water policies incorporate the concept of integrated water resources management, as well as institutional schemes for the participation of water users and society in general in decision making. Thus, it is important to gain acceptance from the community of water users and society in general regarding the management policies or schemes that the decision makers want to adopt.
This demands changes in the way that the problem is managed by the scientific community, so that it might successfully contribute to the development of the numerical tools that are necessary to face the challenges presented by IWRM. The process of social participation necessarily introduces the concept of consensus, which implies that during decision making process, agreement must be reached between water users, government institutions, water management institutions, NGOs, and specialists or experts in different disciplines (scientific or research sector). All of them participate with knowledge levels and viewpoints that are different regarding the development and application of mathematical models as tools supporting decision making. Thus, the question of how to reconcile different approaches requires an answer that the scientific viewpoint can also agree with.

NWL, IWRM, and surface water availability

In a logical order of ideas, to achieve an adequate management of water resources it is necessary to quantify what one meant to administer or manage. The calculation of natural water availability makes it possible to establish an amount of the resource. The challenge of achieving a better management practices of water resources lies in defining the form in which and the limit until which it is sustainable to use this resource, as well as establishing regulatory or control mechanisms (Carabias, *et al*., 2005).
The Mexican NWL considers, in its 22nd article, the concept of water availability (in juridical or regulatory terms) for the granting of water concessions (water use permissions). Additionally, the 13th transitory article of the NWL establishes that the mean annual volumes of available water are determined according to the official Mexican norms created by CNA for this purpose (CNA, 2004). In other words, the NWL considers the concept of water availability and establishes the calculation method in a norm.

LNW, IWRM, availability and normative framework

The Official Mexican Norm NOM-011-CNA-2000 (SEMARNAT, 2002) establishes the basic procedure for the calculation of surface water availability in basins, as well as that of groundwater water availability in aquifers. As part of the method for the calculation of surface water availability established in the norm, natural flows must be determined. They constitute the volume of water that is naturally captured in a water basin and transforms into surface flow, which is collected by the natural draining network of the basin itself. (SEMARNAT, 2002). Natural flows are those that would exist at the exit of the basin if there were no human activity that used the water, or infrastructure for its derivation and/or storage.
The norm provides 2 methods to determine natural flows: 1) the direct method, based on hydrometric records and using the mass conservation equation; 2) the indirect or rainfall-runoff method, which uses rainfall records and physical parameters of the basin. In addition, the norm establishes the direct method as preferential and the indirect method as secondary, to be used when there is not enough information to use the first. The determination of natural flow through the direct method constitutes the

historical reconstruction of the basin's hydrological response. In accordance with the norm, the calculation of surface water availability and the determination of natural flows in a hydrological basin are based on the mass conservation equation.
The analysis of dam storage functioning process, through which it is possible to determine the annual volume that can be used from a dam, is also based on the mass conservation equation (Aparicio, 1987). This procedure is known by those that use water for agriculture, who are themselves familiar with the use and analysis of time series of hydrological variables obtained through hydrometric records.

NWL, IWRM, water availability, normative framework and social participation

Subjects of great importance to users include the way in which water is distributed for its different uses and the operation of the hydraulic infrastructure available throughout the basin for the control, storage, distribution and use of water resources. In a basin that has high social pressure for the use of water resources, the system for the control and assignation of water rights has high priority because there is concern about the assignation of new concessions (water use permissions).
Those that participate in the decision-making process are familiar with the basic principle of mass conservation, as well as with hydrological analyses based on hydrometric records. It is precisely on said principle and on the analysis of hydrometric records that the Official Mexican Norm for the determination of surface water availability is based. Thus, a mathematical basin model that has its foundation on the mass conservation equation and that represents the hydrological behavior of the basin based on hydrometric records would be congruent with the Official Mexican Norm and with the NWL. Mathematical basin models can have a greater acceptance by the users that participate in decision making if these users know and understand the theoretical foundations on which they are based. It is therefore important that the models, in addition to complying with the legal and normative framework, be comprehensible for all the members of the Basin Councils.

Research needs

Natural flows represent or characterize the hydrological behavior of a basin, and can be determined based on hydrometric records and the mass conservation equation or through the application of rain-flow hydrological models (TNRCC, 1997). At this point, the decision must be made of choosing one procedure over the other; however, it is advisable that consensus be reached among the decision makers. The scientific community frequently recommends the use of hydrological models, while users recommend the use of hydrometric records. This creates a contradictory position between users and the scientific community. However, since both alternatives can adequately reproduce the hydrological behavior of gauged basins, it is possible to choose the alternative preferred by the users; their acceptance is thus achieved without compromising hydrological science.
When dealing with non-gauged basins or basins with poor hydrometric records, or when one wants to know the impacts that important changes in climate or soil use can produce, only the alternative of applying hydrological models is eligible to determine hydrological behavior. However, the uncertainty in flow estimation will depend mainly on the selected hydrological model as well as on the amount and quality of climatological records, and the available physical measurements of the parameters in the model. In general terms, if a gauged basin is not considered to be immersed in a process of change that will substantially modify its hydrological response, it is possible to characterize this response through the analysis of representative historic hydrometric records.
Once the natural availability of the resource is quantified, it is necessary to determine the best way to make use of it. This requires not a hydrological model, but a tool for the water distribution analysis. The development of a basin model that represents the operation process of the river/dam system, or the distribution of surface water, is a real research need that must be addressed by the scientific community in the area of water resources management. This model must have at least two purposes: 1) to evaluate and prospect alternatives for the management of the basin in their present concession situation; and 2) to evaluate the actions that could be performed in the basin in order to reduce the volume of the current concessions.
In the first case, the water distribution model has a high potential for the administration of this resource, through the definition of water distribution policies in the basin under different scenarios (abundance, scarcity and normal). Even though these policies cannot modify the juridical availability of water, they can substantially increase the certainty of the mean annual volume that could be supplied to the users.
In the second case, the water distribution model can be used to evaluate the potential benefit of programs that improve the efficiency of water use, concession purchase, or some other kind that contributes to a reduction of concession volumes (such as planning and reordering water distribution).

This application modality can provide elements for decision-making regarding which actions must be taken to guarantee the authorized extraction volume, for new high-priority developments, and for the conservation of the environment. All of this would be provided in terms of juridical availability, as well as in increases or decreases of the certainty of the useable mean annual volume. Considering that the economic resources that are allocated to the rehabilitation or improvement of hydraulic infrastructure are always scarce, the need for a model with these characteristics is significant.

Conclusions

In Mexico there exists a legal order that incorporates IWRM into the national water policies, an institutional structure for water management at the different government levels, and social participation mechanisms that tend to consolidate with time. Because of this, it is of greater importance to define a work frame or general (national) protocol for the development of mathematical basin models that will facilitate the instrumentation and following of water resources management policies.

IWRM imposes new requirements on mathematical basin modelling. Versatile numerical tools are needed whose results can be understood by those that participate in decision making. The level of acceptance of these tools increases even more if they are developed so that they can be used by people that are not modelling experts.

There is a need to develop new mathematical models to represent and analyze the problem of availability and distribution of water in hydrological basins. In order for them to be properly accepted and used, these models must be compatible with the local legal and normative frameworks, must be founded on solid scientific principles, and must be understandable and reliable for those who use them as a tool in decision making.

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