Climate Forcing for Current and Future Hydrological Scenarios in the Lerma–Santiago Basin

Technical Summary for the Environmental Flow Dashboard

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1. Purpose and scope

This note describes the climate forcing used to produce the future discharge scenarios displayed on the environmental flow dashboard for the Lerma–Santiago Basin: the observational forcing of the historical baseline, the downscaled CMIP6 dataset and emission scenarios used for the projections, the criteria and evidence behind the selection of the climate model ensemble, the way the climate fields were converted into hydrological simulations consistent with the calibrated baseline, and the headline results with their associated uncertainty. It accompanies the summary of hydrological modelling, which documents the water balance model, river routing, reservoir representation and the treatment of hydrometric data.

2. Baseline climate forcing (1992–2024)

The historical baseline is forced with observational products: daily CHIRPS v2.0 precipitation (Funk et al., 2015) bias corrected against 315 quality-controlled rain gauges of the national climatological network, and daily grass-reference evapotranspiration from the NOAA/USGS global reference ET product (Hobbins et al., 2023). These products were retained after a multi-forcing evaluation in which four precipitation datasets (CHIRPS v2.0 and v3.0, MSWEP v2.8, ERA5) and two evaporative-demand datasets (NOAA reference ET, GLEAM v4 potential evaporation) were each run through the full modelling chain and evaluated against gauged rainfall and discharge. Basin-mean annual precipitation over the baseline is approximately 750–770 mm, of which more than 80% falls in the June–September wet season under the North American Monsoon (NAM); this strong seasonality, and its correct timing, is the single most important property that the future forcing must reproduce, because monsoon onset and retreat control essentially all runoff generation in the basin.

3. Future climate dataset and emission scenarios

Future projections are forced with the NASA Earth Exchange Global Daily Downscaled Projections dataset (NEX-GDDP-CMIP6, version 2.0; Thrasher et al., 2022). NEX-GDDP-CMIP6 provides daily meteorological fields from CMIP6 global climate models (GCMs), statistically downscaled to 0.25° (approximately 25 km) and bias corrected against an observational climatology by quantile mapping, which makes the product directly usable for hydrological impact modelling while retaining each model's climate change signal. Three Shared Socioeconomic Pathway scenarios were simulated over 2015–2100: SSP1-2.6 (low emissions), SSP2-4.5 (intermediate) and SSP5-8.5 (very high), spanning the plausible range of radiative forcing trajectories assessed by the IPCC Sixth Assessment Report (O'Neill et al., 2016). Daily precipitation and the fields required to derive reference evapotranspiration were extracted for each model and scenario and resampled to the hydrological model grid.

4. Selection of the climate model ensemble

Not all CMIP6 models are equally suitable for this basin: many share code lineage, so using them together inflates apparent consensus without adding independent information (Knutti et al., 2017), and several have equilibrium climate sensitivity (ECS) far above the IPCC AR6 likely range of 2.5–4.0 °C, which would systematically inflate future evaporative demand and depress projected discharge beyond plausible bounds (Merrifield et al., 2023). From the 20 models available in NEX-GDDP-CMIP6, eight were therefore selected through a structured literature review applying four criteria: (i) regional hydroclimatic performance, foremost the ability to reproduce NAM precipitation seasonality (Ye & Wang, 2023) and validated performance over Mexico (Andrade-Velázquez et al., 2023a, 2023b; Cruz-González et al., 2025); (ii) physical plausibility, retaining only models with ECS within or close to the AR6 likely range; (iii) model independence, one model per institutional lineage, preferring the higher-resolution member; and (iv) ensemble spread, so that the subset brackets the plausible range of future precipitation and warming rather than converging on a few similar models. Table 1 lists the retained ensemble. Precipitation, rather than temperature, dominates uncertainty in CMIP6-based runoff projections — about 93% of the total (Miao et al., 2024) — which is why precipitation performance carried the greatest weight in the selection.

Table 1. *The eight CMIP6 models retained to force the future hydrological scenarios.*

Model	ECS (°C)	Principal selection evidence
NorESM2-MM	≈2.5	Classified good for NAM seasonality (Ye & Wang, 2023); strong extreme-precipitation skill in arid and tropical regimes; low-sensitivity end-member
GFDL-ESM4	≈2.7	Top-ranked for hydrological forcing variables (precipitation, ET, soil moisture) in application-specific CMIP6 evaluation (Adhikari et al., 2024)
MIROC6	≈2.6	Repeatedly validated over Mexico with quantile-mapping correction (Andrade-Velázquez et al., 2023a, 2023b); independent Japanese lineage
MPI-ESM1-2-HR	≈3.0	Distinct Max Planck lineage adding structural diversity; strong basin-scale precipitation skill in monsoon-basin evaluations
MRI-ESM2-0	≈3.2	Best pre- and post-correction temperature skill over Mexico; applied in the upper Lerma zone; retained conditionally given a documented NAM retreat-season wet bias, verified over the basin before use
ACCESS-ESM1-5	≈3.9	Applied directly in the upper Lerma headwaters (Cruz-González et al., 2025); represents the strong-drying end of regional projections
IPSL-CM6A-LR	≈4.6	Validated precipitation and temperature downscaling over Mexico with explicit treatment of orographic patterns relevant to the Trans-Mexican Volcanic Belt
EC-Earth3	≈4.3	Highest-ranked extreme-precipitation skill in arid regimes; passes Mexico-domain bias screening (Almazroui et al., 2021); with IPSL-CM6A-LR, spans the warm end of the ensemble

Twelve models were excluded, principally for ECS outside the plausible range (for example CanESM5, ECS ≈ 5.6 °C, and UKESM1-0-LL, ECS ≈ 5.3 °C, both of which nonetheless show genuine monsoon skill and are recommended as supplementary stress-test experiments under SSP5-8.5), for documented precipitation bias over the Mexico domain, for institutional redundancy with a retained model, or for the absence of regional validation evidence. The full model-by-model justification, with the supporting literature, is documented in the CMIP6 model selection review prepared for the project.

5. From climate fields to discharge scenarios

For each of the 24 scenario–model combinations (3 SSPs × 8 GCMs), the downscaled daily fields were processed into VegET forcing on the model grid and the full chain was run for 2015–2100: the VegET water balance with the same calibrated parameter set as the historical baseline, mizuRoute for naturalized discharge and mizuRoute-Lake for the regulated configuration with the same 58 represented water bodies. Holding the calibration and model structure fixed ensures that differences between scenarios reflect the climate forcing alone, not re-tuning. Simulated daily discharge was aggregated to monthly series for the dashboard.

The statistical bias correction estimated for the baseline regulated product at the CONAGUA anchor gauges (see the hydrological modelling summary) was transferred to the future simulations in a signal-preserving form: the correction climatologies are held fixed at their 1992–2024 values, so that only the anomaly simulated by each model and scenario varies. This prevents the correction from dampening or amplifying the climate change signal, and diagnostic checks confirm that the corrected change in discharge tracks the uncorrected change across all 24 combinations. As in the baseline, the naturalized future product is left uncorrected and is used only to derive the reference regime.

6. Projected changes and ensemble spread

Table 2 summarizes the ensemble-median change in basin discharge between the far horizon (2071–2100) and the near horizon (2015–2044). The projections show a consistent drying signal that scales with emissions, driven jointly by reduced monsoon precipitation and increased evaporative demand. Inter-model spread is substantial and, under SSP1-2.6, exceeds the scenario signal itself: individual models range from modest wetting (MPI-ESM1-2-HR, about +15%) to marked drying (EC-Earth3, about −24%) under that scenario, while the driest individual trajectory in the whole ensemble (ACCESS-ESM1-5 under SSP5-8.5, about −81%) should be read as a low-probability, high-impact member rather than a central estimate. For this reason the dashboard presents the ensemble median together with the inter-model range, and users are advised to treat the spread, not any single model, as the projection.

Table 2.*Ensemble-median change in discharge, 2071–2100 relative to 2015–2044, with indicative inter-model spread.*

Scenario	Median change in discharge	Character of the ensemble
SSP1-2.6 (low)	−10.3%	Spread larger than the signal; individual models from ≈+15% to ≈−24%
SSP2-4.5 (intermediate)	−18.9%	Consistent drying across most models; moderate spread
SSP5-8.5 (very high)	−43.8%	Strong, robust drying; driest member ≈−81% (ACCESS-ESM1-5)

7. Uncertainty and appropriate use

Three caveats frame the interpretation of the scenarios. First, precipitation uncertainty dominates: differences among GCMs in monsoon behaviour translate directly into runoff differences, and a documented CMIP6 tendency to extend monsoon rainfall too far into the retreat season (Ye & Wang, 2023) means late-season flows are the least certain part of the projected hydrographs. Second, statistical downscaling and quantile-mapping bias correction improve local realism but can distort precipitation extremes and spatial coherence (Maraun, 2013), so projected changes in flood-scale extremes should be interpreted more cautiously than changes in seasonal and annual volumes. Third, the projections inherit the structural limitations of the hydrological chain: water management is represented by generic reservoir storage–release behaviour under current infrastructure, and future changes in abstraction, land use or operating policy are not simulated. The scenarios are therefore best used to compare relative changes between horizons and scenarios — the purpose they serve in the environmental flow assessment — rather than as deterministic forecasts of absolute discharge.

References

Adhikari, R. K., Yilmaz, A. G., Mainali, B., & Dyson, P. (2024). Performance evaluation of CMIP6 models for application to hydrological modelling studies — A case study of Australia. Science of the Total Environment, 945, 174015. https://doi.org/10.1016/j.scitotenv.2024.174015

Almazroui, M., Saeed, S., Saeed, F., Islam, M. N., & Ismail, M. (2021). Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. Earth Systems and Environment, 5, 1–24. https://doi.org/10.1007/s41748-021-00199-5

Andrade-Velázquez, M., Ávalos-Bravo, V., Maya-Magaña, M. E., & Salinas-Prieto, J. A. (2023a). Historical and projected trends of the mean surface temperature in south-southeast Mexico using ERA5 and CMIP6. Climate, 11(5), 111. https://doi.org/10.3390/cli11050111

Andrade-Velázquez, M., Ávalos-Bravo, V., Maya-Magaña, M. E., & Salinas-Prieto, J. A. (2023b). Statistical downscaling of precipitation in the south and southeast of Mexico. Climate, 11(9), 186. https://doi.org/10.3390/cli11090186

Cruz-González, A., Arteaga-Ramírez, R., Soria-Ruiz, J., Sánchez-Cohen, I., Monterroso-Rivas, A. I., & Quevedo-Nolasco, A. (2025). Climate change projections in temperature and precipitation using CMIP6 in Central Mexico. Theoretical and Applied Climatology, 156, 97. https://doi.org/10.1007/s00704-024-05345-3

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations — A new environmental record for monitoring extremes. Scientific Data, 2, 150066. https://doi.org/10.1038/sdata.2015.66

Hobbins, M., Harrison, L., Blakeley, S., et al. (2023). A global reference evapotranspiration dataset for supporting drought monitoring and hydrologic modeling. Scientific Data, 10, 703. https://doi.org/10.1038/s41597-023-02648-4

Knutti, R., Sedláček, J., Sanderson, B. M., Lorenz, R., Fischer, E. M., & Eyring, V. (2017). A climate model projection weighting scheme accounting for performance and interdependence. Geophysical Research Letters, 44(4), 1909–1918. https://doi.org/10.1002/2016GL072012

Maraun, D. (2013). Bias correction, quantile mapping, and downscaling: Revisiting the inflation issue. Journal of Climate, 26(6), 2137–2143. https://doi.org/10.1175/JCLI-D-12-00821.1

Merrifield, A. L., Brunner, L., Lorenz, R., Humphrey, V., & Knutti, R. (2023). Climate model Selection by Independence, Performance, and Spread (ClimSIPS v1.0.1) for regional applications. Geoscientific Model Development, 16, 4715–4747. https://doi.org/10.5194/gmd-16-4715-2023

Miao, C., Wu, Y., Slater, L., Lu, Q., & Su, T. (2024). Hydrological projections under CMIP5 and CMIP6: Sources and magnitudes of uncertainty. Bulletin of the American Meteorological Society, 105(1), E59–E74. https://doi.org/10.1175/BAMS-D-23-0104.1

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geoscientific Model Development, 9(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Thrasher, B., Wang, W., Michaelis, A., Melton, F., Lee, T., & Nemani, R. (2022). NASA Global Daily Downscaled Projections, CMIP6. Scientific Data, 9, 262. https://doi.org/10.1038/s41597-022-01393-4

Ye, J., & Wang, Z. (2023). An origin of North American Monsoon retreat biases in climate models. Journal of Climate, 36(14), 4663–4676. https://doi.org/10.1175/JCLI-D-22-0592.1