Natural flows determination in gauged hydrological basins. Part II: The effect of time scale

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Abstract

In this work, the effect of the time scale on the determination of natural flows in gauged hydrological basins is analyzed using available hydrometric historic records and the mass conservation equation.

The upper - middle basin of the Florido river (Río Florido), in the northern Mexican State of Chihuahua, was used to perform this study. The basin was divided into the upper sub-basin (U-SB), with no infrastructure for water use; and the middle sub-basin (M-SB), where the complete infrastructure of Irrigation District 103 is located. The mean annual natural flow of both sub-basins was estimated, using the annual and monthly time scales, for the period spanning from 1982 to 2002. There are no return flows in U-SB, while in M-SB flows are generated by the irrigation district.

By correcting the annual hydrogram of mean monthly natural flows, it was estimated that 30% of the irrigation water volume returned to the river during the analysis period, as is discussed in a parallel study (Silva-Hidalgo et al., 2008). The estimated natural flow was 116.8 Mm^3 for the U-SB at the annual scale, and 119.9 Mm^3 at the monthly scale. These results differ in only 2.65%, which shows that the time scale had very low impact. The mean annual natural flow in M-SB, calculated using a return flow of 30% as determined before, results in 59.87 Mm^3 at the monthly scale and of 49.6 Mm^3 at the annual scale. These results are inconsistent, differing 20.7% from each other, which suggests that the time scale is indeed very important in basins where water is used for irrigation.

The inconsistency of the results obtained at different time scales can be explained if it is observed that, during the calculations for both sub-basins, negative natural flows were obtained during several years for some of the dry months between February and June. A

negative natural flow does not have physical meaning, but can be related to water losses along the river, or to water extractions larger than reported.

The detection and correction of the anomaly, if it shows up, can only be achieved when a monthly or shorter time scale is used. The correction is performed by setting all negative calculated values to zero; the obtained results are more reliable than those obtained using the annual time scale. It is concluded that for basins with irrigation infrastructure, the monthly time scale should be used for natural flow determinations. The use of an annual scale is only advised for preliminary evaluations.

Introducción

Mankind's capacity to foresee, plan and administer natural resources, and water in particular, is being put to the test in many parts of the planet. However, in order to plan the use of water resources it is first necessary to spatially and temporally quantify them and determine the limit to which it is possible to sustainably use these resources (Carabias *et al.*, 2005). This can be achieved through the determination of the natural or virgin flows, which correspond to the natural availability of surface water resources in a hydrological basin (SEMARNAP, 2000). Planning the use of water resources is not limited to developing countries. The growing demand for water to satisfy the needs of society, including food production, is forcing us to solve water conflicts that exist between the different user sectors, even in developing countries. Because of this, it is vitally important to temporally and spatially quantify the natural availability of the resource, in order to reorder its use in accordance with the new needs and guarantee continued development in these regions.

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). Thus, natural flows are those that would be found at the end of the basin were it not for the human activity that uses water and for the infrastructure that diverts, withdraws or stores it. Natural flows represent or characterize the hydrological behavior of a basin, and can be determined from the adjustment of the hydrometric records of rivers, through the application of rain-runoff hydrological models or through statistical methods (TNRCC, 1997).

Hydrological models are useful for the determination of hydrological behavior in non-gauged basins, in basins with poor hydrometric records, or when one wants to know the impacts that can produce important changes in the use of soil or in the climate (Xu, 2002). However, the obtained results will depend on the selected hydrological model as well as on the existence and quality of climatological records and the physical measurements of the parameters required by the model. In basins with significant water use, it has been observed that it is necessary to have databases of natural flows that would allow for the calibration of rain-runoff models (Yoshitani and Tianqi, 2007). In this way, the trustworthy application of these models would be conditioned to the existence of hydrometric records and the possibility of calculating natural flows from these records.

The objective of this study is to analyze the effect of the annual and monthly time scales in the determination of natural flow in hydrological basins, through the use of the available historical hydrometric records and the mass conservation equation.

Materials and methods

Description of the basin

The Florido River basin is located in the southern portion of the state of Chihuahua, Mexico; this river is tributary of the Conchos River, which itself is a tributary of the Bravo River. The Bravo River constitutes the territorial limit between Mexico and the United States of America; its basin and resources are shared, as established by a bi-national water agreement agreement (CILA, 1944). The Florido River has its source in the state of Durango, in the Los

Azules Sierra, at an altitude of 2,880 m over sea level. It flows parallel to the border with the state of Chihuahua for about 80 km in a southwest direction before abruptly heading into the territory of the latter state, in a northeast direction. It continues to descend for little more than 100km, and downstream from Jiménez City it turns northwest towards its union with the Conchos River near Camargo City. Along its basin, the mean annual precipitation varies from 500mm at its origin to 300mm at its lower end (CNA, 1997).

The study zone corresponds to what we will call the mid-high basin of the Florido River, from its origin in Durango to Jiménez City, Chih., where the Jiménez Hydrometric Station is located (Figure 1). It has an extension of 7,395 km^2 and within it lies the Irrigation District 103, Rio Florido, which has a surface of 8,238 hectares irrigated with surface water from the San Gabriel and Pico de Águila dams (CNA, 1997). The Irrigation Units (IU), constituted of agricultural lands along the river basin, also draw surface water from the river. Finally, some communities use the river flows for public supply and livestock breeding. According to the Public Record of Water Rights, annual concessions for 171 Mm^3 (CNA, 2004) exist to satisfy the demands of the activities that take place in the mid-high basin of the Florido River.

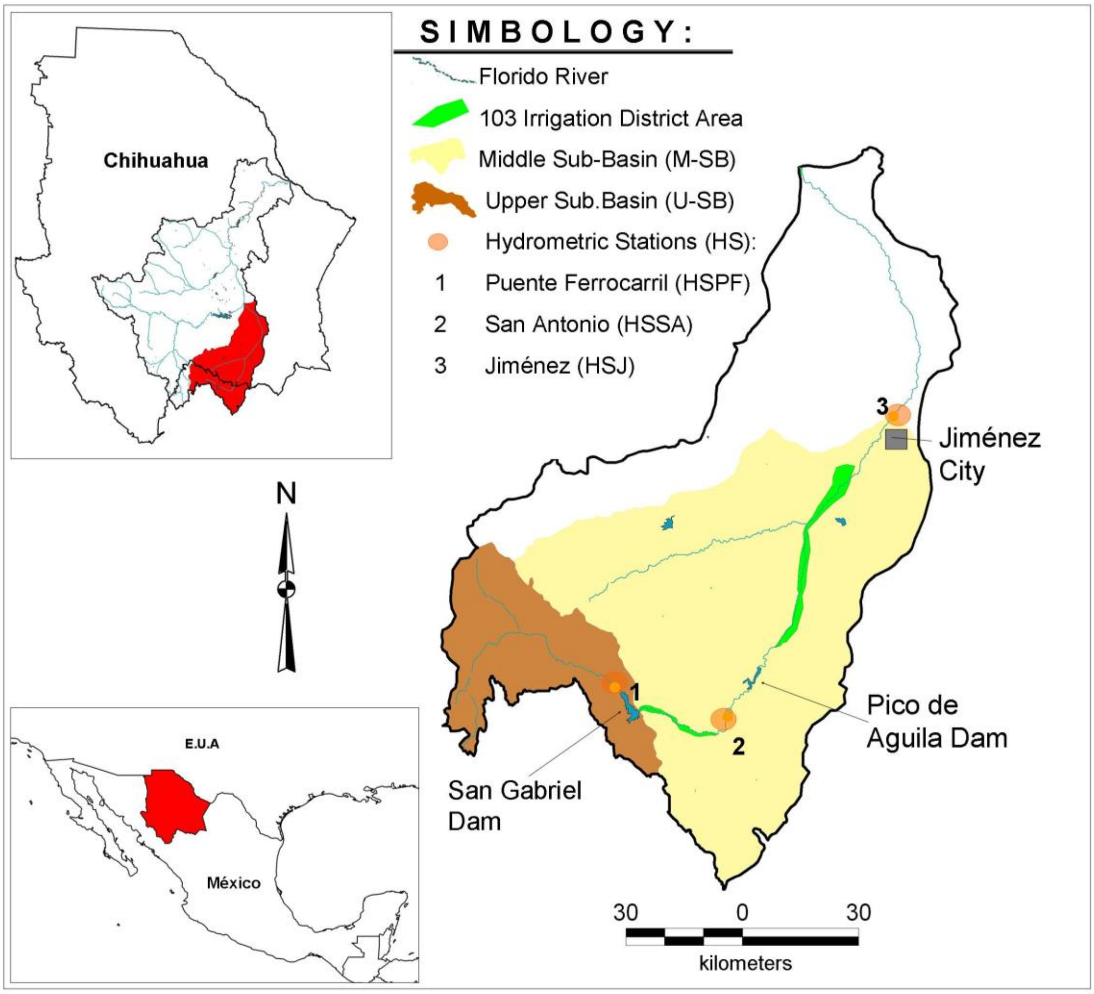

Figure 1. Location of the study area

Hydrommetry of the basin

According to the National Surface Water Data Bank (NSWDB) (IMTA and CNA, 2002), there are three hydrometric stations in the medium-upper basin of the Florido River, located along the main river bed: 1) Puente Ferrocarril (HSPF), 2) San Antonio (HSSA) and 3) Jiménez (HSJ). The HSPF station has records from 1953 to the present day; HSSA, however, stopped operating in 1985 and no records have been made since that year. The HSJ station has records spanning from 1950 to 2006.

Additionally, there are hydrometric records from the San Gabriel and Pico de Águila dams that have been made since they were built in 1980 and 1994, respectively. The HSPF station measures the inflow to the San Gabriel dam, and because of their proximity the records for both are considered to represent a single control point with information spanning from 1953 to 2006.

The HSSA station and Pico de Águila dam are distant from each other, and because of this they were not integrated into a single control point. Since these sites have incomplete records for the required period of time, they were not considered for purposes of the present analysis. As a result of the hydrometric record analysis, the study area was divided into two sub-basins: 1) from the origin of the Florido River to the San Gabriel dam (U-SB), and 2) from the San Gabriel dam to the Jiménez Hydrometric Station (M-SB).

Determination of natural flow

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 transforms into surface flow, which is later collected by the basin's own natural draining system (SEMARNAT, 2002). The natural flow (Cp) in gauged basins is determined through the following expression, which incorporates the existence of surface water accumulation in the basin:

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

Where V1 is the annual gauged volume coming from the upstream basin, V2 is the annual gauged volume exiting to the downstream basin, Exb is the annual volume of surface water extracted or diverted in the basin, Ev 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), the study zone contains concessions for 171 Mm^3. For the time period between 1982 and 2000, an annual mean use of 2.28 Mm^3 was estimated for U-SB. Agricultural production in the IUs received 89.04% of the volume, while the remaining 10.96% was destined to livestock farming and urban public use (CNA-OCRB, 2006b). An annual mean use of 108.6 Mm^3 is estimated for M-SB, 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 storage volumes

From 1982 to 2002, the San Gabriel dam presented a mean annual evaporation of 16.2% of the wáter volume that entered the dam, while in Pico de Águila this percentage was 6.34% from 1994 to 2002. In the case of the latter dam, the mean storage volume during this period was in the order of 40% of the dam's storage capacity. 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 other basins from the mid-upper basin of the Florido River; all that leaves the system is included in the mass balance equation within the annual volume gauged in the downstream basin. Also, this part of the basin receives no water imports from adjacent basins.

Return

a) Return from urban public use:

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

b) Irrigation return:

Irrigation return flows exist in the study zone, which are generated by Irrigation District 103. It was determined through the correction of the annual hydrogram of mean monthly natural flow that 30% of the water volume used in irrigation of the basin returned to the river during the period of analysis, as detailed in a work developed by Silva-Hidalgo *et al.* (2008).

Results and Discussion

Annual mean natural flow in sub-basins U-SB and M-SB

U-SB. From the origin of the Florido River to the San Gabriel Dam.

In U-SB, which corresponds to the origin of the Florido River basin, water use is minimal and thus no irrigation return is considered. This can be verified when observing that the hydrogram of natural flows in Figure 2 shows no deformation with respect to a theoretical hydrogram of the natural flow, in a basin with summer precipitations regime. Consistently, the distribution of the mean monthly extraction is kept at a minimum level throughout the year.

The use of annual values of the parameters of the mass conservation equation was considered for the estimation of natural flow at the annual time scale, while monthly values are used for the monthly time scale. The mean natural annual flow estimated for U-SB using the annual time scale was 116.8Mm^3.

This same result was initially obtained considering the corresponding monthly values in the mass conservation equation for the same period of time. However, during the calculation of natural flows negative values were obtained for some of the months between February and June (which correspond to the summer season in the study zone) for several of the years that were analyzed. The lower limit of the natural flow is reached when there is no flow, so a negative value of natural flow has no physical meaning. It can, however, be related to losses by infiltration, evaporation, evapotranspiration and other natural losses that occur throughout the length of the river basin, and also to water extractions greater than those reported in the basin (losses of anthropogenic origin). The detection of this anomaly when it shows, as well as its correction, is only possible when the monthly time scale or a smaller one is used. Once the originally calculated negative values of mean monthly natural flow were corrected, a mean annual flow of 119.9 Mm^3 was obtained. The results at both time scales differ in only 2.65%, which shows that in the case of U-SB the chosen time scale had little effect.

Figure 2 shows the annual hydrograms of monthly mean natural flow: a) including the negative values initially calculated for some years, and b) correcting the negative values by assigning a value of zero. It is observed in this same figure that the difference between both hydrograms shows up mainly during the months between February and June.

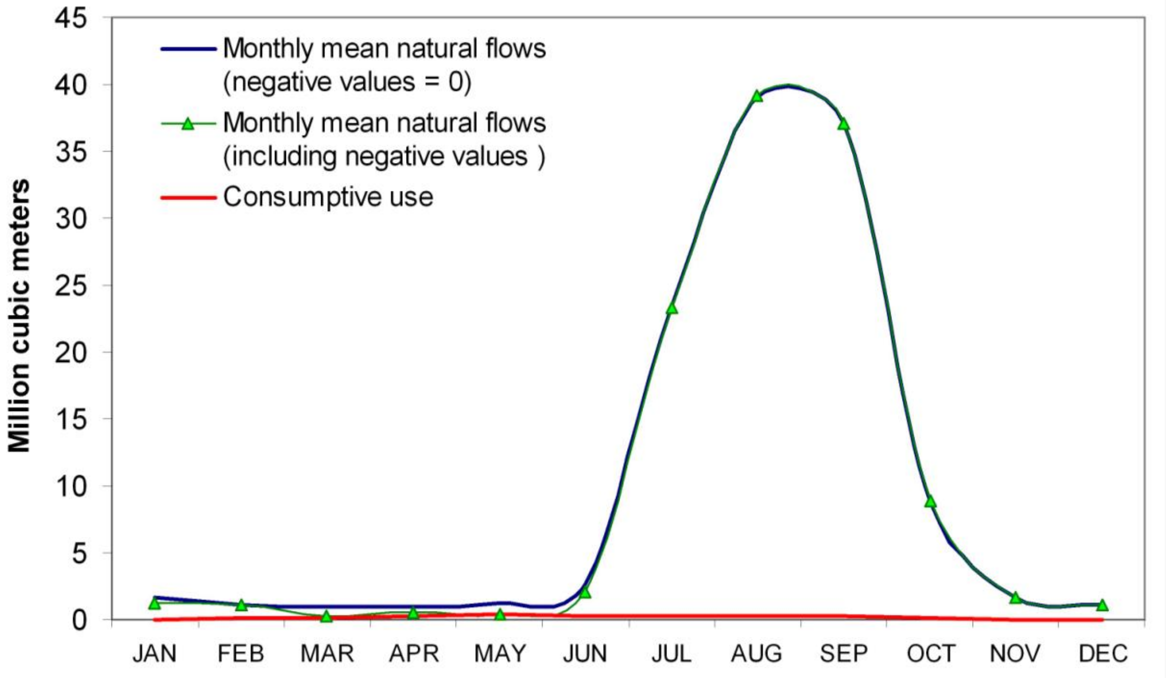

Figure 2. Natural flow and monthly consumptive use from 1982 to 2002

M-SB. From the San Gabriel Dam to the Jiménez hydrometric station.

The annual mean natural flow estimated for M-SB was 75.20 Mm^3 using the annual time scale without initially considering irrigation return. This same value was obtained when performing the estimation from monthly values of the variables that intervene in the mass conservation equation. As in U-SB, this calculation yielded negative flow values during the summer months in some of the studied years. Once these values were corrected by setting them to zero, the annual mean natural flow became 77.44 Mm^3 still without including return flows. Figure 3 shows the annual hydrograms of natural flow including negative and corrected values; it can be observed that the shift shows mainly during the months of February to June.

Irrigation district 103, as well as other Irrigation Units, is located in this sub-basin (M-SB). This can be verified by observing the consumptive use graph in Figure 3, which shows the distribution of mean monthly use (typical of agricultural activity) throughout the year. Part of the volume used in agricultural activity returns to the river through the drainage infrastructure. The mean annual natural flow from 1982 to 2002 in sub-basin M-SB, estimated from monthly values of the components of the mass conservation equation and including an irrigation return of 30% (see Figure 3), was 59.87 Mm^3; the same analysis using the annual scale yielded a value of 49.6 Mm^3. These results are inconsistent, since they differ by 20.7%; this suggests that the used time scale is very important in basins with significant water use.

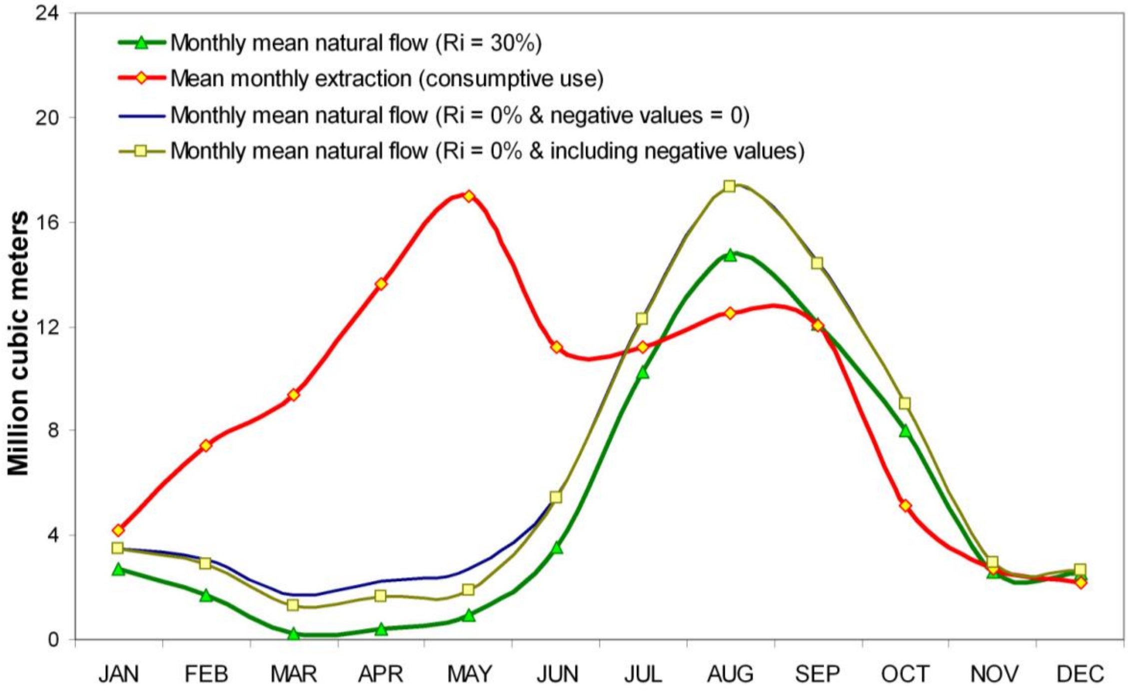

Figure 3. Natural flow and monthly mean consumptive use from 1982 to 2002.

Time series of natural flows estimated at the monthly scale.

U-SB. From the origin of the Florido River to the San Gabriel Dam.

The Florido River has its origin in this sub-basin, and so it receives no more flow contributions than those that originate in its own surface. As was previously established, the water use in this basin is minimal (Figure 2). The extraction performed in U-SB has practically no effect on the natural flow pattern, so the historical gauged flows are very similar to the estimated natural flows (Figure 4).

Figure 4 shows the annual flows for the analyzed period; it can be observed that there is a sensible decrease in natural flows from 1992 to 2002 (with the exception of 1993 and 1996). This follows a decrease in precipitations during a period of drought (Núñez-López *et al.*, 2007).

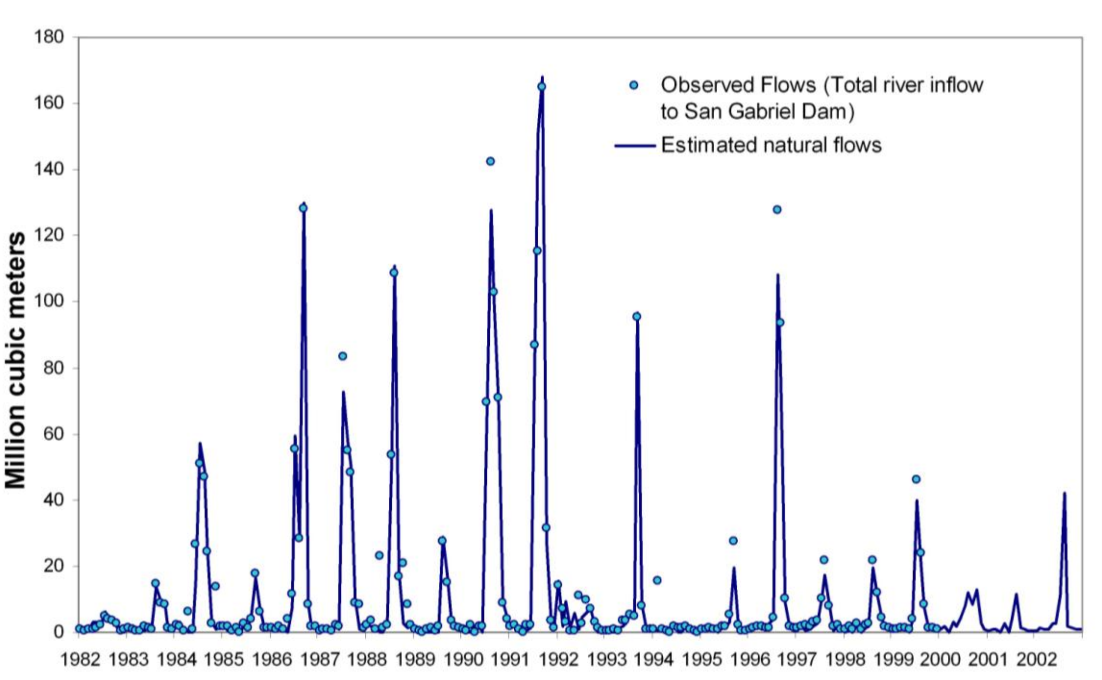

Figure 4. Natural flow estimated from 1982 to 2002 at the exit of U-SB, and total river inflow to San Grabriel Dam of the NSWDB (IMTA and CNA, 2000).

M-SB. From the San Gabriel Dam to the Jiménez hydrometric station.

M-SB is located downstream from U-SB, so it receives the flows that leave the other. The flows from U-SB have a great influence over the gauged volumes at the exit of M-SB. Figure 5 shows that until before 1994 the gauged flow in HSJ was very similar to the sum of the natural flow generated in M-SB and the flow coming from U-SB. The Pico de Águila dam started operating in 1994, making it possible to store, regularize and use during summertime the volumes from San Gabriel and part of the natural flow generated in M-SB. Irrigation District 103 operates both dams together and performs water transferences as necessary to satisfy irrigation demands. Since 1994, the gauged flows in HSJ incorporate the effect of storage and regulation of the Pico de Águila dam; thus, at least during the analyzed period the flows from U-SB cease to have influence. Consistently with this, the estimated natural flow is greater than the observed flow since the Pico de Aguila dam started operating.

Since 1992 and until 2002, it is observed that natural flows decrease significantly; this is related to the years of low precipitation occurred during the drought years (Núñez-López *et al.*, 2007), which also affected U-SB.

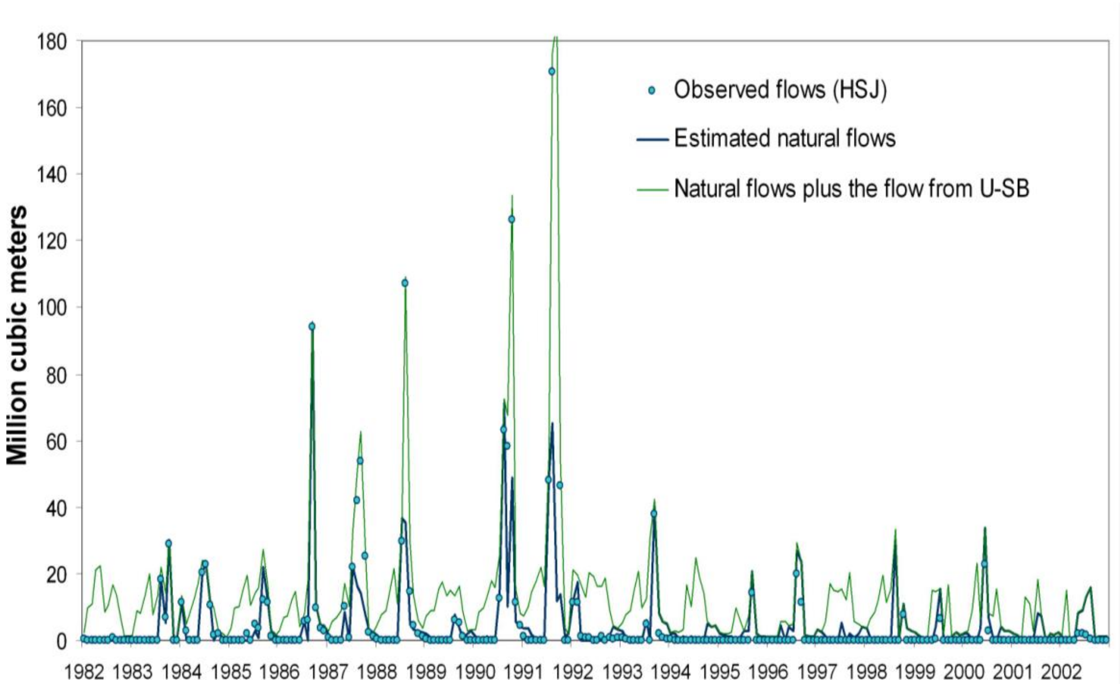

Figure 5. Monthly natural flow estimated from 1982 to 2002 at the exit of sub-basin M-SB, historical flow gauged at the Jiménez Hydrometric Station, and natural flow plus the flow from sub-basin U-SB.

Conclusions

During the calculation of natural flows at the monthly time scale, it is possible that some months will show negative values, especially during the summer months. This can be caused by surface water losses along the basin and can have a natural or anthropogenic origin. The detection and correction of these anomalous values when they show up can only be done using a monthly or smaller time scale. In the studied case, this situation had little effect in the sub-basin with little water use (U-SB), while the effect was significant in the sub-basin with important water use (M-SB). It is concluded that in order to determine natural flow in basins that have water use infrastructure one must use the monthly time scale, while the use of the annual time scale is only recommended for preliminary evaluations.

In basins where surface water use is limited or non-existent, the determination of natural flow at the monthly and annual time scales produce a very similar result. However, the annual time scale only makes it possible to quantify the mean annual natural availability; only the monthly time scale or a smaller one makes it possible to know distribution throughout the year. This information is indispensible for purposes of planning or reordering the use of surface water resources.

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