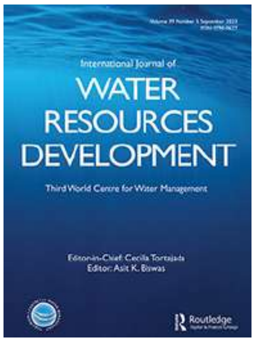

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Unsustainable use of surface water due to water balance miscalculation: the Culiacán River basin, Mexico

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ABSTRACT

The development of instruments for the administration of water use is a pending issue in both developing and developed countries. UNESCO has published guidance on determining water availability in Latin American and Caribbean countries. We applied this method to the Culiacán River basin, the most significant basin in Mexico for agricultural productivity. We find that surface water availability has been overestimated due to the inclusion of non-physical terms in the water balance equation, miscalculation of natural runoff and the omission of ecological water flow. Thus, unsustainable surface water use is allowed based on a miscalculation of physical water availability.

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Water balance miscalculation; water availability method; water availability at the basin level; unsustainable water use; water rights; Culiacán River basin

Introduction

Sustainable development can be defined as the proper management of human, material, economic and natural resources without depletion of natural resources (Cepeliauskaite & Stasiskiene, 2020). Based on this definition, sustainable development in a region depends on the effective management of its water resources to support economic and population growth (Ahmadov, 2020). Water is an indispensable resource for life and the development of economic activities; water scarcity creates hardship and social, political and economic conflicts (Damania, 2020; Oki & Quiocho, 2020; Tzanakakis et al., 2020). Sustainability means that water resources can meet the demand for various water uses without being over-exploited. To this end, proper water resources administration must be established to preserve ecosystems and provide legal protection to water users, including ecosystems (He et al., 2020; Pahl-Wostl, 2020; Schreiner & van Koppen, 2020). Monitoring must also be provided to allow the water authority to track the magnitude, type and location of points of diversion of water resources (Gawel & Bretschneider, 2017).

Strategies to enhance sustainable water resources management might involve a water rights framework regulated by the government (McKenzie, 2018). This framework can

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include definitions and provisions regarding water resources management, such as the regulation of water use. However, there is room for improvement in the development and application of instruments for the administration of water use, even in developed countries. For example, Grantham and Viers (2014) describe a hundred years of inaccurate and incomplete accounting of water rights in California. Schneider and Andreaus (2018) showed the long-term implications of perpetual water rights agreements in northern British Columbia, Canada. Tello et al. (2016) suggest producing transparent and auditable water accounts that can be compared and reconciled across jurisdictional restrictions. These water accounts should provide confidence in the amount of water being traded, extracted for consumptive use, and recovered and managed for environmental and other public benefit outcomes.

In Latin America and the Caribbean, federal governments have established normative frames in this regard. Countries such as Argentina (MJDH, 2002), Chile (MJ, 2018), Colombia (MAVDR, 2004), Ecuador (ANCRE, 2014) and Peru (CM, 2009) have legal instruments to regulate water use. The application of these instruments is based on estimates of water availability, which solid technical procedures should underpin to avoid inconsistencies. The procedures need to properly delineate the river basin and correctly apply hydrological principles (García et al., 2017). For that purpose, UNESCO (2006) provides guidance for Latin American and Caribbean countries based on the official Mexican method established in the norm NOM-011-CONAGUA-2015 (NOM-011).

In Mexico, water use is regulated through water allocations called concessions. They grant water rights based on the water availability in a basin, calculated by the water authority (the National Water Commission – CONAGUA). NOM-011 establishes the official (mandatory) method of determining water availability (SEMARNAT, 2015). Results are periodically published in the official government gazette (*Diario Oficial de la Federación*) and provide values for the terms involved in the water balance of each basin. However, the specific procedures, assumptions and calculations used to obtain these values are not provided, even if requested through legally supported channels, such as the National Transparency Platform.

Researchers, hydrologists, consultants and other professionals would want to use the NOM-011 method to verify the figures for surface water availability. It adapts, adopts and applies the continuity principle to the surface water in a basin. However, the official methods (and, therefore, results) have been contested. For example, Rentería-Guevara et al. (2019) argued that river basins are established by the Mexican government when they do not represent drainage units even though the NOM-011 method requires these geographical units to perform hydrological analysis. Besides, CONAGUA has published hydrological balances with negative values that are inconsistent with the continuity principle (CONAGUA, 2020).

Sustainable water management depends crucially on a correct estimation of available water resources. Official Mexican websites have information that is publicly available to estimate water balances, but CONAGUA does not provide specific procedures and assumptions required to obtain the official results. However, the NOM-011 method suggests using traditional methodologies to estimate water balances. Hence, in the present study, the NOM-011 methodology was implemented, but also some novel strategies were proposed to determine surface water availability in the Culiacán River basin, the most significant river basin in Mexico for agricultural productivity. We then compare our results with the official published results to determine how accurate the official method results are.

Materials and methods

Study area

The Humaya and Tamazula river basins collect runoff from higher ground, which these two rivers conduct to their confluence to form the Culiacán River in the city of Culiacán, Mexico. The Culiacán River is 305 km long and is a sixth-order stream with an angular drainage pattern. The Humaya River is the largest tributary of the Culiacán River. It arises at more than 3100 masl in the state of Durango. According to CONAGUA (2016a), precipitation of 950 mm/y, a natural runoff of 1900 million m^3/y, a surface area of 11,000 km^2 and a specific runoff of 172,730 m^3/km^2/y are registered in the Humaya River basin. The Adolfo López Mateos (ALM) reservoir is downstream the Humaya River basin and regulates the water supply, mainly for agriculture.

The Tamazula River basin has a maximum elevation of 1145 masl, precipitation of 985 mm/y and a natural runoff of 755 million m^3/y (CONAGUA, 2016a), a surface area of 3300 km^2 and a specific runoff of 228,790 m^3/km^2/y. The Sanalona reservoir is on the Tamazula River, upstream from its confluence with the Humaya. Since the difference between the precipitation of the Humaya and Tamazula river basins is small, the noticeable difference between their specific runoffs comes from the runoff coefficients, which are 0.17 and 0.22, respectively. The values of runoff coefficients are not available publicly but were obtained through direct communication (CONAGUA, personal communication, 2022).

The Culiacán River basin is exorheic and drains towards the Gulf of California (Figure 1). Given its size and intense agricultural activity, it is one of the most important basins in Mexico. This basin has a surface area of 2600 km^2 and is between parallels 26°03′13″N and 24°27′10″N, and between meridians 107°45′39″W and 105°48′34.16″W.

The National Institute of Geography and Statistics (INEGI) (2021) and the CONAGUA (2016a) published official boundaries for the basin. These delineations are based on the Humaya, Tamazula and Culiacán river basins and were generated using digital elevation data to identify catchment boundaries. INEGI and CONAGUA use the same names for these basins, yet they assign different boundaries and sizes (Figure 1). CONAGUA's description also includes another watercourse, the Pericos River, but this river does not drain into the Culiacán River, and official publications do not explain the reason for this association.

The geological frame of the Culiacán River basin consists mainly of rock from the volcanic origin of the Sierra Madre Occidental plateau, crossed by canyons and sediments of the Costa del Pacífico plain. Both groups are composed of rock with different ages that vary from the Superior Palaeozoic to the Holocene and include meta-volcanic sedimentary, volcanic sedimentary, sedimentary, igneous, intrusive and extrusive rocks, and sediments of alluvial, fluvial, littoral and lacustrine origin. The basement of the region consists of a meta-volcanic sedimentary sequence formed with slates, schists, quartzites, meta-andesites and phyllites. This basement unconformably underlies Mesozoic and Cenozoic rocks (CONAGUA, 2015a).

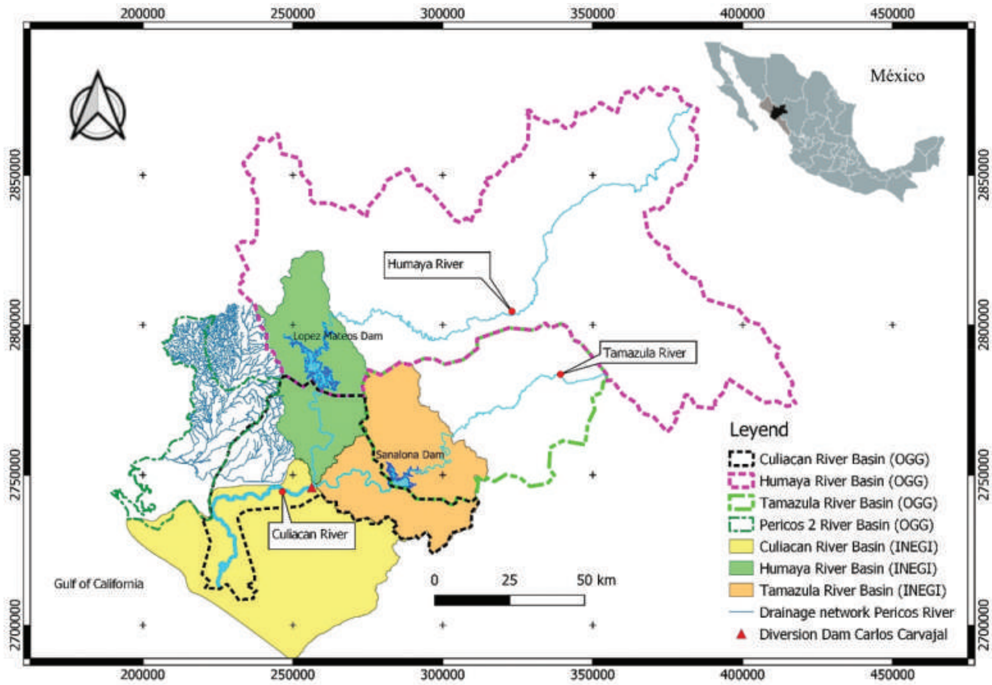

Figure 1. Geographical location and main hydrological features of the study area. Source: Elaborated by the authors based on CONAGUA (2016a) and INEGI (2021).

There are 10 soil types in the Culiacán River basin, according to the IUSS (2015) classification. Vertisols, phaeozems and leptosols cover more than 80% of the basin surface. Vertisols (36%) are concentrated in zones of dry and warm climates with summer rains. These soils are in the coastal plains and valleys of mild-slope hillsides and mainly consist of clay. Phaeozoms (30%) soils have a dark surface layer that is rich in organic matter and used for rainfed agriculture. These soils are in plains, mainly to the north and south-west of the basin. Leptosols (15%) are sallow soils that lie over rock or gravel soils and are in the mountainous zone of the basin. The rest of the soil types in the basin are solonez (5%), regosols (5%), cambisols (3%), solonchaks (2%), arenosols (2%), gleysols (1%) and luvisols (1%) (INEGI, 2019).

Water balance

The principle of mass conservation is commonly applied to the mass of water in a catchment, considered a finite-sized control volume (Hornberger et al., 2014):

$$\Delta S = (P - ET + G_{in} - G_{out} + Q_{in} - Q_{out})\Delta t \quad (1)$$

where P is the precipitation rate, ET is the rate at which water evaporates or transpires from plants in the catchment, G_{in} and G_{out} are the rates at which groundwater enters and leaves the catchment, Q_{in} and Q_{out} are the rates at which surface water enters and leaves the catchment, Δt is an arbitrary period, and ΔS is the change in mass stored over the period Δt. Each term in the parentheses has dimensions of mass per unit time (M/T).

On the same principle, the hydrological water budget for a region (the water balance between inflows, outflows and changes in storage) is:

$$\Delta S = P - R - G - E - T \tag{2}$$

where P is precipitation, R is net surface runoff, G is net groundwater flow, E is total evaporation, T is total transpiration and ΔS is the change in storage. Equation (2) solves all hydrological problems (Viessman & Lewis, 1997). In Mexico, the NOM-011 method to determine surface water availability is based on a surface water balance for a year:

$$\Delta s = In - Out = (Up + Nr + Rt + Im)_{\text{in}} - (Ex + Aw + Ev + Dn)_{\text{out}} \tag{3}$$

where Δs is the change of surface water storage in reservoirs, In is the total volume entering the basin, Out is the total volume leaving the basin, Up is the mean upstream runoff, Nr is the natural runoff generated in the catchment, Rt is the return volume, Im is the volume imported from artificially connected basins, Ex is the volume exported to artificially connected basins, Aw is the volume of administrative withdrawal, Ev is the evaporation from reservoirs, and Dn is the downstream runoff. It is important to point out that equation (3) is an adaptation of equation (1) and considers only surface water terms, and specific factors such as inter-basin transfers and withdrawals are also included. The units are millions m^3/y. Dropping the subscripts and rearranging terms, the relation can be written as:

$$Dn = Up + Nr + Rt + Im - Ex - Aw - Ev - \Delta s \tag{4}$$

which is the mathematical model presented in the NOM-011.

According to the Mexican water-resource normative frame, the method should be applied to official river basins, whose geographical vertex coordinates are published in the *Diario Oficial de la Federación*. To implement the NOM-011 method, we evaluate each term of equation (4) for the area officially designated the 'Culiacán River basin'. We next describe these evaluation procedures in detail.

Upstream runoff (Up)

Up for any basin is the sum of annual downstream volumes (*Dn*) from tributary basins. For the Culiacán River basin, *Up* is the sum of the *Dn* from the Humaya and Tamazula basins, evaluated by calculating their surface water balance with equation (4).

Natural runoff (Nr)

Dn of both basins essentially corresponds to their natural runoff (*Nr*). For this term we use simple inflow estimations for the ALM and Sanalona reservoirs (Figure 1). This is because these basins are uppermost, so they do not receive upstream runoff. They are also in undeveloped, scarcely inhabited, mountainous territories with practically no consumptive water use (*Aw*). For the same reason, imported (*Im*) and exported (*Ex*) volumes are zero for both basins. Evaporation (*Ev*) and surface storage variation (Δs) were obtained from the operation records of the two reservoirs.

According to NOM-011, *Nr* can be calculated using the direct or indirect methods. The direct method is applied in basins where inflow and outflow have been measured, and the indirect method, where they have not. In the Culiacán River basin, consistent upstream inflow measurements are carried out in the ALM and Sanalona reservoirs. In addition, there are downstream-flow records in the Puente Sudpacífico hydrometric station, which is in a strategic site: the confluence of the Humaya and Tamazula rivers at the Carlos Carvajal Diversion Dam (Figure 1). However, these records are inconsistent (Dahmen & Hall, 1990). Flow data are available from 1924 to 1992 with a gap from 1959 to 1961. The time series from 1962 to 1992 data exhibit a one-order-of-magnitude jump from the previously registered period. Statistical procedures could not correct this jump, and it was not possible to obtain information to explain such an anomaly. It is worth noting that the Sanalona and ALM dams were put into operation in 1948 and 1962, respectively. Therefore, the flow regimen was altered, and the old data cannot be used for estimating current conditions.

The indirect method consists of determining *Nr* from mean annual precipitation (*P*), basin area (A_b) and a runoff coefficient (*Ce*):

$$Nr = P \times A_b \times Ce \tag{5}$$

Ce can be found in three ways: information transfer from neighbouring river basins with similar hydrological properties; as a function of soil type, soil use and annual precipitation; or from previous hydrological studies. We used the first two because there were no previous hydrological studies in the study area.

The first way consists of transferring flow information from the Humaya and Tamazula river basins. The transfer factor is simply the proportion of basin areas. We consider the appropriate use of this method for the basin under study later in this paper.

The second way is an adaptation of a method originally proposed by the US Bureau of Reclamation (Soil Conservation Service, 1972) and consists of determining a runoff coefficient based on the parameter *K*:

$$K \leq 0.15 \quad Ce = K(P - 250)/2000 \tag{6}$$

$$K > 0.15 \quad Ce = K(P - 250)/2000 + (K - 0.15)/1.5 \tag{7}$$

where *K* depends on the use and type of soil, *Ce* is the runoff coefficient, and *P* is the mean annual precipitation in the basin (mm/y).

In this study, equations (6) and (7) were implemented using QGIS (2016). This is an open-source desktop platform for mathematical operations among raster files. Precipitation, soil type and soil-use maps were prepared to obtain raster maps which spatially represented runoff coefficient, natural runoff and *K* in the basin. First, a mean annual precipitation raster map was generated. Representative climatological stations were selected, and statistical tests were conducted to ensure the data's homogeneity, consistency and stationariness (Dahmen & Hall, 1990; Kocsis et al., 2020). These stations were represented as a vectorial layer of points in the Culiacán River basin map. The precipitation data were distributed over the basin map with multilevel B-spline interpolation (Sharifi et al., 2019). A raster map of areal precipitation was obtained with a pixel resolution of 10×10 m.

Next, a raster map of the *K* parameter was prepared based on soil type and use. To do this, official vector maps of land use and vegetation and soil type (INEGI, 2017) were converted to raster maps with a pixel resolution of 10×10 m (Figure 2). Matrix *a* is a soil type raster map of the basin; the numbers correspond to pixels with soil types. Matrix *b* is a raster map of single land use in the basin; the number 1 indicates zones associated with this single land use, while 0 indicates zones with any other use.

Multiplication of the two maps results in a third map (matrix *c*) where zones of this single land use are classified by soil type, while the remaining zones have a value of 0. Matrix *c* is then reclassified (Matrix *d*) based on the values suggested by UNESCO (2006), generating a fourth map, matrix *e*. This last map consists of (1) pixels with values of *K* corresponding to the soil type under this single land use and (2) pixels corresponding to 'any other' land use. A raster map of the *K* parameter for the complete basin was obtained by adding similar maps for all the land uses.

Nr was evaluated using four procedures. We called the first procedure 'Pixel sum' and calculated *Ce* at the pixel scale using the QGIS raster calculator to implement equations (6) and (7). The raster operations were carried out by combining the *K* and precipitation maps described above. This combination generates a raster file of runoff coefficient (*Ce*) values distributed over the basin map. The multiplication of this map by the mean annual precipitation (*P*) map according to equation (5) generates a map of natural runoff, where pixel-value summation corresponds to the annual natural runoff (*Nr*) of the Culiacán River basin.

For comparison, other procedures were implemented as follows:

- Mean *K* and *P*: *Nr* were obtained from the pixel mean of the precipitation map and the pixel means of *K* and *P*.
- Mean *P* and *Ce*: this procedure used the pixel values of *P* and *K* to obtain *Ce* values at the pixel level. The mean *Ce* was then obtained and used to calculate *Nr* with equation (5), using the mean *P*.
- Thiessen *P* and mean *Ce*: the Thiessen method was used to interpolate *P* across the basin. This map was used to calculate *Nr*, using equation (5) with the mean *Ce*.

We also assessed the accuracy of the indirect runoff model. Since the principal affluent of the Culiacán River is gauged, an adjustment was carried out to adapt the *K* parameter criteria to the basin under study. *Nr* was calculated while varying *K* for the main soil types until the result approximated the *Nr* measured in the Humaya River basin based on gauged flows. The adjusted *K* values were then used to estimate the Culiacán River

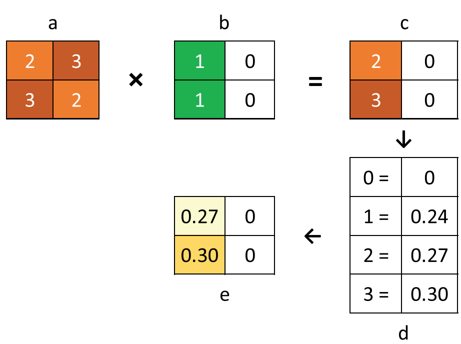

Figure 2. Procedure to assign *K* values combining type and soil use cover. Source: Elaborated by the authors.

basin runoff (*Nr*) using the pixel sum procedure. This procedure was chosen because it calculates *Nr* at a pixel level instead of using mean values over the map.

*Return (*Rt*)*

According to NOM-011, the annual volume of water returning to the drainage network (*Rt*) can be evaluated directly by flow measurement or as percentages of surface water withdrawal, which are proposed in the norm. Since there are no flow measurements, the second procedure was applied to estimate the surface water withdrawals for irrigation, representing 95% of the total consumptive use in the basin, and the respective percentages were applied to the rest of the water uses.

*Imported (*Im*) and exported (*Ex*) volumes*

From the San Lorenzo River basin, an agricultural canal conveys water towards the Culiacán River basin. However, the canal does not cross the basin boundary as shown in Figure 3. Here the San Lorenzo Canal conveys flow to the north-west and converges with the Oriental Main Canal before crossing the watershed divide. This canal carries flow to the south-west, so the flow from the Oriental Canal does not enter the basin and cannot be considered an import. Therefore, surface water imports (*Im*) are zero for the Culiacán River basin. In contrast, surface water is diverted from the Andrew Weiss reservoir in the

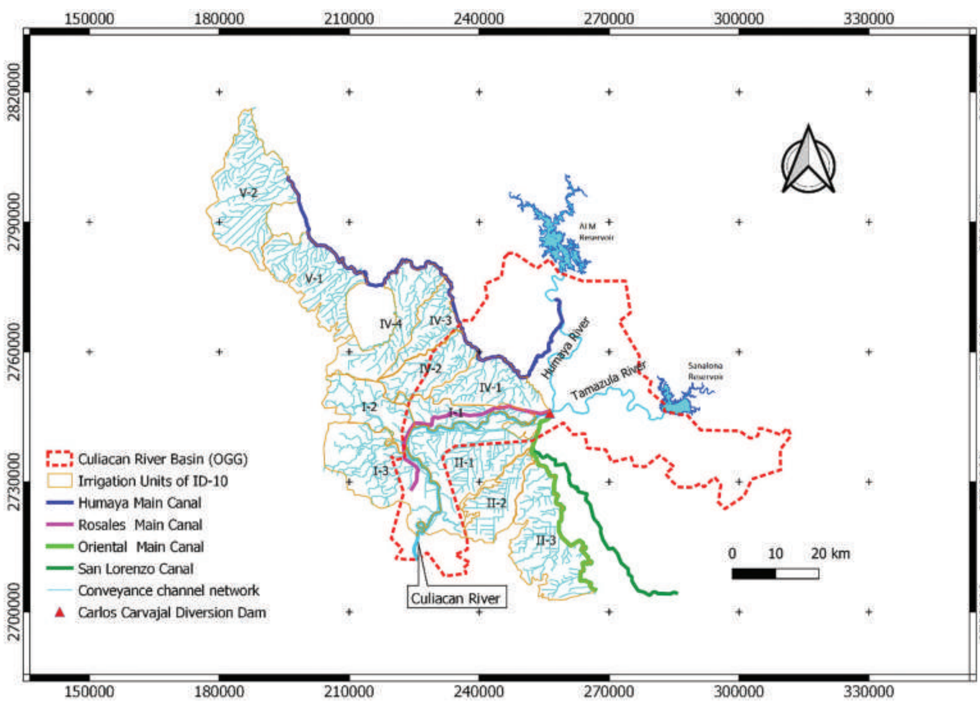

Figure 3. Surface-water conveyance network of irrigation units of Irrigation District 10 Culiacán-Humaya. Source: Elaborated by the authors.

Culiacán River basin and sent to the Mocorito River basin through the Humaya Main Canal. The outflow is measured in the reservoir and other subsequent diversion points along this canal, giving us the annual exported surface water volume (*Ex*).

Administrative withdrawals (Aw)

The annual volume of administrative surface water withdrawal (*Aw*) consists of surface water volumes in three categories: *Aw*(a) is the water allocations registered in the Public Registry of Water Rights (REPDA); *Aw*(b) is the approved applications in process of obtaining water allocations and water allocations in the process of being registered in the REPDA; and *Aw*(c) is water reserves, which includes environmental flow and regulated zones.

REPDA has an online database that includes information on irrigation districts and other users (*Aw*(a)). More than 147,000 nationwide surface water allocations are registered (CONAGUA, 2017). However, we found serious inconsistencies and applied a database refinement process. Field inspection work, web searches and expert consultation were needed to refine this information.

Agriculture is the main water use in the study basin, and the principal water user is Irrigation District 010 Culiacán-Humaya. The district is organized into 12 irrigation units, which are legal entities and receive water allocations. Some irrigation units are within the Culiacán River basin, but others are partially or totally outside it. Hence, not all surface water rights are exercised within the study basin. Each surface water allocation title indicates the volume corresponding to an irrigation unit, but no geographical distribution within its territory is specified. However, separating these volumes was necessary to apply equation (4). Assuming a uniform areal volume distribution as an approximation, the proportion of the irrigation unit area inside and outside the study basin was used to separate the allocated surface water volumes. Thus, volumes corresponding to irrigation unit area in the basin under study were considered as *Aw*(a), and the rest were exports (*Ex*).

The annual volumes of water allocations in the process of being registered in the REPDA and approved applications (*Aw*(b)) were obtained by individual requests from CONAGUA (personal communications; CONAGUA, 2020). This federal department also provided the annual volumes for reserves and regulated zones (*Aw*(c)). However, this last term includes the environmental volume, which was calculated according to the hydrological method described in the Mexican norm NMX-AA-159-SCFI-2012. This method assumes that the operation of hydraulic infrastructure does not alter the flow regime. After the unaltered flow condition was verified, the environmental objective was established based on the environmental importance of the basin and the degree of water stress (Salinas-Rodríguez et al., 2020). The environmental importance of a basin is assessed based on biotic aspects (fauna and flora species), environmental integrity (significance of ecosystems as potential water reserves) and eco-hydrological alteration (conservation of flow regime; Salinas-Rodríguez et al., 2018). Biotic aspects and particularity of ecosystems in the Culiacán River basin were found in Aguilar et al. (2010), while significance as a potential water reserve and eco-hydrological alteration was found in CONAGUA (2011). The water stress index was calculated as the volume of allocated surface water as a percentage of surface water availability. The monthly ecological flow (*Qenv*) was calculated for a mean hydrological year, separated into dry and rainy seasons. The percentage of surface water flow was then used to calculate the environmental flow based on the environmental objective and the season (King, 2016). The mean annual environmental volume was computed from the *Qenv* of each month.

Evaporated volume (Ev)

The mean annual evaporation from reservoirs (*Ev*) was calculated using the annual evaporation rates measured by the climatologic stations. Evaporation data were distributed over the basin map using the multilevel B-spline interpolation method in QGIS. This procedure assigned evaporation values to the sites where the main reservoirs are in the basin. The annual evaporation of each reservoir was calculated based on its surface. The total of these values was taken to be the mean annual evaporation. Since the ALM and Sanalona reservoirs are not in the Culiacán River basin, their evaporation volumes were not considered in the water balance of the Culiacán River basin.

Change of surface water storage in reservoirs (Δs)

This is zero because there are no storage reservoirs (only diversion dams) in the Culiacán River basin.

Uncertainty of the water balance terms

Given the random nature of the water balance terms, it is convenient to calculate their uncertainty. The official water balance method suggests using monthly and annual values with a minimum period of 25 years because the mean values (monthly or annual data) show less variation than point measurements (daily or hourly data). Equation (8) shows the uncertainty of the water balance model (Φ) in the Culiacán River basin, which is based on the standard error $(\Phi_t)_i$ and the standard error of fit $(\Phi_s)_i$ (Campos-Aranda, 2022; Kite, 1977):

$$\Phi = \sum_{i=1}^{n} (\Phi_{\mathrm{t}})_i + \sum_{i=1}^{n} (\Phi_{\mathrm{s}})_i \tag{8}$$

The standard error of the water balance $(\Phi_t)_i$ depends on the dispersion of each measurement (σ_i) and the sample size (n). According to equation (9), the larger the sample size, the smaller the standard error is:

$$\Phi_{\mathrm{t}} = \frac{\sigma_i}{\sqrt{n}} \tag{9}$$

In addition, Kite (1977) suggests the use of the standard error of fit $(\Phi_s)_i$ in the uncertainty analysis to improve the estimation of the water balance (equation 10). This error is related to the measurements since it includes the number of variables used to estimate each of the terms in the water balance. Therefore, the greater the number of variables (np) used, the greater the model uncertainty:

$$\Phi_s = \frac{\sigma_i}{\sqrt{n - np}} \tag{10}$$

Surface water availability

According to the NOM-011 method, annual surface water availability (Mm^3/y) can be simplified to:

$$Sa = Dn - Cxy \tag{11}$$

where *Sa* is the annual surface water availability, *Dn* is the annual downstream runoff, and *Cxy* is the annual 'committed volume' from catchment *x* to catchment *y*. The committed volume is intended to satisfy the downstream surface water requirements; it is the part of *Dn* necessary to fulfil downstream water allocations, prohibitions, water reserves, ecological flow, regulations and water-resource planning. In response to formal requests, CONAGUA (personal communications, 18 November 2020) officially stated that the volumes corresponding to these categories were zero, except for surface water allocations. The water allocations were published for the official surface water availability in the *Diario Oficial de la Federación* (CONAGUA, 2020, 2016b). Calculation of *Cxy* is based on these equations:

$$surface\ water\ offer\ (SWO) = Nr + Up + Rt + Im \tag{12}$$

$$surface\ dater\ demand\,(SWD) = Ex + Aw + Ev + \Delta s \tag{13}$$

$$annual\ committed\ volume\ from\ catchment\ x\ to\ catchment\ y\ (Cxy) = Dn(SWD/SWO) \tag{14}$$

SWO and SWD were evaluated for the Culiacán River basin, and their values were then used to calculate the *Cxy* of the upstream catchment (Humaya or Tamazula) based on its *Dn*. *Cxy* should consider allocation volumes (*Aw*), prohibitions, reserves, environmental use, regulations and water resources planning. However, only *Aw* is mentioned in the official results of all the terms in equations (12) and (13). All the terms were considered in this study to calculate *Cxy* thoroughly according to the NOM-011 method.

Results

Official results

CONAGUA has issued two comprehensive lists of surface water availability for Mexico's 757 official river basins (CONAGUA, 2020, 2016b). These data are presented in Table 1 for the Culiacán River basin and the Humaya and Tamazula river basins. These latter are needed because some of their values are used for the Culiacán River basin.

CONAGUA does not explain how the values of the terms were obtained, nor the mathematical relationships among them; we had to work that out. For instance, given the hydrographical configuration of the basin, the *Up* values for the Humaya and Tamazula basins are zero because they do not receive surface water from upstream.

Table 1. Surface water balances of the Humaya, Tamazula and Culiacán river basins published in 2016 and 2020.

	River basin	*Nr*	*Up*	*Aw*(a)	*Aw*(b)	*Aw*(c)	*Rt*	*Im*	*Ex*	*Ev*	*Δs*	*Dn*	*Cxy*	*Dn* – *Cxy*	*Sa*
2016	Humaya	1907.1	0.0	1889.3	0.0	0.0	1883.3	0.0	351.6	108.4	10.4	1430.7	1293.7	137.0	137.0
	Tamazula	755.4	0.0	530.1	0.0	0.0	526.5	0.0	0.0	40.3	9.4	702.1	634.8	67.2	67.2
	Culiacán	466.1	2132.7	2613.2	19.6	0.0	0.0	312.7	0.0	0.0	0.0	278.8	0.0	278.8	278.8
2020	Humaya	1869.4	0.0	1284.6	0.2	0.0	0.0	0.0	351.6	106.6	26.0	100.5	91.2	9.3	9.3
	Tamazula	758.5	0.0	530.4	0.0	0.0	0.0	0.0	0.0	40.6	6.0	181.6	164.8	16.8	16.8
	Culiacán	444.5	282.0	2111.4	5.2	0.0	1850.2	309.4	503.0	0.0	0.0	266.5	0.0	266.5	266.5

Notes: *Nr* is the mean annual natural runoff generated in the catchment; *Up* is the mean annual volume of runoff from upstream; *Aw*(a) is the annual surface water volume allocated that is registered in the Public Registry of Water Rights (REPDA); *Aw*(b) is the annual surface water volume allocated that is in the process of been registered in the REPDA; *Aw*(c) is the annual volume for water reserves, ecological flow and regulated zones; *Rt* is the annual volume that returns to the drainage network; *Im* is the annual volume imported from artificially connected basins; *Ex* is the annual volume exported to artificially connected basins; *Ev* is the mean annual volume evaporated from reservoirs; *Δs* is the mean annual change of surface water storage in reservoirs; *Dn* is the annual downstream volume of runoff; *Cxy* is the annual committed volume from catchment *x* to catchment *y*; and *Sa* is the annual surface water availability volume; the units of all terms are Mm^3/y.

Source: Adapted from CONAGUA (2016b, 2020).

The *Up* value for the Culiacán basin is the sum of the *Dn* values of the Humaya and Tamazula basins.

Significant differences are observed in some water balance terms in the Culiacán River basin between 2016 and 2020. In 2016, *Up* is an order of magnitude greater than in 2020. The explanation is that the *Dn*'s for the Humaya and Tamazula basins in 2016 are substantially higher than in 2020. *Rt* and *Ex* in 2016 are zero, while in 2020 they are four- and three-figure numbers, respectively. *Cxy* of the Humaya River basin in 2016 is two orders of magnitude higher than that of 2020. These observations imply that prohibitions, reserves, environmental use, regulations and water resources planning were not considered by CONAGUA in applying equations (12)–(14). The remaining terms are of similar magnitude, including annual surface water availability, even though it was calculated from terms with significantly different magnitudes. We now consider the detailed computation of each term.

Calculation of water balance by the NOM-011 method

*Upstream runoff (*Up*)*

As explained above, *Up* is the sum of the mean annual downstream volume (*Dn*) of the Humaya and Tamazula basins, evaluated using equation (4). These terms are calculated in equations (15) and (16). Their sum is 2356.8 Mm^3/y:

$$Dn_{\text{Humaya}} = 0 + 1,819.8 + 1,887.9 + 0 - 0 - 1,889.3 - 124.1 - 31.6 = 1,662.7\text{Mm}^3 \tag{15}$$

$$Dn_{\text{Tamazula}} = 0 + 750.7 + 529.5 + 0 - 0 - 530.1 - 42.6 - 13.4 = 694.1\text{Mm}^3 \tag{16}$$

The uncertainty of *Up* in the Culiacán River basin mainly comes from the natural runoffs (*Nr*) of the Humaya and Tamazula river basins. They are essentially equal to the outflows of ALM and Sanalona dams which are at the outlet of each basin, respectively. These outflows are registered in the dams' operation record, which is the variable used to calculate the uncertainty of *Up*. *Ev* and Δ*s* are also registered in this record, but their uncertainties are small. The uncertainty of *Aw* is zero because it is a constant volume established in allocations granted for hydropower generation. Since *Rt* is calculated as a percentage of *Aw*, its uncertainty is also zero as well as the rest of the variables whose values are zero in equations (15) and (16).

*Natural runoff (*Nr*)*

The annual natural surface runoff (*Nr*) of the Culiacán River basin was calculated by transferring flow-measurement information from homogeneous neighbouring basins (Table 2). The surface area ratios were calculated by dividing the area of the Culiacán River basin by the area of each of the basins indicated, and *Nr* was calculated by multiplying the inflow to each reservoir by the area ratio. The value we obtain, 470.1 Mm^3/y, is only 1% and 5% different from the values published by CONAGUA in 2016 and 2020, respectively. This close match suggests that CONAGUA used the same method to calculate *Nr* for the Culiacán River basin. However, the validity of this method is questionable.

Table 2. Terms used to calculate the mean annual natural runoff (*Nr*) in the Culiacán River basin by the method of flow-measurement information transfer from homogeneous neighbouring basins.

Reservoir/basin	Inflow to dams (Mm^3/y)	Surface ratio (transfer factor)	*Nr* for Culiacán River basin (Mm^3/y)
Sanalona/Tamazula River	750.7	0.789	592.5
Adolfo López Mateos (ALM) reservoir/ Humaya River	1819.8	0.238	433.2
Sanalona and ALM/Humaya and Tamazula	2570.5	0.183	470.1

Source: Elaborated by the authors with data from CONAGUA (personal communications, 2020).

This method assumes that both basins are hydrologically homogeneous. NOM-011 requires this condition but does not define hydrological homogeneity. It mainly depends on the basin's surface area, local precipitation and length of the principal channel (Wazneh et al., 2015). Thus, the basin should have a common drainage network (i.e. a drainage unit). But this is not true of the Culiacán River basin delineated by CONAGUA because a separate channel network drains part of its surface. This official delineation of the Culiacán River basin includes the Pericos River, which flows to the Gulf of California, independently from the Culiacán River (Figure 1). Besides, according to Campos-Aranda (2009), a basic requirement for homogeneity is a minimum surface area ratio of 0.4, which is not true for Sanalona, ALM/Humaya or Tamazula (Table 2). Hence, the method of flow information transfer from homogeneous neighbouring basins should not be used to estimate the surface runoff of the Culiacán River basin.

We adapted the method given by the US Bureau of Reclamation (Soil Conservation Service, 1972). Figure 4(a–c) maps mean annual precipitation, *K*, and the runoff coefficient, respectively. These maps were used to generate a map of annual natural runoff (*Nr*) (Figure 4d), which we can then use to calculate the mean annual natural runoff in the basin by the pixel sum procedure (Table 3). These maps were also used to calculate the mean values of *P, K* and *Ce*. These values were used to calculate the basin's mean annual natural runoff (*Nr*). Our results differ significantly from the official results (Table 3). All our values are smaller than those reported by CONAGUA, with the percentage difference ranging from 36.1% to 38.9%.

The pixel sum procedure was then applied to the Humaya River basin because this basin is gauged, and hydrometric information can be used to validate the results. We find an *Nr* of 1088.3 Mm^3/y for this basin, only 58% of the measured value of 1819.7 Mm^3/y. We can adjust *K* to get a closer fit. With adjusted *K* values, we obtain an *Nr* of 1768.0 Mm^3/y, close to the value obtained by hydrometry – close enough to be acceptable according to Molina et al. (2020). The adjusted values of *K* were 0.17, 0.24 and 0.07 for soil type 1 and forest, irrigated agriculture, and wood soil use, respectively; and 0.3 for soil types 2 and 3 and all soil uses in the basin. This adjustment was carried out by selecting the larger surfaces of the Humaya River basin classified by type of soil and soil use and progressively increasing their *K* values until the *Nr* obtained was close to the measured values.

We then infer that these adjusted K values should be applied to the Culiacán River basin for the most accurate estimate. Using these values gives us an adjusted *Nr* of 322.9 Mm^3/y. But this is 30.7% lower than the official result. Thus, CONAGUA's estimate of *Nr* for the Culiacán River basin is much too high, which means that the official estimate of surface water availability is also much too high.

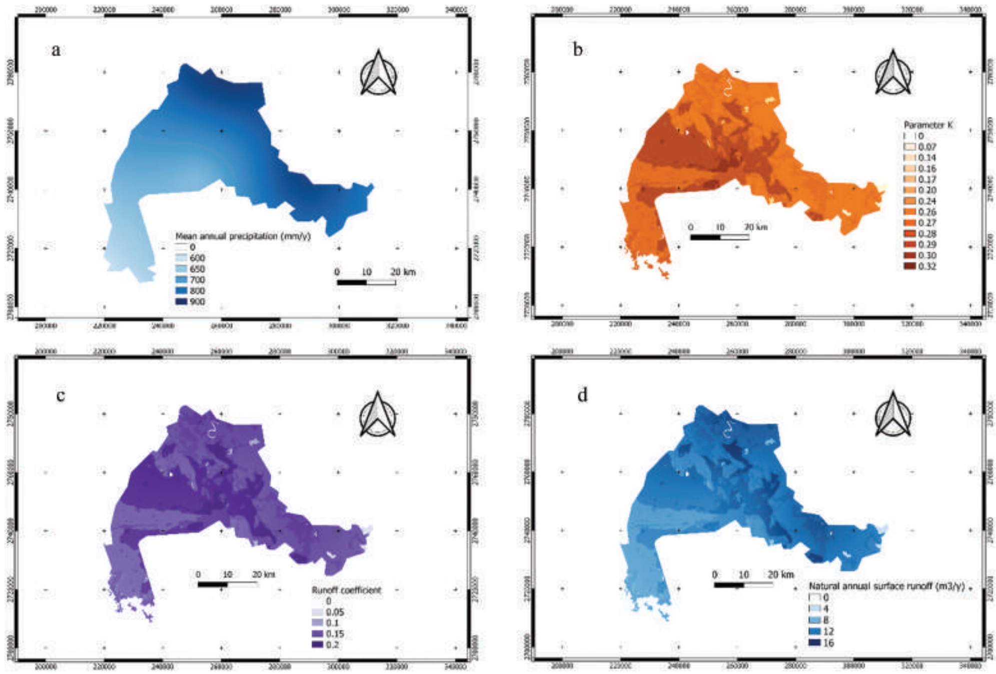

Figure 4. *Nr* calculation in the Culiacán River basin using geographical information system (GIS) capabilities: (a) mean annual precipitation (mm); (b) *K* parameter (dimensionless); (c) runoff coefficient (dimensionless); and (d) natural runoff (m^3/y). Source: Elaborated by the authors.

Table 3. Comparison between the magnitudes of mean annual natural runoff (*Nr*) of the Culiacán River basin calculated by different procedures and the official result.

Procedure	*Nr* (Mm^3/y)	Difference from the official results
Pixel sum	293.9	−36.9%
Mean *K* and *P*	284.8	−38.9%
Mean *P* and *Ce*	291.9	−37.4%
Thiessen *P* and mean *Ce*	298.0	−36.1%
Official result	466.1	0

Source: Elaborated by the authors.

The official delineation of the Culiacán River basin has two main issues that must be considered for proper hydrological analysis. First, it is not a drainage unit because it groups the Culiacán River and Pericos River catchments and several small coastal catchments. This means that not all the runoff generated in the official basin territory is conveyed to the Culiacán River, so surface water availability could be better analysed on a geographical scale that considers this hydrological configuration using separate surface water balances. Second, the most important hydraulic infrastructure of the Culiacán River basin consists of a dense network of irrigation channels, which modifies the natural drainage network. This difference in physical water distribution means that further analysis must be used for surface water runoff and the rest of the surface water balance terms. The uncertainty of *Nr* is calculated based on four variables: basin area, precipitation, soil type and soil use. Precipitation provides a random nature to *Nr* since the other variables are not random.

*Imported volume (*Im*)*

As explained in the preceding section, this is zero for the Culiacán River basin and its uncertainty.

*Administrative withdrawals (*Aw*), return volume (*Rt*) and exported volume (*Ex*)*

The allocations (*Aw*(a)) registered in the REPDA for Irrigation District 010, and the export volume (*Ex*), are presented in Figure 5. According to the officially published balances, all the allocations registered in the REPDA for Irrigation District 010 were considered in the term *Aw*. But this cannot be correct because most of the allocated volume is assigned to irrigation units outside the basin under study (Figure 5). That should be considered exported volume (*Ex*). Since both terms in equation (3) represent water leaving the basin, the effect on the water balance is insignificant, but the scheme proposed here is more appropriate.

Figure 6 shows the total *Aw*(a), the approved applications in the process of obtaining water allocations, the water allocations in the process of being registered in the REPDA (*Aw*(b)), and the annual volume returning to the drainage network (*Rt*), according to their use in the Culiacán River basin. *Aw*(b) is included in several uses other than agriculture (ID-10).

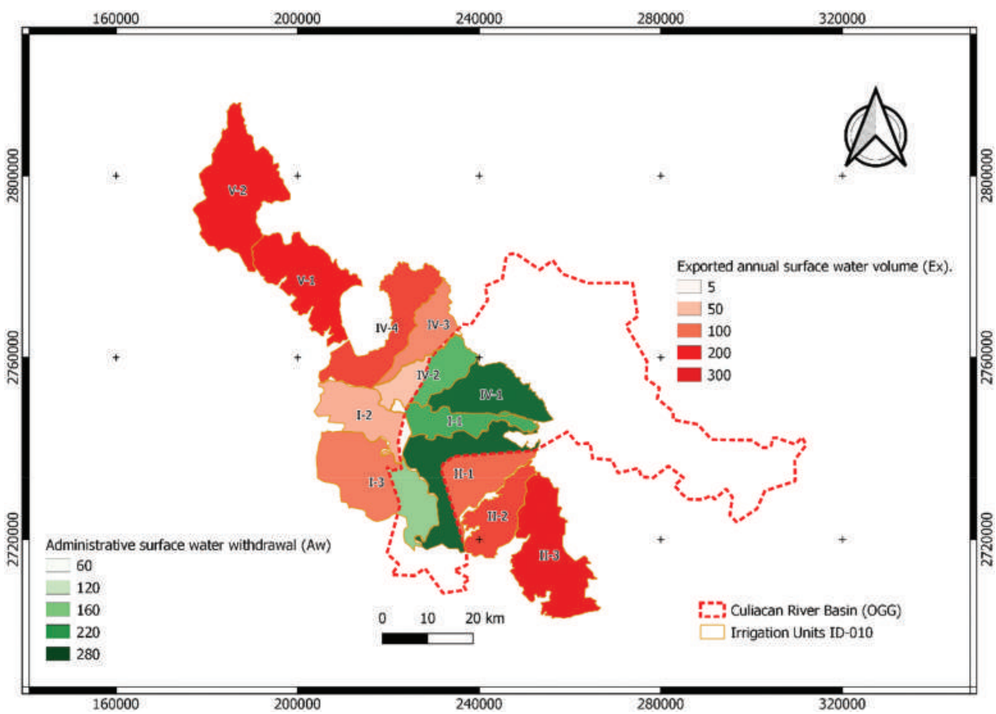

Figure 5. Administrative water withdrawal (*Aw*) and exported water volume (*Ex*) of Irrigation District 10 in the Culiacán River basin. Source: Elaborated by the authors.

The precise evaluation of *Rt* from agriculture is complex since the Culiacán River basin is a highly developed agricultural zone. This return volume is reintegrated into the distribution network as pumped flows from drainage channels or as gravity-moved surface, subsurface and underground flows from crop fields. These flows are neither pumped nor measured regularly. Pumped volume depends on water scarcity, equipment availability and economic resources. The second-most important type of return volume in the Culiacán River basin is the urban returned volume, partially measured in the wastewater treatment plants, but water leaks are only estimated as a percentage of water supply. The rest of the uses represent a minor part of total *Aw* in the study basin, but they are not systematically measured. Thus, the precise calculation of returns is beyond the scope of this study, and the criterion suggested in NOM-011 was used.

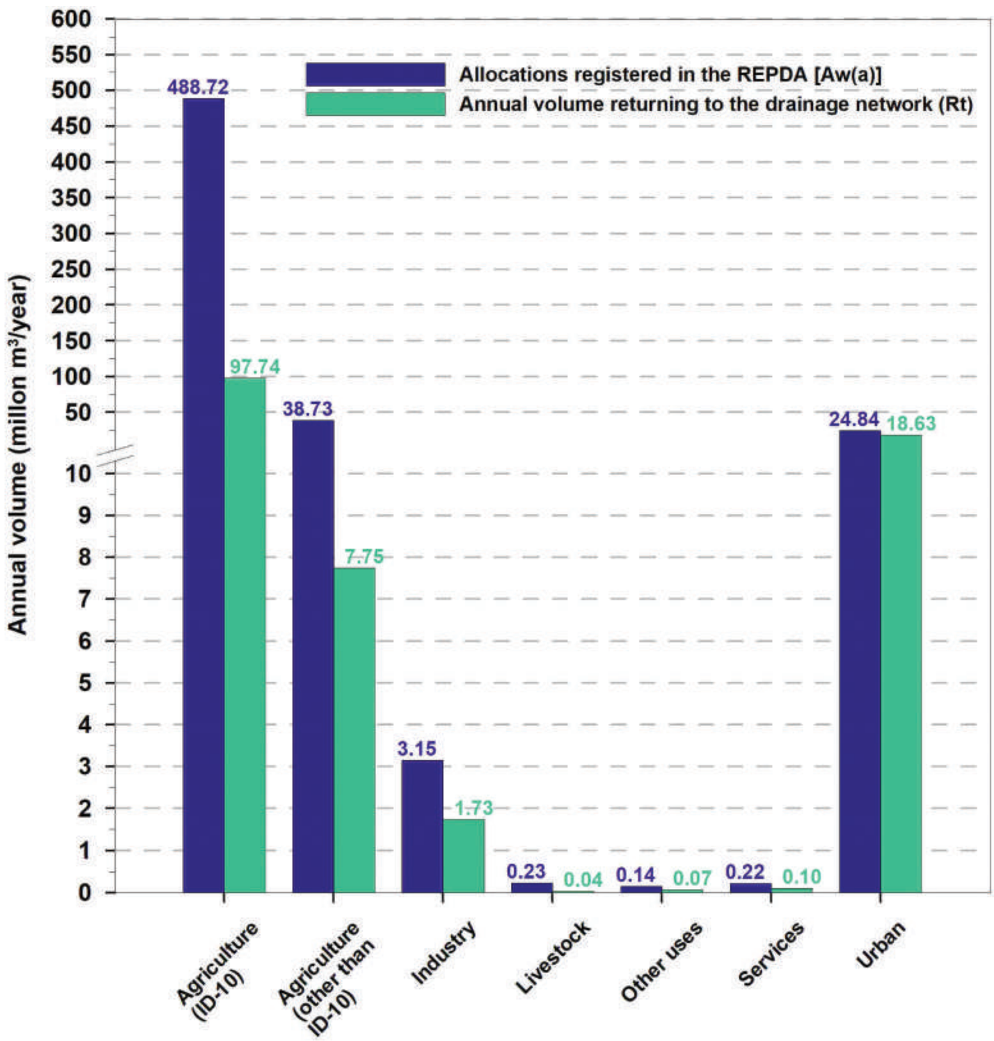

Figure 6. Annual surface water volume allocated that is registered in the Public Registry of Water Rights (REPDA) (*Aw*(a)) and annual volume that returns to the drainage network (*Rt*). Source: Elaborated by the authors.

Aw(c) includes the annual volumes for reserves, regulated zones and annual environmental flow. According to the registry of prohibitions, reserves and regulated zones, the volumes for reserves and regulated zones are zero (CONAGUA, 2015b). But the annual environmental flow must be determined and incorporated into the water balance. For this determination, an unaltered flow condition is required. We used frequency analysis to estimate the flow regime alteration. The monthly flows' flow ranges were defined by the 10th and 90th percentiles at the Puente SudPacífico hydrometric station. The frequencies of the monthly outflows from Carlos Carvajal Diversion Dam were then calculated to determine the current flow regime. Since the unaltered monthly condition was seen for seven months, the stream up to the dam can be considered an unaltered seasonal flow.

We assessed the water stress and environmental importance of the Culiacán River basin according to the methodology proposed by King and Louw (1998). The official results published in 2020 give the water stress of the basin as very high, based on this equation:

$$water\ stress = [Aw(a) + Aw(b)]\ /Sa = (2111.4 + 5.2)\ /\ 266.5 = 794\% \quad (17)$$

According to the NOM-011 method, a value smaller than 10% indicates low pressure, while a value higher than 80% points out a very high pressure. Therefore, the value of 794% is an out-range high-pressure condition. This situation suggests that the Culiacán River basin mainly depends on external runoff to satisfy its surface water demands.

According to Aguilar et al. (2010), the environmental importance of the Culiacán River basin is low. These criteria define the environmental objective of the basin, which in turn establishes the applicable percentages of mean annual flow and monthly flow. The monthly environmental flows for the Culiacán River were 11.5 m^3/s for January–June and October–November. For July, August, September and December, environmental flows were 32.6, 55.3, 60.2 and 25.9 m^3/s, respectively. Adding the corresponding monthly volumes, the annual environmental volume is 702.3 Mm^3/y. The uncertainties of *Aw*(a) and *Aw*(b) are zero because they are constant volumes established in allocations granted to water users. Their uncertainties are also zero since *Rt* and *Ex* are calculated based on *Aw* (a). On the other hand, *Aw*(c) has a non-zero uncertainty since its estimation is based on the outflow records of the Carlos Carvajal Diversion Dam which is the only calculation variable.

*Evaporated volume (*Ev*)*

The mean annual evaporation from each of the main reservoirs in the Culiacán River basin and the total are presented in Table 4. The uncertainty of *Ev* is small and was calculated based on evaporation records and reservoir areas.

Change of surface water storage (Δs) in reservoirs

As explained above, the value of this term is zero in the basin under study and its uncertainty.

Surface water availability in the Culiacán River basin

According to the NOM-011 method, the terms of equation (11) should be evaluated to calculate the annual surface water availability (*Sa*) for the Culiacán River basin. Combining

Table 4. Mean annual volume of evaporation from reservoirs in the Culiacán River basin.

Reservoir	Surface area (km^2)	Mean annual level lost (mm)	Mean annual evaporation (Mm^3)
'Juan Guerrero Alcocer' Diversion Dam	1.822	1924.2	3.506
'Andrew Weiss' Diversion Dam	0.626	2148.8	1.345
Diversion Dam 'Carlos Carvajal'	0.190	2019.4	0.384
Dike 2 'Humaya'	0.106	2141.5	0.227
Lake 'Humaya'	0.066	2114.4	0.140
Dike 3 'Humaya'	0.036	2141.3	0.077
Dike 1 'Humaya'	0.034	2142.8	0.073
Total	2.88		5.751

Source: Elaborated by the authors.

the findings for the variables considered up to this point, equation (4) can be used to calculate the downstream runoff annual volume (*Dn*). The annual committed volume from catchment *x* to catchment *y* (*Cxy*) can then be calculated. *Cxy* is intended to satisfy downstream requirements, which are non-existent according to officially published results and consultation with CONAGUA (personal communication, 2022). We have confirmed that there are no prohibitions, reserves, environmental-use requirements or regulations regarding uses downstream of the Culiacán River basin. However, the water volumes established by the National Water Resources Programme 2019–2024 (PNH) must be provided. The PNH specifies the following annual surface water volumes for water resources planning (SEMARNAT, 2020). The requirement for 'additional [water] for environmental use' (685.1 Mm^3/y) is estimated following NMX-AA-159-SCFI-2012, but no further explanation is given in that publication, and none was provided in the responses to information requests by the authors. The PNH also states that the requirement 'for the human right to water' (5.8 Mm^3/y) must be considered in water balances after 2012. Volumes for 'strategic projects' (0 Mm^3/y) and 'received applications' (26.8 Mm^3/y) are listed with no explanation. The total of these requirements is 717.7 Mm^3/y.

According to NOM-011, these concepts are considered in the water balance through the *Cxy* variable. But although the Mexican water authority (CONAGUA) thus establishes the requirement of including volumes for water resources planning in the surface water balance, such volumes are ignored in the official results published by the same authority. Arranging the previously described values and using equations (4) and (11), the detailed water balance parameters of the Culiacán River basin and their uncertainties are shown in Table 5. The uncertainty of *Sa* is the absolute value summation of the uncertainties of all other terms in the balance (Kite, 1977).

Discussion

In Latin America, federal governments have made efforts to manage water use. UNESCO (2006) published a comprehensive manual calculating surface water and underground water availability in Latin America and Caribbean countries. This manual is based on the Mexican norm NOM-011. Therefore, the methods established by CONAGUA to estimate water availability underlie the guidance for Latin America.

Although there are numerous publications on water balance in Latin American countries (De Anda et al., 1998; Del Toro-Guerrero et al., 2014; Martínez-Austria &

Table 5. Surface water balance of the Culiacán River basin and its uncertainty (all terms in Mm^3/y).

Water balance term		*Nr*	*Up*	*Aw* (a)	*Aw* (b)	*Aw* (c)	*Rt*	*Im*	*Ex*	*Ev*	*Δv*	*Dn*	*Cxy*	*Dn – Cxy*	*Sa*
Water balance value		322.9	2356.6	556	19.6	702.3	126.1	0	1428.65.80			93.3717.7–624.3			–624.3
Uncertainty analysis	*σ*	62.9	812.2	0	0	47.6	0	0	0	0.3	0	–	–	–	–
	p	4.0	1	–	–	1	–	–	–	2	–	–	–	–	–
	Φt	8.3	112.6	0	0	13.7	0	0	0	0.0	0	134.7	0	134.7	134.7
	Φs	8.6	113.7	0	0	2.5	0	0	0	0.0	0	124.9	0	124.9	124.9
	Φ	17.0	226.4	0	0	16.3	0	0	0	0.1	0	259.7	0	259.7	259.7

Source: Elaborated by the authors.

Patiño-Gómez, 2012), scholarly work on water availability as an administrative and legal instrument for water use regulation is scarce. Silva-Hidalgo et al. (2013) proposed a method to calculate surface water deficit independently from surface water availability. Sánchez-Ortiz (2013) suggested a relative surface water availability index, while Suárez-Medina et al. (2015) described an automatic procedure to calculate surface water availability using ArcHydro. Salinas-Rodríguez et al. (2020) estimated environmental flows by a hydrological method based on surface water availability data published by CONAGUA. However, none of these publications has questioned the NOM-011 method. Instead, the results published by CONAGUA are assumed to be valid and have been used as inputs in many investigations.

In Mexico, the official method has been widely applied; however, the accuracy of the official values is a pending issue that should be integrated as a standard part of the published results. This would give a better perspective on making decisions aimed at sustainable water use. Hence, the Mexican official methodology should describe the criteria for estimating the uncertainty of the surface water balance. As described in this study, it is the summation of the uncertainties of terms with different realms. The administrative terms such as *Aw*(a), *Aw*(b) and those calculated based on them as *R, Ex* and *Im* would have no uncertainty since they are constant volumes. Controlled surface water volumes such as Δ*s* and dam outflows are expected to have a low level of uncertainty (Voelker & Orton, 1993). This is because they are driven by water requirements that commonly are as constant as possible from one year to another. Uncertainty is expected in natural runoff (*Nr*), upstream flow (*Up*), ecological volumes (*Aw*(c)) and evaporation from reservoirs (*Ev*) because they come from aleatory data. The total uncertainty of the water balance is then the combination of the uncertainty of these terms and equal to the uncertainty of *Sa* in equation (11).

This paper has made a systematic analysis of the NOM-011 method. The value of each water balance term was evaluated rigorously following the criteria given in norm NOM-011. We obtained values differing significantly from those given in the official publications (Table 1). The value of *Up* in the water balance published in 2016 and that calculated in this study are an order of magnitude larger than the value of this term in the water balance published in 2020. The 2020 value is wrong because the return volume (*Rt*) was considered as part of the water budget of the Culiacán River basin instead of the Humaya and Tamazula basins. The magnitude of this term corresponds to the annual volumes of water used for hydropower generation in the ALM and Sanalona reservoirs. Thus, we see a lack of consistency in applying the concepts provided in the NOM-011. Besides, we calculated the uncertainty of the surface water balance although it is not a requirement of this norm.

Another major difference is in the annual volume of allocated surface water registered in the REPDA (*Aw*(a)). The published term is an order of magnitude greater than the one we calculate in this study. The explanation here is that in the volume allocated to Irrigation District 010, CONAGUA does not separate the water for cultivated areas outside the Culiacán River basin from water for areas inside the basin. In this study, we separated them and assigned them to the terms *Ex* and *Aw*(a), respectively. Besides, in the official water balances, some amount of water is imported from artificially connected basins (*Im*). We set the term to zero in our balance because the flow diverted from the San Lorenzo River basin towards the Culiacán River basin does not enter the Culiacán River basin, as explained in the section 'Imported (Im) and Exported (Ex) volumes'.

In this study, the main outcome of the water balance – annual surface water availability – is negative, in contrast to the official results. According to equation (1), negative water balances could occur in some years if subsurface water is transferred into groundwater. This means that negative values can be calculated for *Dn* (equation 4) and consequently for *Sa* (equation 11, where *Cxy* can be positive or zero). However, the results suggest that in the water balances of 2016 and 2020, this situation might not occur. This is because these balances use average annual volumes up to 2016 and 2020 for all the terms, except *Aw* and *Rt* which are cumulative over time. *Rt* is calculated as a fraction of *Aw*, an administrative (not physical) water outflow. Therefore, this last term could exceed the physical surface water offer which might explain the negative value obtained for *Sa*. In addition, the surface water balance (equations 3 and 4) already considers the transfer of subsurface water into groundwater through infiltration. Hence, the negative values of *Sa* could not be explained by an interaction with groundwater. However, negative water balance values (even larger ones) have been officially reported for numerous river basins in Mexico (CONAGUA, 2020). For instance, the water balance for the Bajo Atoyac basin is –738.810 Mm^3/y, and for the Medio Balsas is –2,427.829 Mm^3/y.

In the Culiacán River basin, the negative value obtained in this study can be explained by our inclusion in the water balance of non-zero magnitudes for two terms that are taken to be zero in the official calculations. These terms are *Aw*(c) and *Cxy*, both related to environmental flow and thus could be duplicative. But both terms were used in this study, specifically to follow the NOM-011 requirements. In the official balances, these terms' values are zero but should not be. According to the NOM-011 method, they should be calculated and included in the water balance like in this study case. However, non-consumptive uses, such as the environmental volume or volumes for hydropower generation, should be excluded from the water balance because they are not real outflows in the continuity equation. In addition, there is no reference in the PNH or the official water availability publications to the possible double counting of this concept in the water balance of the basin under study. The water requirement 'additional [water] for environmental use' evokes the idea that this annual volume complements other unspecified water volumes. But even though this last volume was not considered, a surface water availability near zero is recognized.

Conclusions

This paper retrieved and processed hydrological, hydrometric and allocation information on the Culiacán River basin. Field inspection work, web searches, expert consultation and a geographical information system (GIS) were used to refine this information. An innovative technique was used to estimate the natural annual surface runoff in the Culiacán River basin, with adjustments based on gauged flow. GIS raster calculations were used to carry out mathematical operations among precipitation, the parameter *K* and runoff coefficient values assigned to the pixels in raster maps. The uncertainty of the surface water balance was assessed based on the random terms of the water balance model. The method given in NOM-011 was thoroughly applied to the study basin, producing results that differ from those published by CONAGUA. This careful implementation of the official method produces a negative surface water availability in the Culiacán River basin, which is physically unfeasible but indicates that the official results significantly overestimate the surface water availability.

Further analysis is necessary to determine the actual surface water availability in the Culiacán River basin. This study has identified inconsistencies in the procedures behind the officially published data, including the use of unrevised basin delineation, lack of database refinement, absence of environmental flow estimation, omission of water resource planning requirements, and improper assessment of imports, exports and returns. The result is that allocations can be granted for the distribution of volumes of non-existent water to users legally. As pressure on water resources increases and users compete for water rights, social conflicts can arise, such as those that occurred in the Fuerte River basin (Castillo-Castillo et al., 2018), the Yaqui River basin (Moreno, 2015) and other regions of Mexico (Dobler-Morales & Bocco, 2021). The omission of environmental flow from the calculations also pushes water resources development towards an unsustainable use of surface water.

Our results show that surface water availability must be correctly assessed. The water balance method must be conceptually sound, and its application must be carefully performed and monitored. The combination of terms from different realms (actual water withdrawal versus administrative allocation) results in a procedure with no solid interpretation in the physical or administrative context. Allocations may or may not correspond to physical withdrawals. The inclusion of mean annual environmental volume in the water balance equation is inappropriate because this term represents non-consumptive use. Likewise, the accuracy of the water balance should be included as a regular part of the official methodology and published results. This would support better decision-making aimed at water-resources planning and administration.

Despite the technical problems we have reviewed here, the method of NOM-011 is mandatory in Mexico and suggested by UNESCO in other countries in Latin America. Since this method represents the principal criterion under which surface water allocations are granted, the water authority could grant new surface water allocations in a territory where there is no water availability according to the same authority's guidelines. Thus, the federal government is led to grant legal authority to the unsustainable over-exploitation of surface water.

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Author contributions

S. A. Rentería-Guevara: conceptualization, methodology, investigation, writing – original draft preparation, writing – reviewing and editing. J. G. Rangel-Peraza: conceptualization, writing – original draft preparation, writing – reviewing and editing, project administration. A. J. Sanhouse-García: writing – original draft preparation, software, formal analysis, visualization, resources, supervision. F. García-Páez: conceptualization, investigation, validation, supervision. Y. A. Bustos-Terrones: resources, data curation, supervision, writing – reviewing and editing. C. Franco-Ochoa: software, visualization, validation, writing – reviewing and editing.

Data and materials availability

All data presented in this study are available from the corresponding author upon request.

Disclosure statement

No potential conflict of interest was reported by the authors.

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