Hydrological Modelling of Naturalized and Regulated Flows in the Lerma–Santiago Basin

Technical Summary for the Environmental Flow Dashboard

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1. Purpose and scope

This note summarizes the hydrological modelling that underpins the environmental flow (e-flow) dashboard for the Lerma–Santiago Basin. It describes the water balance and river routing framework, the treatment and analysis of the hydrometric data used to constrain the simulations, the way the two discharge products (naturalized and regulated) are used in the e-flow assessment, and the watercourses of the basin that are currently subject to legal restrictions on surface water use. A companion note describes the climate forcing used for the future scenarios displayed on the dashboard. The document is intended as a concise methodological reference for dashboard users; full technical detail is provided in the underlying project reports and manuscripts.

2. Overview of the modelling chain

Discharge across the basin (approximately 132,000 km²) is simulated with a three-component chain. First, the VegET v2.0 agro-hydrologic model (Senay et al., 2023) computes the daily, gridded land-surface water balance, producing actual evapotranspiration, soil moisture, surface runoff and deep drainage at approximately 250 m resolution for 1992–2024. Second, the gridded runoff is routed through the river network with mizuRoute (Mizukami et al., 2016) to obtain naturalized discharge, that is, the flow regime that would occur in the absence of reservoirs. Third, the same runoff is routed with mizuRoute-Lake, in which the major reservoirs and lakes of the basin are represented explicitly, to obtain a regulated discharge product. The regulated product is then bias corrected against gauge observations (Section 4.3). The naturalized product provides the hydrological reference from which environmental flow targets are derived, while the corrected regulated product and gauge observations are used to assess compliance with those targets.

3. Water balance model and calibration

VegET is a one-dimensional root-zone water balance model driven by daily precipitation, grass-reference evapotranspiration (ETo) and a Normalized Difference Vegetation Index (NDVI) climatology that represents land surface phenology. Effective precipitation is obtained after subtracting canopy interception, evapotranspiration is computed from an NDVI-based landscape coefficient limited by a soil moisture stress function, and soil water in excess of the water holding capacity generates runoff, which is partitioned into surface runoff and deep drainage. Soil water properties (wilting point, field capacity and saturation over 0–100 cm) were derived from SoilGrids 2.0 (Poggio et al., 2021) through the Saxton and Rawls (2006) pedotransfer functions, with dedicated treatment of the high-retention Andosols of the Trans-Mexican Volcanic Belt. Canopy interception fractions were assigned by land cover class using the MODIS MCD12Q1 classification and literature-based class values.

Because no single gridded climate product is reliable over the orographically complex Trans-Mexican Volcanic Belt, four daily precipitation products (CHIRPS v2.0, CHIRPS v3.0, MSWEP v2.8 and ERA5) were each bias corrected against the quality-controlled national rain-gauge network (Section 4.1) and used to force the full VegET–mizuRoute chain, and two reference evapotranspiration products (the NOAA/USGS global reference ET and GLEAM v4 potential evaporation) were evaluated in the same way. CHIRPS v2.0 and the NOAA reference ET were retained for the final configuration: CHIRPS v2.0 showed the best agreement with gauged rainfall after correction and the most consistent routed discharge, and the NOAA product is a grass-reference ET consistent with the crop-coefficient formulation of VegET.

Model parameters were calibrated against independent, literature-based basin water balance benchmarks rather than against observed discharge, because observed flows in this heavily managed basin are 30–60% below natural runoff generation owing to irrigation diversions, groundwater abstraction of roughly 1,000 $Mm^3\ yr^{-1}$ of overdraft and reservoir retention (Wester et al., 2009). The benchmarks were naturalized total runoff of 90–130 mm yr^{-1} (runoff coefficient 0.12–0.16), deep drainage of 45–72 mm yr^{-1} consistent with isotope-based and administrative recharge estimates, and actual evapotranspiration bounded by energy-balance remote sensing products (SSEBop, WaPOR, GLEAM) and by Budyko-type closure. The main input datasets are listed in Table 1.

Table 1. *Principal datasets used in the hydrological modelling*

Dataset	Variable / use	Resolution	Period	Source
CHIRPS v2.0 (bias corrected)	Daily precipitation forcing	0.05°	1992–2024	Funk et al. (2015); SMN gauges
NOAA/USGS reference ET	Daily grass-reference ETo (FAO-56)	0.125°	1992–2024	Hobbins et al. (2023)
MODIS NDVI climatology	Land surface phenology (Kcp)	250 m–1 km	2003–2017	Didan (2015)
SoilGrids 2.0 + pedotransfer functions	Soil water properties (WP, FC, SAT)	250 m	Static	Poggio et al. (2021); Saxton & Rawls (2006)
MODIS MCD12Q1	Land cover for interception fractions	500 m	2020	Friedl & Sulla-Menashe (2019)
MERIT Hydro river network	Routing topology and reach geometry	≈90 m derived	Static	Yamazaki et al. (2019)
HydroLAKES / GRanD	Lake and reservoir geometry and storage	Vector	Static	Messager et al. (2016); Lehner et al. (2011)
CONAGUA BANDAS	Observed daily/monthly discharge	Station	1992–2024	CONAGUA (SINA/BANDAS)
SMN climatological network	Observed daily rainfall (bias correction)	Station	1994–2024	SMN/CONAGUA (CLICOM)

4. Treatment and analysis of hydrometric data

4.1 Rain-gauge data

Daily rainfall records from the Servicio Meteorológico Nacional (SMN) climatological network were screened for record length, completeness and internal consistency over 1994–2024; 315 stations passed the quality control and were retained. These stations were used to bias correct each candidate precipitation product with monthly, station-anchored correction factors interpolated across the basin, so that the gridded forcing reproduces the observed basin-mean precipitation of approximately 750–770 mm yr^{-1} and its strong monsoon seasonality (more than 80% of annual rainfall in June–September).

4.2 Discharge data

Observed discharge was obtained from the CONAGUA national surface water data bank (BANDAS), which underlies the hydrometric layers of the National Water Information System (SINA). Stations were subjected to a multi-step quality control: removal of physically implausible values and flatlined segments, verification of drainage-area consistency between the station metadata and the routing network, matching of each station to a model reach, and screening for minimum record length and completeness within the 1992–2024 simulation window. Seventy-six stations passed all criteria and were retained as anchor gauges for the bias correction; stations dominated by diversion canals or located immediately downstream of intake structures were excluded. It must be emphasized that the retained observations describe the regulated, post-abstraction flow regime, not natural runoff.

4.3 Bias correction of simulated discharge

Monthly multiplicative correction factors were estimated at each anchor gauge by comparing the simulated regulated discharge with the observations, and transferred to ungauged reaches along the flow path, with a regionalized correction (inverse-distance and random-forest estimators were compared) covering the remainder of the network. Corrections were limited to plausible ranges and capped so that corrected regulated flow does not exceed the simulated naturalized flow. At the anchor gauges the corrected regulated product achieves a median Kling–Gupta efficiency (KGE) of 0.57, a median Nash–Sutcliffe efficiency of 0.48 and a median absolute percent bias of 8.6%, with 74 of 76 gauges attaining positive KGE, compared with a median KGE of −0.62 before correction. Leave-one-gauge-out cross-validation of the regionalized correction yields a median KGE of −0.14, so skill at ungauged reaches is markedly weaker than at gauged reaches, and both figures are reported on the dashboard documentation for transparency.

The bias correction is applied to the regulated product only. The naturalized simulation is deliberately left uncorrected: because the gauge observations are themselves regulated, a statistical correction of the naturalized product against them would transfer reservoir releases, return flows and peak attenuation into the reference regime and bias the resulting environmental flow targets precisely in the reaches where regulation is strongest. The credibility of the naturalized product rests instead on the station-based precipitation bias correction and on the benchmark-constrained calibration of the water balance (Section 3).

5. River routing, regulation and use in the e-flow assessment

Naturalized discharge was routed with the kinematic wave tracking scheme of mizuRoute on the MERIT-derived river network, with channelization applied above a 25 km² drainage-area threshold; routing parameters (Manning coefficient 0.07, channel width scale factor 0.002) were adopted from a prior continental sensitivity analysis and verified at basin scale. In the regulated configuration, 58 water bodies were represented, including Lake Chapala and the major hydropower and irrigation reservoirs of the system (Aguamilpa, El Cajón, La Yesca and Santa Rosa on the Santiago; Solís and Tepuxtepec on the Lerma); 55 were simulated with a storage-dependent, non-linear release parameterization (Döll et al., 2003) and three endorheic lakes were treated as terminal sinks, with the lake water balance closed using the bias-corrected precipitation and simulated open-water evaporation. The impulse-response-function routing scheme was used for this configuration for numerical stability at lake-reach junctions. Groundwater abstraction, inter-basin transfers (notably the Cutzamala and Lerma conveyances to the Mexico City metropolitan area) and irrigation diversions are not represented explicitly; their aggregate effect on river discharge is captured statistically through the bias correction of the regulated product.

In the environmental flow assessment, ecological flow targets are derived from the monthly naturalized discharge following the frequency-of-occurrence approach of the Mexican environmental flow norm (NMX-AA-159-SCFI-2012; Secretaría de Economía, 2012), and compliance is evaluated by comparing those targets with the corrected regulated discharge or, where available, directly with gauge observations. The dashboard displays both products, the targets and the resulting compliance classification at the reach scale.

6. Watercourses under current legal restrictions

All principal watercourses of the basin are currently subject to federal restrictions on new surface water appropriation, established by presidential decree and published in the Diario Oficial de la Federación (DOF). Table 2 summarizes the instruments in force. In the Lerma–Chapala subregion, the decree of 8 April 2014 suppressed the pre-existing partial vedas and established a single veda (ban on new concessions) covering the surface waters of all 19 hydrological basins of the subregion, with water allocation governed by the distribution rules agreed in the basin council framework. In the Río Santiago subregion, the decree of 6 June 2018 — one of the ten water reserve decrees signed on 5 June 2018 — suppressed the historical vedas in the 30 hydrological basins of the subregion and replaced them with water reserves for domestic and public-urban use and for environmental use or ecological conservation, thereby securing environmental flow volumes in the Santiago mainstem and its tributaries (Ríos Verde, Juchipila, Bolaños and Huaynamota, among others). Groundwater in the basin is additionally subject to longstanding veda decrees over the principal aquifers (issued progressively since the late 1940s in Guanajuato, Querétaro, Michoacán, Jalisco and the State of Mexico), and published mean annual availability is negative for many of them. Official mean annual surface water availability per basin is computed and updated under NOM-011-CONAGUA-2015 and published in the DOF; concession volumes are recorded in the Public Registry of Water Rights (REPDA). These are the authoritative sources for the restriction status shown or referenced by the dashboard.

Table 2. *Legal instruments restricting surface water use in the Lerma–Santiago Basin*

Instrument (DOF date)	**Coverage**	**Effect**
Decree of 8 April 2014	All 19 hydrological basins of the Lerma–Chapala subregion (Río Lerma mainstem basins, La Gavia, Jaltepec, La Laja, Querétaro, Yuriria, Turbio, Angulo, Zula, among others)	Suppresses prior vedas and establishes a surface-water veda over the whole subregion: no new concessions; allocation governed by the subregional distribution rules; availability per DOF acuerdos
Decree of 6 June 2018	The 30 hydrological basins of the Río Santiago subregion (Santiago 1–6, Verde, Juchipila, Bolaños, Huaynamota, and associated reservoir basins)	Suppresses historical vedas and establishes reserves for domestic, public-urban and environmental use / ecological conservation, securing environmental flow volumes
Groundwater veda decrees (1948–1987, various)	Principal aquifers of the Bajío, Toluca, Querétaro, Morelia and Jalisco zones	Prohibit or restrict new groundwater development; current availability published per aquifer in the DOF
NOM-011-CONAGUA-2015	All basins and aquifers	Standard method for computing mean annual water availability; the published values determine whether new titles may be issued

7. Limitations

The simulations do not represent groundwater–surface water exchange, explicit irrigation abstraction or inter-basin transfers, and reservoir operation is generic storage–release behaviour rather than site-specific operating rules, which are being compiled with CONAGUA. Skill at ungauged reaches is substantially lower than at gauged reaches, and dry-season low flows carry the largest relative uncertainty. Users should treat reach-scale absolute volumes on ungauged tributaries with caution and rely on the compliance classification, which is more robust to residual bias, for interpretation.

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