Natural flows determination in gauged hydrological basins. Part I: Alternative method for irrigation return flows estimation

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Water Availability, Use and Management (Theme), Hydrological Diagnosis and Forecasting (sub theme)

Keywords: Irrigation return flows, Natural flows, Water availability, Water balance, Hydrological assessment

Abstract

The correct determination of natural flows in a hydrological basin is of great help in defining control mechanisms that would permit the sustainable use of water resources. The possibility of quantifying the natural flows is conditioned to the existence of historical records of booth gauged flows and the remainder parameters of the mass conservation equation.

In most basins water is used for agricultural activity; however, in very few occasions is it possible to have measurements of the water volume that returns to surface flow after its agricultural use. Therefore, agricultural return flow is commonly quantified as a percentage of the total water volume used for this activity. When no previous estimates of the agricultural return flows in the studied basin are available, it is a common practice to use typical values reported in literature, usually taking the return flow to be between 20% to 50%. This introduces severe uncertainty to the determination of natural flows in the basin.

The objective of the present work is to propose an alternative method for the estimation of agricultural return flow in hydrological basins, based on the detection and correction of the anomaly generated by return flow in the annual hydrogram of monthly mean natural flows.

The method consists of determining the annual hydrogram of monthly mean natural flow from the available historical hydrometric records and the mass conservation equation, with no initial consideration of agricultural return flows. If increments in the natural flows are observed during the dry season, they can only be attributed to return flows. This constitutes an anomaly with respect to the theoretical hydrogram, and occurs during the dry months with the greater demand of irrigation water (from March to June in the Rio Florido basin). The anomaly can be corrected by introducing irrigation return flow values (as a percentage of the volume used for

irrigation), until the deformation of the hydrogram disappears. With this procedure it is possible to determine a return flow ratio to a higher degree of certainty.

In order to exemplify the method here presented, the middle basin of the Florido river (Río Florido) in the northern Mexican state of Chihuahua was used. In this basin is located the Irrigation District 103, and has hydraulic infrastructure for the use of surface water in agricultural production. The results of the developed example case show that the proposed method is consistent with the values reported in literature, and reduces uncertainty in the estimation of natural flows.

Introduction

Planning the use of water resources is not restricted to developing countries. The growing demand for water to satisfy the needs of society, including food production, can lead to an increasing number of basins, even in developed countries, to face water conflicts among the different user sectors. Thus, it is of vital importance to quantify the natural availability of water resources in order to reorganize their spatial and temporal use in accordance with new needs, if development in many parts of the planet is to continue.

Natural flows represent or characterize the hydrological behavior of a basin and can be determined based on historic hydrometric records and the mass conservation equation, through the application of rainfall-runoff hydrological models or through statistical models (TNRCC, 1997). The determination of the time series of natural flows through gauged historical flows consists of removing the effects of the human activity that used water and of the hydraulic infrastructure that stored or derived it; this includes extractions, return flows and storage effects (Wurbs, 2005).

All the sectors that use water can generate a volume that is eventually returned or discharged into the natural drainage system of the basin. Hydroelectric activity, for example, does not consume water in the power generation process, and 100% of the water used in this sector is returned (CNA, 2004). Of the volume supplied to population centers for urban public use, it is estimated that 75% (CNA, 1994) is discharged into surface water bodies like municipal served waters; these can be either treated or raw wastewaters. In Mexico, the main use of water is agriculture, which uses 77% of the available water (CNA, 2006). However, in very few cases do measurements or studies exist that quantify the water volume that returns to surface flows after being used in this activity. Whether or not return flows are generated by agricultural activity depends mainly on the efficiency of the hydraulic infrastructure used to conduct and distribute water, as well as the method used to apply water to the farmlands. For example, it is estimated that watering individual plots of land with traditional methods like flood irrigation (gravity) is performed with an efficiency that lies between 50% and 70% (Mejía et al., 2002).

Usually, agricultural return flow is quantified as a percentage of the total water volume used by this activity. When there are no previous estimations in the studied basin, one must rely on typical values reported in literature, taking the return flow to have a value between 20% and 50% (Yoshitani & Tianqi, 2007; Jothiprakash, 2003). The arbitrary selection of the irrigation return percentage introduces a high uncertainty into the estimation of natural flows.

The object of this work is to propose an alternative method for the estimation of the irrigation return flows in hydrological basins, based on the detection and correction of the anomaly generated by return flows in the annual hydrogram of mean monthly natural flow. Natural flow is determined through the mass conservation equation applied to a historical time period for which hydrometric records exist of the parameters that enter into this equation.

Materials and methods

Description of the basin

The basin of the Florido River is located in the southern portion of the state of Chihuahua, Mexico; this river is a tributary of the Conchos River, which itself is a tributary of the Bravo

River. The Bravo River constitutes the territorial limit between the Mexico and the United States of America. Its basin lies in both nations and its water resources are shared as established by a bi-national water agreement (CILA, 1944)

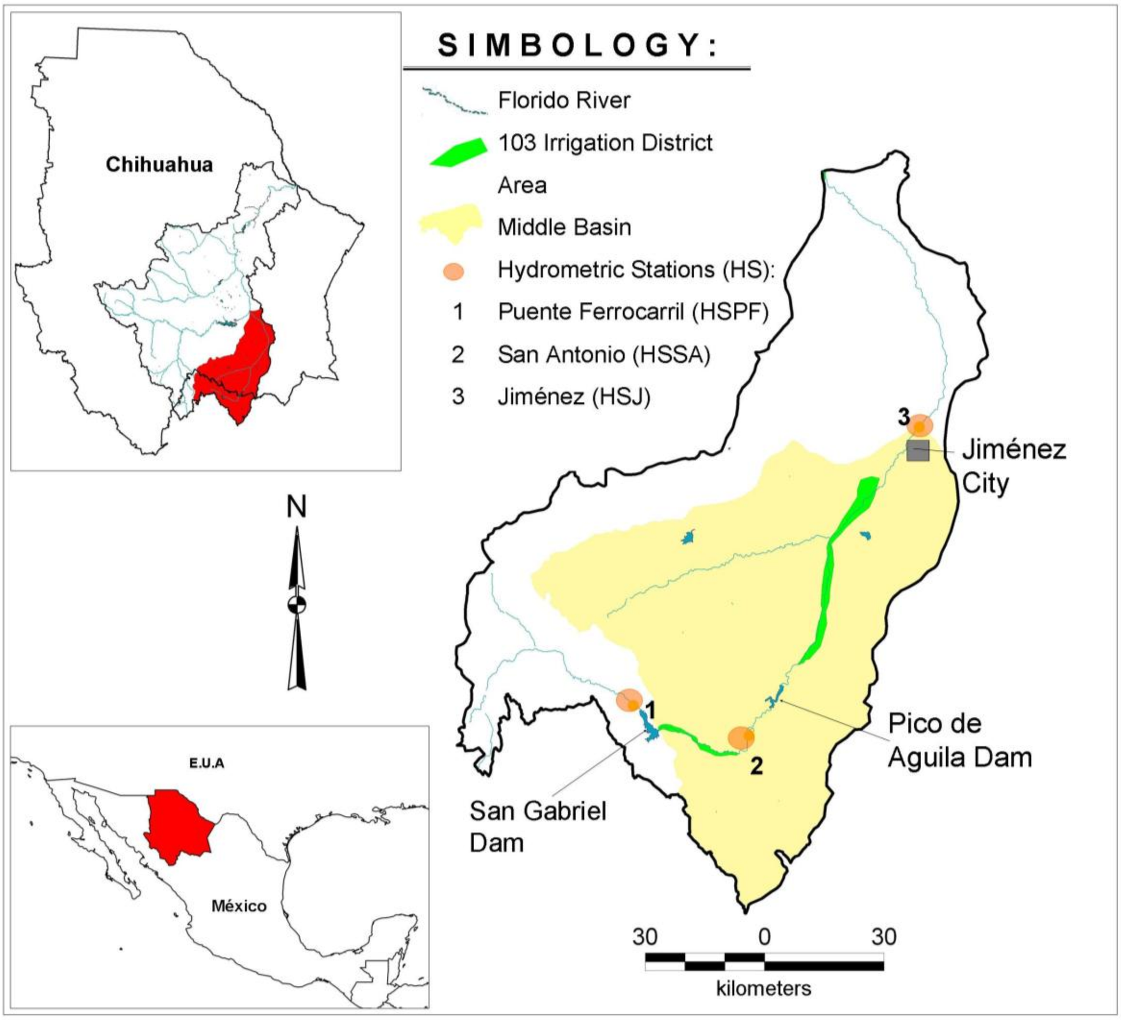

Figure 1. Location of study area

From its origin to the Jiménez hydrometric station, the Florido River basin has an area of 7,395 km^2 (CNA, 1997). After subtracting the 1150 km^2 from the beginning of the basin to the San Gabriel dam (CNA and SEMARNAP, 1999), the study area is 6245 km^2.The study zone corresponds to what we will call the middle basin of the Florido River, from the San Gabriel dam in the State of Durango and close to the state border with Chihuahua to the hydrometric station near Jiménez city in the State of Chihuahua (Figure 1). This zone contains the Irrigation District 103, with a surface of 8,238 hectares and irrigated with surface water from the San Gabriel and Pico de Águila dams (CNA, 1997). Irrigation Units (IR) constituted by farmlands along the river basin also use the surface water. Some communities, finally, use the river flows for supplying the public and livestock farms.

Hydrometry of the Basin

According to the National Surface Water Data Bank (IMTA and CNA, 2002), there are three hydrometric stations (HS) located on the main bed of the Florido River: 1) Puente Ferrocarril (HSPF), 2) San Antonio (HSSA) and 3) Jiménez (HSJ). The HSPF station has records ranging from 1953 to the present day; HSSA contains records taken until 1985, the year it was closed; HSJ has records ranging from 1950 to 2006.

In addition, the hydrometry records from the San Gabriel and Pico de Águila dams are available since 1980 and 1994, respectively, when they started operating. The HSPF station measures the entrances to the San Gabriel dam, and since the station is so close to the dam one can consider them both to be a single control point with information from 1953 to 2006.

Both HSSA and the records from the Pico de Águila dam correspond to sites that are relatively distant from each other, and so their integration into a single control point was not considered. Since these sites have incomplete records for the required period of time, they were not considered for purposes of this analysis.

Determination of natural flows

According to the Official Mexican Norm NOM-011-CNA-2000, natural flows constitute the volume of water that is naturally captured in a hydrological basin, and that is transformed into surface flow that is collected by the natural draining system of the basin itself (SEMARNAT, 2002). Natural flow (Cp) in gauged basins is determined through the following expression, which incorporates the existence of a reservoir of surface water in the basin:

$$Cp = V_2 + E_{xb} + E_v – V_1 + Ex - Im – R + \Delta V$$

Where V_1 is the annual gauged volume coming from the upstream basin, V_2 is the annual gauged volume exiting to the downstream basin, E_{xb} is the annual volume of surface water extracted or diverted in the basin, E_v is the annual evaporation, Ex is the annual exported volume, Im is the annual imported volume, R is the annual volume of return flows, and ΔV is the change in storage volume of water. This equation is derived from the general mass conservation equation, and is also applicable to the monthly time scale.

Surface water use in the basin

According to the Public Record of Water Rights (CNA-OCRB, 2006a), there are water rights for 164.45 Mm^3 in the study area (the study zone contains concessions for 164.45 Mm^3). For the time period between 1982 and 2000, an annual mean use of 108.6 Mm^3 was estimated. Irrigation district 103 received 81.56% of the distributed volume, while 18.43% was used in the IUs and only 0.01% was destined to livestock farming and public urban use (CNA-OCRB, 2006b).

Evaporation and changes in accumulated water

From 1982 to 2002, the San Gabriel dam presented a mean annual evaporation of 16.2% of the water volume that entered the dam, while in Pico de Águila this percentage was 6.34% from 1994 to 2002. In the case of the former dam, the mean storage during this period was in the order of 43% of the dam's storage capacity, while in the latter dam it was closer to 40%. The changes in storage volumes were determined for the same period of time as the evaporation values, both of them from the records of the dams (IMTA and CNA, 2000).

Imported and Exported Water

There are no water exports to adjacent basins from the basin of the Florido River; all water leaving the system is included in the mass balance equation within the annual volume gauged in the downstream basin. Also, this basin receives no water imports from neighboring basins.

Return flows

a) Returns from public urban use:

In the study zone, no return flows were considered from urban public use. This is because the communities in this area are very small and their use of surface water for this purpose is very small.

b) Irrigation returns:

Irrigation return flows exist within the study zone; they are generated by Irrigation District 103. In the 1996-2002 Grand Vision Hydraulic Program of the State of Chihuahua (CNA, 1997), it is considered that 20% of the water used in agricultural activity returns to the river. However, there are no detailed studies or measurements to quantify the water volumes that in fact do return to the river after being used in irrigation. Some authors report return percentages of 50% with respect to the volume used for irrigation (Yoshitani and Tianqi, 2007); others report return ranges between 20% and 40% (with 35% assumed in practice) for surface water and 30% for groundwater (Jothiprakash, 2003). The election of some value within this range introduces a great uncertainty into the determination of natural flows, and naturally of the return volume as well.

c) Proposed method:

The method consists of determining the annual hydrogram of mean monthly natural flow for a historical period of time that is representative of the basin's hydrological behavior. Calculation of the natural flows is performed using the available historical hydrometric records and the mass conservation equation, without initially taking into consideration any irrigation return flows. If the annual hydrogram of mean monthly flow shows increments in natural flow during the dry season, they can only be attributed to return flows. This constitutes an anomaly with respect to the theoretical hydrogram, and occurs during the dry months that have the greatest demand for irrigation water.

The anomaly can be corrected by re-calculating the historical natural flows while introducing irrigation return values (as a percentage of the volume used for irrigation), until a value is found for which the deformation of the annual flow hydrogram of mean monthly flow disappears.

Results and Discussion

Natural mean annual flow without considering irrigation returns.

The natural mean annual flow from 1982 to 2002, estimated from monthly values of the components of the mass conservation equation, was 77.44 Mm^3. Figure 2 shows the annual hydrogram of mean monthly flow for this analysis interval.

Figure 2 also shows the mean monthly distribution throughout the year of the water use performed during the period of basin analysis. It can be observed that the greatest demand occurs during the dry months (March to June in the middle basin of the Florido River) and that part of this water volume used by agricultural activities, returns to the river through agricultural drainage infrastructure. This is manifested in the deformation of the annual hydrogram of mean monthly flow, showing during the dry months as an increment in natural flows without the presence of rainfall. During these months, natural or base flows are minimal (they can even become null in some years) and the demand for irrigation is greater; consequently, the presence of agricultural water excesses returning to the river is also greater.

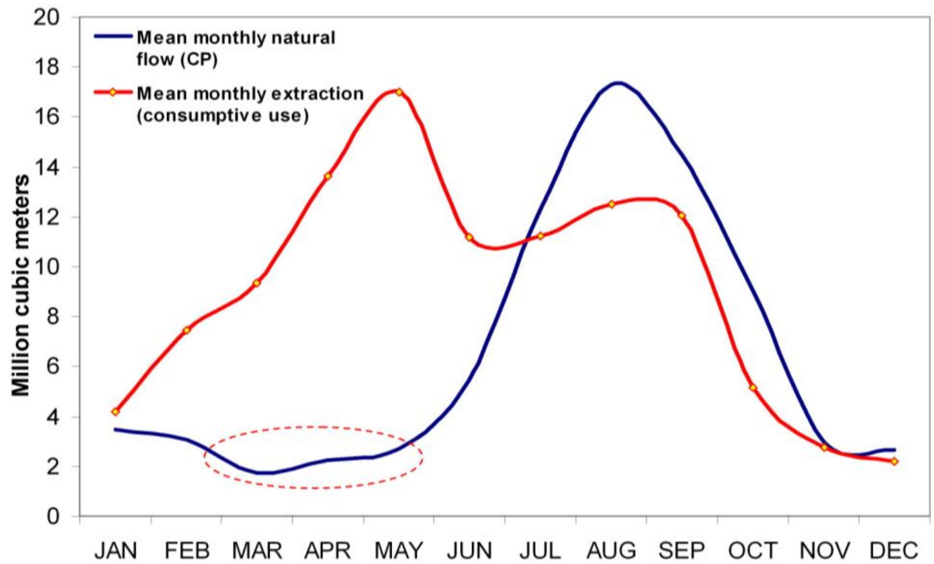

Figure 2. Natural flow and mean monthly consumptive use from 1982 to 2002.

Estimation of the percentage of the water volume used for irrigation that returns to the Florido River, using the proposed alternative method.

In order to evaluate the percentage of the water volume used in irrigation that returns to the river in sub-basin SC2, the mean monthly flow was recalculated for the period of analysis, considering irrigation return percentages between 10% and 60% with increments of 10 percentage points. Figure 3 shows the calculated annual hydrograms of mean monthly natural flow.

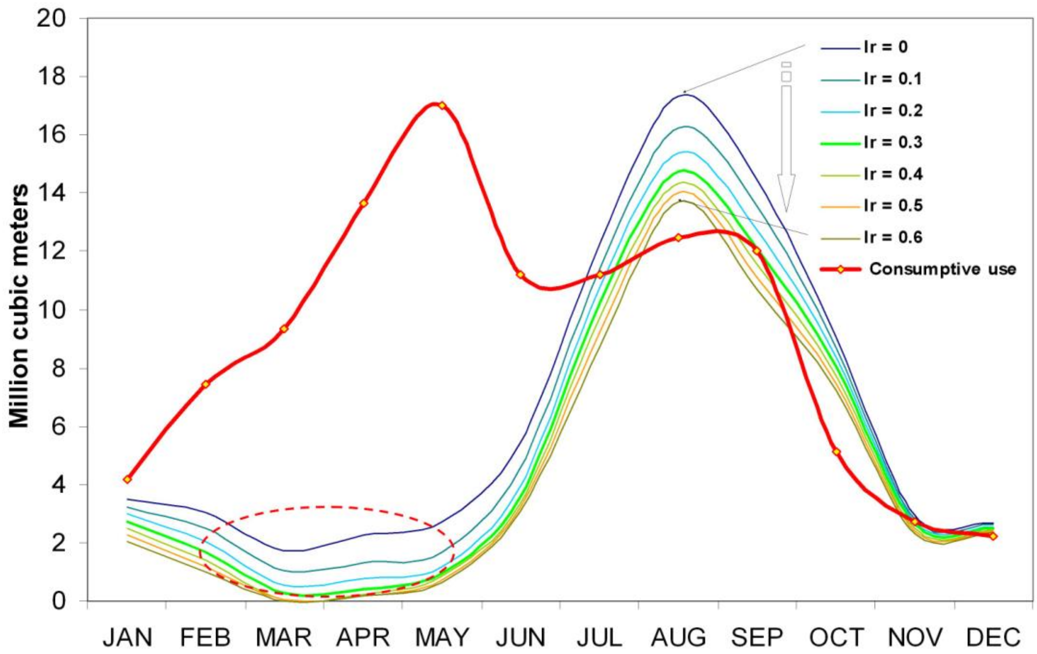

Figure 3. Natural flow and mean monthly consumptive use from 1982 to 2002 (including irrigation returns)

Starting at a return corresponding to 30% of the volume used in agricultural activity, it is observed that the natural flow hydrogram stops presenting the said deformation during the months of March, April and May. Thirty percent is a reasonable value, and observation of the hydrograms in Figure 3 does not justify a greater percentage.

Natural mean annual flow including irrigation returns.

The natural mean annual flow of the basin from 1982 and 2002, estimated from the monthly values of the components of the mass conservation equation and including a return flow corresponding to 30% of the volume used in irrigation, was 59.87 Mm^3. Figure 4 shows the initial annual hydrogram of mean monthly flow (without considering agricultural return flows) and the final hydrogram (considering an irrigation return flow of 30%). This figure shows how the anomaly generated by irrigation return flows was corrected, making it possible to quantify natural flows more precisely.

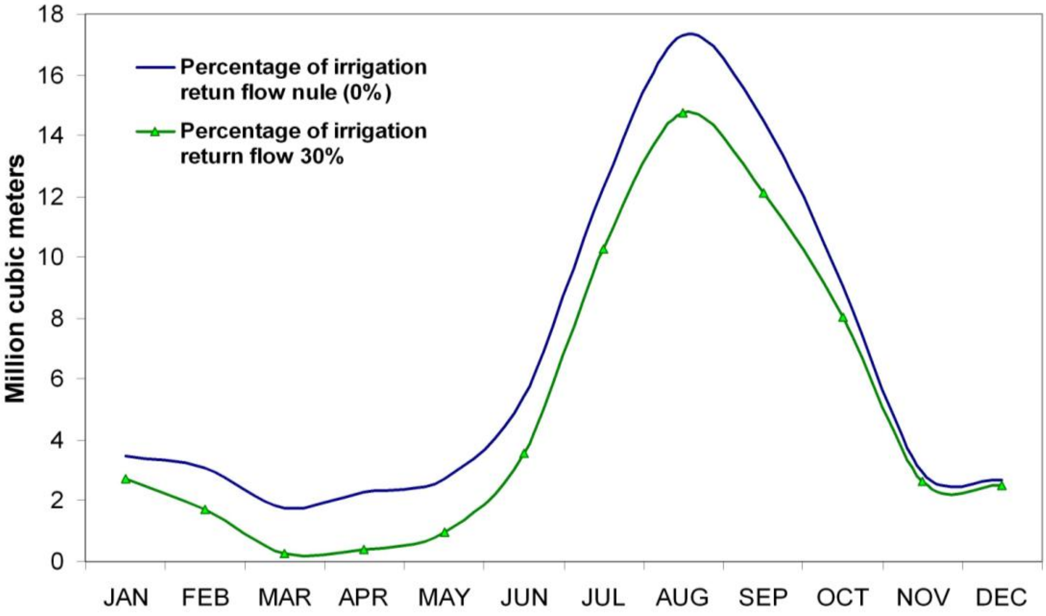

Figure 4. Natural flow and mean monthly consumptive use from 1982 to 2002 (considering 30% and 0% irrigation returns).

This proposal to determine the percentage of irrigation water which returns to the river is valid as a mean value for the period of analysis. Return flow could be different for a different interval or for a specific event-based analysis.

Conclusions

Through the detection and correction of the anomaly generated by irrigation return flow in a historical time period's annual hydrogram of mean monthly flow, it was possible to estimate the average percentage of irrigation water that is re-incorporated to the surface flow of the river in a hydrological basin. The results obtained for the Florido River basin (the developed example case) show that the proposed method produces results consistent with the values reported in literature and reduces the uncertainty of the estimation of return flows. The proposed allows for the more precise determination of the natural flows in a hydrological basin.

Acknowledgements

The present work was performed as part of a research project CHIH-2006-C01-54912, supported with funds from the Fondo Mixto CONACyT – Gobierno del Estado de Chihuahua, México.

The authors wish to thank Mr. Daniel A. Martín-Alarcón, of New Mexico State University, for the proofreading and translation of the manuscript.

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