A safe and just operating space for water at municipal scale: population, agriculture and mining in Chihuahua, Mexico, to 2050

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Highlights

- Municipal water ceilings and floors for Chihuahua are derived from Mexican law
- 15 of 67 municipalities exceed their renewable space in all 324 scenarios
- Mining is under 0.3% of state water use but up to 78% of local use in the Sierra
- Mining dominates water use exactly where no aquifer has ever been delimited
- The minimum-vital choice, not climate or mining, decides the capital's space

Abstract

Water allocation decisions in Mexico are taken municipality by municipality, yet water scarcity is assessed at national or basin scale. We operationalize a safe and just operating space for water for each of the 67 municipalities of Chihuahua, Mexico's largest and driest mining state, with both bounds drawn from national law rather than imposed by the analyst: an ecological ceiling equal to the renewable availability published by the federal water authority, and a social floor equal to the domestic water quantity that Mexican courts are now making enforceable. Between them lies the space legitimately available to agriculture and mining. We couple official data on population, irrigated agriculture and metal mining in an open, formula-transparent spreadsheet calculator, and run every combination of demographic (SSP), mineral-demand (IEA), water-intensity, climate-elasticity and social-floor assumptions — 324 scenario combinations to 2050. Three findings are robust across the entire scenario space. First, overdraft is structural, not scenario-dependent: 15 municipalities, concentrated in the irrigated districts of the Conchos basin, exceed their development space in every combination, by 1,205–1,388 hm^3 per year in aggregate. Second, mining never exceeds 0.3% of state water use, but reaches 36–78% of municipal use in Sierra Tarahumara municipalities that lie in a ~45,000 km^2 area for which no aquifer has ever been delimited — where the administrative instrument the law requires does not exist. Third, for the state capital and Ciudad Juárez, the choice of the legal minimum vital (50, 100 or 150 L per person per day) — not climate or mining — decides whether any development space remains. The calculator runs in Excel or LibreOffice with visible formulas and is released with the paper.

Keywords

safe and just operating space; water allocation; municipal scale; mining; energy transition; Mexico

1. Introduction

Water scarcity in arid regions is usually reported as a stress ratio: withdrawals over renewable supply, computed for a country or a basin. Such ratios are useful for comparison, but they answer a question no one has to decide. Scarcity in an arid region is rarely the simple absence of water; it is the outcome of choices about who is entitled to use it, in what order, and up to what limit. Those choices are made — and their consequences are lived — at a scale that national and basin-level assessments do not resolve. A state can appear moderately stressed while some of its municipalities have already committed every renewable cubic metre they have, and a sector can look negligible in the aggregate while dominating the water balance of the places where it operates.

A second limitation follows from the first. Stress ratios treat all water use as equivalent. They do not distinguish the water that meets basic human needs from the water that supports export agriculture or mineral extraction, and so they cannot say whether a given allocation is defensible — only whether it is large. Frameworks that do make this distinction exist. The safe and just operating space, and its downscaled expressions in the doughnut literature, pair an ecological ceiling with a social floor and treat the space between them as the domain of legitimate economic activity (Rockström et al., 2009; Raworth, 2012, 2017; Dearing et al., 2014; O'Neill et al., 2018; Rockström et al., 2023). Yet reviews of these frameworks' local operability find that they have rarely been brought down to the administrative level where allocation decisions are actually taken (Hoornweg et al., 2016; Turner and Wills, 2022; Ferretto et al., 2022), and water in particular remains under-operationalized at subnational scale despite explicit calls to connect the water boundary to local management (Zipper et al., 2020).

Mexico makes this gap both urgent and unusually tractable, because there the floor and the ceiling are not analytical conveniences imposed from outside: they are statutory. Article 22 of the National Waters Act states that domestic and urban public use "shall always be preferential" over any other use when granting concessions, and requires the water authority to consider the mean annual availability of the resource, the volumes already registered, and any declared bans or reserves. Article 4 of the Constitution establishes the human right to water for personal and domestic use. In December 2025 a new General Water Law came into force to implement that right, obliging water utilities to guarantee a minimum vital supply without quantifying it (DOF, 2025), and in August 2026 the Supreme Court began quantifying it case by case, ordering a utility to deliver 100 L per person per day (SCJN, 2026). Municipal-scale water accounting has therefore become a legal necessity in Mexico before the tools to do it became available. A model built on this structure does not propose a norm; it evaluates the state against the one it has already adopted.

Chihuahua is where that evaluation bites hardest. It is Mexico's largest state by area, arid to semi-arid across most of it, and it combines three water uses that are usually studied apart: irrigated agriculture concentrated in the Conchos basin, a growing urban population on the border and in the state capital, and one of the country's leading silver- and gold-mining districts. Thirty-eight of its sixty-one aquifers are officially in deficit. Between the 2018 and 2023 publications of the federal availability decree, the state's net groundwater balance deepened from −2,004 to −2,638 hm^3 per year while published recharge remained essentially constant: the deficit deepened through allocation, not through hydrology (CONAGUA, 2018, 2023). This mirrors the national pattern, in which concessioned volumes have grown faster than any hydrological change (Castellazzi et al., 2016; Scott, 2011; Martínez-Austria and Vargas-Hidalgo, 2017).

The state is also where the global energy transition is expected to press on water. Rising demand for transition minerals is widely assumed to intensify water competition in the arid regions that host them (Meißner, 2021; Northey et al., 2017; Lèbre et al., 2020; Sonter et al., 2020; IEA, 2024). Chihuahua tests that assumption directly, and complicates it: as we show, the great majority of the water embedded in its mining output is attributable to gold and silver, metals with no transition-driven demand signal, rather than to copper, zinc or iron.

One further feature of Chihuahua motivates the approach taken here. The municipalities where mining dominates the local water balance — Ocampo, Chínipas and their neighbours in the Sierra Tarahumara — lie in or beside a contiguous area of roughly 45,000 km² for which CONAGUA has never delimited an aquifer. Eight municipalities have no published recharge figure, no concessioned volume, no deficit declaration and no ban. The administrative instrument that Article 22 obliges the authority to consider before granting a concession does not exist for them. This is not a data gap in our model; it is a feature of the governance system that only becomes visible when the analysis is conducted municipality by municipality.

We therefore ask: given projected population growth, transition-driven mineral demand and downscaled climate change, how much water remains available for economic development in each of Chihuahua's 67 municipalities once basic domestic needs are met and renewable availability is respected — and which of these outcomes depend on the scenario at all? Rather than selecting a handful of narrative scenarios, we run the model over every combination of its scenario levers — four demographic pathways, three mineral-demand trajectories, three mining water intensities, three climate elasticities and three social-floor levels, 324 combinations in all — and report which municipal outcomes hold across the entire envelope and which are decided by a single assumption.

The paper makes three contributions. First, it operationalizes a safe and just operating space for water at municipal scale in an arid extractive frontier, with both bounds drawn from national law rather than imposed by the analyst. Second, it couples three competing water uses — population, agriculture and mining — in a single accounting frame, which is what makes the scale mismatch legible: a sector that is at most 0.3% of state water use is two thirds of one municipality's. Third, it releases the model as an open, formula-transparent spreadsheet calculator designed to be run and modified by non-specialists, following the design philosophy of the FABLE Calculator (Mosnier et al., 2020, 2023) and the broader case for accessible models in policy settings (Howells et al., 2011), so that the analysis can be repeated, contested and extended by the actors who will have to act on it.

Section 2 describes the study area and its legal setting. Section 3 sets out the model, its data sources and the scenario design. Section 4 presents results. Section 5 discusses what they imply for water governance in northern Mexico and how far the approach transfers, and Section 6 concludes.

2. Study area and policy context

Chihuahua covers 247,455 km² of the Mexican north, most of it in the Chihuahuan Desert, with the Sierra Madre Occidental (locally, Sierra Tarahumara) along its western flank. Its 3.81 million inhabitants (2020) are concentrated in Ciudad Juárez on the United States border and in the state capital; 67 municipalities span four orders of magnitude in population. Renewable water is supplied by 61 administratively delimited aquifers and by two surface systems: the Río Bravo–Conchos, whose availability CONAGUA publishes at subregional level, and the Pacific-draining basins of the Sierra, published per basin (CONAGUA, 2016, 2020). Irrigated agriculture — alfalfa, pecan, cotton and chile, concentrated in irrigation districts along the Conchos and its tributaries — is by far the largest consumptive water user. Mining has operated in the Sierra and the central valleys since the colonial period; the state is among Mexico's leading producers of silver, gold, zinc and lead (SGM, 2023).

Three features of the Mexican legal frame define the accounting space. First, the ceiling: the National Waters Act (Ley de Aguas Nacionales, art. 22) requires the authority to consider the published mean annual availability — computed under the official norm NOM-011-CONAGUA-2015 — before granting any concession, and the availability decrees themselves are published in the official gazette, aquifer by aquifer and basin by basin (CONAGUA, 2015, 2023). Second, the floor: constitutional article 4 establishes the human right to water; the 2025 General Water Law obliges utilities to guarantee a minimum vital supply even in case of non-payment, but leaves the quantity open (DOF, 2025); the Supreme Court has now ordered 100 L per person per day in a specific case (SCJN, 2026), while the WHO service-level ladder brackets the range: 50 L covers basic needs, 100 L approaches optimal access (Gleick, 1996; Howard et al., 2020). Third, the preference order: domestic and urban public use is always preferential, so the floor is subtracted before any economic use is entitled to the remainder.

The groundwater situation deteriorated markedly between the two most recent availability decrees. Published recharge for the 61 aquifers is 3,910 hm³ per year and changed little between 2018 and 2023, yet the net balance across all aquifers deepened from −2,004 to −2,638 hm³ per year and the number of aquifers in deficit reached 38 of 61. Because recharge was essentially constant, the deterioration is attributable to the growth of concessioned volumes — an allocation dynamic, not a hydrological one. Groundwater quality adds a further constraint not modelled here: arsenic and fluoride co-occur naturally in the alluvial aquifers of the central valleys, including the Meoqui-Delicias aquifer that underlies the state's most water-stressed irrigation districts (Reyes-Gómez et al., 2013; Bencomo-Calderón et al., 2024).

3. Materials and methods

3.1. Accounting frame

For each municipality m and year t between 2003 and 2050 the model computes four quantities. The ecological ceiling T(m,t) is the renewable water assigned to the municipality — aquifer recharge allocated by area intersection plus published surface availability — adjusted by a climate multiplier that phases in linearly between 2020 and 2050. The social floor F(m,t) is the projected population times a per-capita floor allowance times 365 days. The development space is S(m,t) = T(m,t) − F(m,t). The economic use E(m,t) is the sum of agricultural and mining consumptive water. A municipality is in overdraft when E exceeds S (equivalently, when the ratio E/S exceeds one, or when S itself is non-positive). All quantities are expressed in hm^3 per year. The model quantifies consumptive use (evapotranspired or embedded in products) rather than withdrawals, with one deliberate exception: population water use is gross supply including network losses, which makes the mining share of total use conservative. Population use is reported alongside the accounts but is not part of E, since the floor already represents the population's protected claim; the difference between actual population use and the floor is reported as the population gap.

3.2. Ecological ceiling

The groundwater component was constructed from primary sources. The polygon of each of the 61 aquifers was reconstructed from the vertex tables published in the official gazette (DOF), including a transcription error detected in the Meoqui-Delicias decree (15 vertices printed with latitude 28° where 27° is required; the correction was verified five ways, including polygon validity, the declared area, and the containment of the five head towns of irrigation district 005). Aquifer recharge was allocated to municipalities by area intersection between the reconstructed polygons and municipal boundaries (GADM v4.1), computed in an equal-area projection (EPSG:6372); 96.7% of published state recharge is assigned. The surface component uses the published availability of the 13 Bravo-Conchos basins — allocated to municipalities by area within each subregion, an assumption flagged in the model output for the 41 municipalities it affects — and the Pacific-slope basins, taken from their own availability decrees (CONAGUA, 2016, 2020, 2023). One municipality, Moris, drains to the Río Mayo, whose availability decree is not yet incorporated: it carries no ceiling and is excluded from overdraft counts. Climate enters through the elasticity of runoff to precipitation: municipal precipitation-change projections for 2041–2060 (INECC, n.d.) are converted to availability multipliers using an elasticity of 1.3, 1.5 or 1.8 — a range re-anchored on Conchos-basin estimates implying 1.48–1.76 (Martínez-Austria and Patiño-Gómez, 2012), following the streamflow-elasticity concept of Sankarasubramanian et al. (2001).

3.3. Social floor and population

Municipal population is CONAPO's official reconstruction and projection to 2040 (CONAPO, 2023), extended to 2050 with state-specific SSP growth factors. These factors were generated by re-running the published multi-regional cohort-component model of Regules-García et al. (2024) for all 32 states and five SSPs from its open repository, in the variant with internal migration; we verified that net internal migration sums to zero (the model conserves national population) and that the output reproduces the published figures. For Chihuahua the 2050 factors relative to 2020 are 1.178 (SSP1), 1.193 (SSP2), 1.258 (SSP3), 1.141 (SSP4) and 1.282 (SSP5). Two properties matter for interpretation. First, SSP3 tracks CONAPO's official projection most closely over the 2020–2040 overlap (deviation $\leq$ 1%), and is therefore used as the central demographic pathway; the SSP label is used here as a demographic trajectory, not as a fully coupled socioeconomic narrative (O'Neill et al., 2017; Riahi et al., 2017). Second, the ordering of the Mexican SSPs is driven by international migration assumptions rather than fertility, so it does not reproduce the canonical global ordering — SSP5, not SSP3, yields the largest population. The floor allowance takes three values spanning the legal and technical range: 50 L per person per day (basic survival and hygiene; Gleick, 1996), 100 L (the quantity the Supreme Court has now made enforceable, within the WHO 'optimal access' band;

Howard et al., 2020; SCJN, 2026) and 150 L (an urban-efficiency benchmark). Actual population water use applies a gross per-capita supply of 189 L per person per day (measured for the capital; IMPLAN Chihuahua, 2024), with 279.5 and 370 L as sensitivity values.

3.4. Agriculture

Agricultural water use is computed from municipal production records for 52 crops and two modalities (irrigated and rainfed) over 2003–2022 (SIAP, 2023), multiplied by crop-specific blue-water coefficients. Blue water is attributed to irrigated production only. Coefficients come from the global water-footprint database (Mekonnen and Hoekstra, 2011), replaced where Chihuahua-specific field measurements exist: pecan uses a satellite-based measurement of mature orchards in the Delicias–Rosales–Meoqui zone, 6,666 m^3 per tonne (11,332 m^3 per hectare at the observed district yield of 1.7 t per hectare; Salcido Mundo et al., 2021); alfalfa, winter cereals and forages use INIFAP irrigation-sheet measurements for the region; peach uses a local measurement (Suárez Guerra et al., 2022). Under the water-abundance of the 2018–2022 record, alfalfa accounts for 45% and pecan for 19% of the state's agricultural blue water. Because the model projects no land-use change, agricultural water after 2022 is held at the municipality's 2018–2022 mean — a deliberately conservative baseline that represents the continuation of the current cropping pattern rather than a forecast.

3.5. Mining

Mining water use is computed from municipal production of each metal (SGM, 2023), multiplied by metal-specific water intensities from the global assessment of Meißner (2021), whose ranges (minimum, central, maximum) form one scenario dimension; the limitations of mining water-footprint coefficients — in particular the mixture of concentrate-basis and refined-metal-basis values — follow Northey et al. (2016) and are carried in the model's documentation. Production is projected from a 2020–2021 base by geometric interpolation to 2050 demand multipliers derived from the IEA's critical-minerals scenarios (Current Policies, Stated Policies, High Demand; IEA, 2024): copper directly from the IEA projection (1.29–1.37), iron from steel-demand scenarios for the transition (Van der Voet et al., 2019), silver from the IEA energy-sector projection combined with a constant non-energy market, zinc and lead as minor-transition-share markets, and gold — which the IEA does not cover, having no transition driver — held constant (1.10 in High Demand). Where a deposit yields several metals, water is allocated among co-products by their share of the economic value of the municipality's base-year production, preventing the same water from being counted once per metal; the allocation uses multi-year average prices. Twenty-six municipalities have recorded metal production (81 municipality–metal pairs).

3.6. Scenario design

Rather than analysing selected narratives, we run the full factorial of the model's scenario levers (Table 1): four demographic pathways (SSP1, SSP2, SSP3, SSP5 — SSP4 is excluded because the INECC municipal climate service does not provide it), three social-floor levels, three climate elasticities, three mineral-demand trajectories and three mining water intensities: 4 × 3 × 3 × 3 × 3 = 324 combinations of the balance-relevant levers, each evaluated for all 67 municipalities in 2050. The three population-supply intensities affect only the reported population gap, not the balance, and would triple the count to 972 without changing any conclusion; polymetallic value allocation is kept on throughout (switching it off is a diagnostic that double-counts water). This design asks of every municipal outcome: does it depend on the future at all, and if so, on which lever?

Table 1. Scenario levers and levels. The first five levers define the 324-combination balance sweep; the population supply intensity (*) affects only the reported population gap, not the balance.

Lever	Levels	Source
Demographic pathway (SSP)	SSP1 · SSP2 · SSP3 (central) · SSP5; Chihuahua-specific 2050 factors 1.178 · 1.193 · 1.258 · 1.282	Regules-García et al. (2024), re-run
Social floor (L person^{-1} day^{-1})	50 (vital) · 100 (basic, central) · 150 (efficient)	Gleick (1996); Howard et al. (2020); SCJN (2026)
Climate elasticity of runoff	1.3 · 1.5 (central) · 1.8	Martínez-Austria and Patiño-Gómez (2012)
Mineral demand to 2050	Current Policies · Stated Policies (central) · High Demand	IEA (2024); Van der Voet et al. (2019)
Mining water intensity	minimum · central · maximum, per metal	Meißner (2021)
Population supply intensity*	189 (central) · 279.5 · 370 L person^{-1} day^{-1}	IMPLAN Chihuahua (2024)

3.7. Implementation and validation

The model is implemented as a 20-sheet spreadsheet Excel calculator in which every number lives in a parameter or data sheet with its source documented row by row, every calculation is a visible formula, and scenarios are selected from nine dropdown cells; no macros are used. A step-by-step user manual accompanies the calculator as supplementary material. For this paper the calculation chain was additionally replicated in Python; the replica reproduces the spreadsheet's municipal balances (maximum absolute difference below 10^{-12} hm³ across all 67 municipalities and all reported quantities), and was used to execute the 324-combination sweep. An audit protocol — duplicate-key checks, missing-input flags, and a per-municipality provenance column for the ceiling — is built into the calculator itself, and detected during development an error class worth reporting: a municipality (Batopilas de Manuel Gómez Morín) whose ceiling was silently zeroed by a name mismatch between data sources, making it appear to have no space by artefact. The published version distinguishes that condition explicitly.

4. Results

4.1. State accounts: the overdraft is structural

Fig. 1a shows the state-level accounts from 2003 to 2050 under the central combination (SSP3, 100 L floor, central elasticity, Stated Policies demand, central intensities). The ecological ceiling is 6,625 hm³ per year before climate adjustment and declines to 6,244 hm³ by 2050 under the central elasticity; across the full sweep the 2050 ceiling spans 6,168–6,691 hm³, a range of ±4% around the unadjusted value. The social floor at 100 L per person per day is 175 hm³ in 2050 — 2.8% of the ceiling — and spans 82–268 hm³ across all floor levels and demographic pathways. Agriculture, held at its 2018–2022 pattern, uses 3,462 hm³; population supply uses 331 hm³ (range 310–660 across supply intensities and pathways); mining uses 5.4

hm³ (range 2.3–11.0 across all demand and intensity combinations; Fig. 1b). Mining is thus between 0.06% and 0.29% of total state water use in every future considered (central: 0.14%).

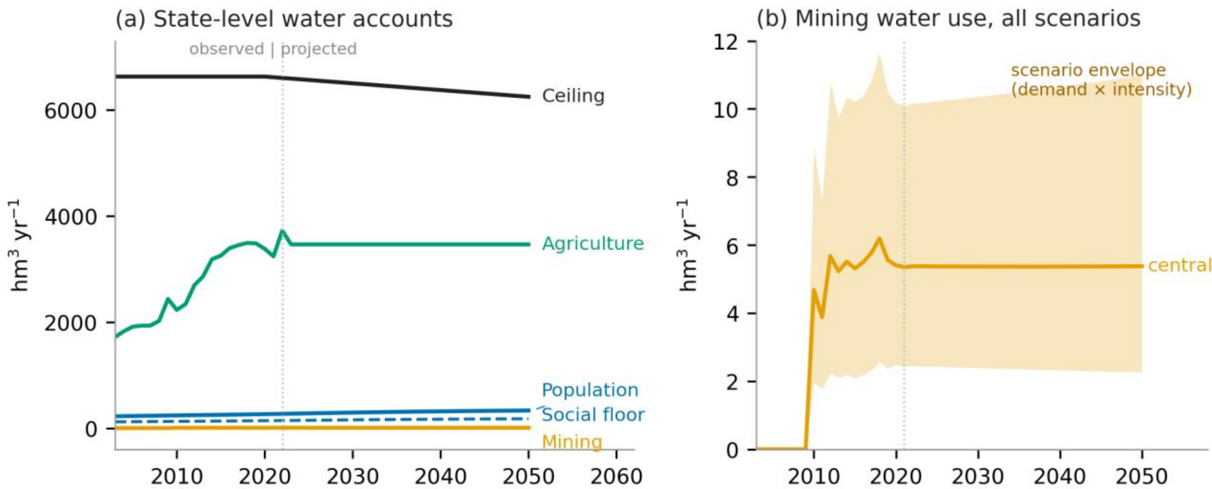

Fig. 1. (a) State-level water accounts, 2003–2050, central scenario: ecological ceiling, agricultural and population water use, social floor (100 L per person per day) and mining. Agricultural use after 2022 is held at the 2018–2022 municipal mean (Section 3.4). (b) Mining water use under all demand-by-intensity combinations; the envelope spans Current Policies × minimum intensity to High Demand × maximum intensity.

The aggregate overdraft — the excess of economic use over development space, summed over municipalities in overdraft — is 1,305 hm³ per year in 2050 under the central combination, and ranges only from 1,205 to 1,388 hm³ across all 324 combinations (Table 2). The two mining levers have no visible effect on this total: the mean aggregate overdraft is identical to the nearest hm³ across the three demand trajectories and the three intensity levels. The overdraft is also not a projection artefact: run on observed data, the same accounting already shows 7 municipalities in overdraft in 2003, 13 by 2020 and 16 by 2022. The state's water problem was committed before any of the scenario levers takes effect.

Table 2. State-level results across the 324 scenario combinations. "Central" is SSP3, 100 L floor, central elasticity, Stated Policies, central intensities. Population supply min–max additionally spans the three supply intensities. Moris (no published ceiling) is excluded from overdraft counts.

Indicator (2050, hm³ yr⁻¹ unless noted)	Central	Min	Max
Ecological ceiling	6,244	6,168	6,691
Social floor	175	82	268
Population supply	331	310	660
Agricultural use (fixed pattern)	3,462	3,462	3,462
Mining use	5.4	2.3	11.0
Mining share of total use (%)	0.14	0.06	0.29
Municipalities in overdraft (of 66 with ceiling)	18	15	18
Aggregate overdraft	1,305	1,205	1,388

4.2. Municipal outcomes are decided, not scenario-dependent

Fig. 2 shows, for every municipality with a published ceiling, the 2050 ratio of economic use to development space across all 324 combinations. The scenario envelope barely moves any municipality across the overdraft threshold: 15 of 67 municipalities are in overdraft in every combination, 48 are within their space in every combination, one (Moris) has no published ceiling, and only three — Praxedis G. Guerrero, Ciudad Juárez and the state capital — change status depending on the assumptions. The 15 always-overdrawn municipalities are concentrated in the irrigated districts of the Conchos system (Delicias exceeds its space 12- to 21-fold, Meoqui 12- to 15-fold) and the groundwater-irrigated northwest (Ahumada, Buenaventura, Galeana, Nuevo Casas Grandes, Ascensión, Janos). Their identity, not just their number, is invariant: no plausible combination of demography, climate, mineral demand or floor choice changes which places are overcommitted.

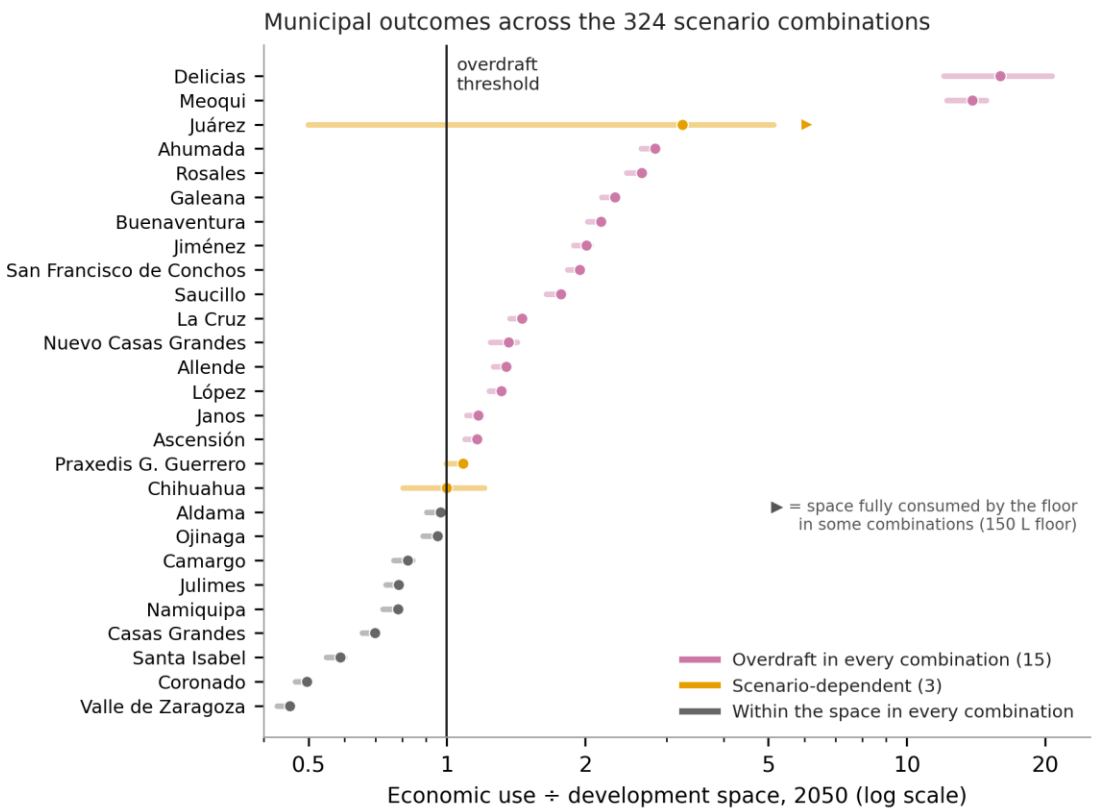

Fig. 2. Ratio of economic use to development space in 2050 for the 27 municipalities with the highest ratios, across all 324 scenario combinations. Dots mark the central combination; bars span the minimum–maximum across combinations (computed where development space is positive). Arrowhead: for Juárez, the 150 L floor consumes the entire ceiling in some combinations, so the ratio is undefined there. Municipalities are classed by whether they are in overdraft in all, some, or none of the combinations.

4.3. Mining

The mining sector's 2.3–11.0 hm³ never registers at state scale, but Fig. 3 shows its municipal geography. In Ocampo, mining is 36–78% of total municipal water use in 2050 depending on the intensity and demand assumptions (central: 65%); in Chínipas, 37–73% (central: 58%); in Urique, San Francisco del Oro, Guazapares and Madera it can exceed 30%. Five of the eight municipalities where mining exceeds 10% of local use in the central case lie wholly or partly in the ~45,000 km² Sierra Tarahumara zone with no delimited aquifer — no published recharge, no registered concessions, no deficit status, no ban. Their ceilings in the model come entirely from surface-water decrees. The water-intensity parameter, not the demand scenario, dominates this local uncertainty: moving from minimum to maximum intensity multiplies Ocampo's mining share by 2.2, while moving from Current Policies to High Demand changes it by a few points (Section 4.5).

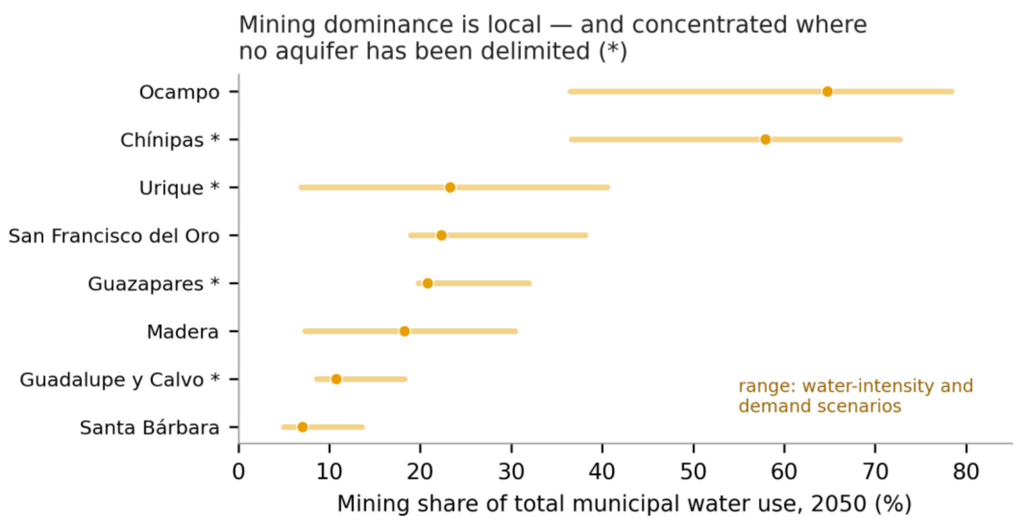

Fig. 3. Mining share of total municipal water use in 2050 for the eight municipalities where the maximum-case share exceeds 10%. Dots: central combination (Stated Policies demand, central intensity); bars: minimum (Current Policies, minimum intensity) to maximum (High Demand, maximum intensity). Asterisks mark municipalities lying in the Sierra Tarahumara zone without a delimited aquifer.

The composition of mining water also matters for how the energy transition should be discussed in this region. Gold and silver, which have no transition-demand driver, account for 74.5% of the state's mining water in the central 2050 case; copper, zinc and iron — the transition-linked metals — account for most of the remainder. Consequently, even the High Demand trajectory raises state mining water by only 7% over Stated Policies (5.78 vs 5.38 hm³ at central intensity). In Chihuahua, the water footprint of mining is a precious-metals question, not a transition-minerals question.

4.4. What moves the frontier: the floor, not the climate

The three scenario-dependent municipalities isolate which lever matters at the margin. Ciudad Juárez (1.5 million inhabitants projected in 2050 under SSP3) is within its space at a 50 L floor in every combination, and in overdraft at 100 L and 150 L in every combination; at 150 L, the floor exceeds the entire ceiling in some demographic-climate combinations, leaving no development space at all. The state capital sits on a knife edge: its central-case ratio is 1.0001 — economic use and development space equal to four decimal places — so at the 100 L floor its status is decided by the climate elasticity and the demographic pathway, at 150 L it is always in overdraft, and at 50 L never. Praxedis G. Guerrero is in overdraft in 94% of combinations, escaping only under the most favourable floor-climate corners. For these municipalities, the single most consequential number is the one the Supreme Court is now quantifying: whether the enforceable minimum vital is 50, 100 or 150 L per person per day does more to their accounted water future than any climate or mining scenario in the envelope. We report the capital's knife-edge position as a finding about threshold sensitivity, not as a classification: three independent parameter revisions during model development (the pecan coefficient, the climate elasticity, the demographic factors) each moved it across the threshold in different directions.

4.5. Parameter uncertainty exceeds scenario uncertainty

For the mining sector, the spread induced by the water-intensity parameter (2.26–9.93 hm^3 at fixed Current Policies demand; factor of 4.4) is much larger than the spread induced by the demand scenario at fixed intensity (5.24–5.78 hm^3 at central intensity; factor of 1.1). Reducing the uncertainty of the intensity coefficients — ideally with site-level data from the operating mines themselves — would therefore narrow the local projections far more than refining demand scenarios. The same asymmetry holds for the ceiling: the climate multiplier moves the state ceiling by at most 7%, while the allocation assumptions embedded in the availability decrees (the subregional surface-water split affects 41 municipalities, flagged per municipality in the model output) are untested against any published basin-level balance. In both cases the binding uncertainty is in parameters and administrative data, not in futures.

5. Discussion

5.1. An allocation problem wearing a scarcity costume

The headline result is negative in a useful way: almost nothing about Chihuahua's 2050 municipal water accounts depends on the future. Fifteen municipalities exceed their renewable space under every combination of demography, climate, mineral demand and floor level, by an aggregate 1,205–1,388 hm^3 per year — roughly a third of the state's renewable ceiling — and their overdraft was already visible in observed data two decades ago. This is consistent with the diagnosis that Mexico's groundwater crisis is driven by the growth of concessioned volumes rather than by hydrology (Scott, 2011; Castellazzi et al., 2016; Martínez-Austria and Vargas-Hidalgo, 2017), and our comparison of the 2018 and 2023 availability decrees quantifies it for Chihuahua: the deficit deepened 32% in five years with recharge essentially unchanged. For policy, the implication is uncomfortable but clarifying: scenario planning aimed at demand futures addresses the margin, while the core imbalance is a stock of existing entitlements. Instruments that operate on allocation — concession review, buyback, irrigation-district conversion, enforcement against unregistered extraction — are the ones that reach the 1,300 hm^3; efficiency gains in sectors that use 0.1–0.3% of the water cannot.

5.2. The governance void where mining meets the map's edge

The second finding inverts the usual scale of concern about mining and water. Statewide, mining could triple its water use without appearing in the accounts; locally, it is the majority water user in municipalities that administratively have no groundwater to allocate because no aquifer was ever delimited there. The instrument sequence that the National Waters Act prescribes — publish availability, register concessions, compare, restrict — cannot begin in the Sierra Tarahumara zone, because its first step has no object. This is a distinctive kind of governance gap: not weak enforcement of an existing rule, but the absence of the administrative object the rule operates on, in exactly the places where the extractive pressure on local water is proportionally largest. It is also invisible at any aggregation level above the municipality, which is the methodological point of this paper: the same feature that makes mining negligible statewide (its spatial concentration) makes it dominant in particular places, and only an account kept at the decision scale renders both simultaneously. Comparable blind spots — mining pressure concentrated where water governance data are thinnest — have been noted globally (Lèbre et al., 2020; Luckeneder et al., 2021), but the Chihuahua case is unusually sharp because the missing instrument is a statutory prerequisite.

5.3. Quantifying the floor the law left open

The 2025 General Water Law obliges utilities to guarantee a minimum vital without saying how much it is; the Supreme Court has begun filling the number in case by case (SCJN, 2026). Our results give that choice a quantitative stake it does not have in the legal debate: at 50 L the floor is 2% of the state ceiling and no large city's development space is at risk; at 100 L the capital sits exactly on its threshold and Juárez crosses it; at 150 L Juárez's floor can exceed its entire renewable ceiling. The floor choice is, for the two largest cities, the single most consequential lever in the entire scenario space — larger than climate, demography, or mining combined. This connects the jurisprudence of the human right to water (Martínez-Austria and Vargas-Hidalgo, 2017) to allocation arithmetic: an enforceable 100 L standard is not merely a service obligation on utilities, it is an implicit reallocation of renewable water away from economic entitlements, and courts quantifying the right are, in effect, setting the social floor of a state-level operating space. Making that arithmetic visible to the actors involved is precisely what a transparent municipal account is for.

5.4. The energy transition, tested and complicated

Chihuahua was selected partly to examine the expectation that transition-mineral demand will intensify water competition in arid mining regions (Meißner, 2021; Northey et al., 2017; Sonter et al., 2020; IEA, 2024). The expectation survives only in heavily qualified form. The demand signal exists — copper demand rises by a third in the IEA scenarios — but in this region it lands on a metal mix dominated by gold and silver, which carry three quarters of the mining water and no transition driver. High Demand raises state mining water by 7% over Stated Policies; the intensity parameter moves it by a factor of four. Two conclusions follow. Analytically, regional assessments of transition-water pressure should decompose the local metal mix before importing the global narrative; a silver-gold district's water future is set by precious-metal markets and by mining technique, not by decarbonization. Practically, the uncertainty that matters is measurable now: site-level water intensities from the operating mines would collapse most of the projection envelope, and the mining sector itself is the actor best placed to supply them — a concrete, low-cost transparency ask for a sector whose social licence in the Sierra increasingly runs through water.

5.5. Transferability and the case for open calculators

The approach transfers to any jurisdiction that publishes availability and use data at administrative scale — in Mexico, immediately to the other 31 states, since every data source used here (DOF availability decrees, CONAPO, SIAP, SGM, INECC) is national in coverage. Two design choices are the transferable core.

First, drawing both bounds from law rather than from analyst judgment changes the model's epistemic status: disagreement with its results is disagreement with the jurisdiction's own published numbers and adopted norms, not with our scenario taste. Second, implementing the account as a formula-transparent spreadsheet rather than a code base follows the FABLE Calculator's demonstration that spreadsheet models can support serious policy processes while remaining auditable by non-programmers (Mosnier et al., 2020, 2023; Howells et al., 2011). The audit history of this model argues for that choice from the inside: the errors that mattered — a name mismatch silently zeroing a municipality's ceiling, a crop coefficient imported from the wrong state, demographic multipliers with no reconstructable provenance — were all found because formulas and sources were inspectable row by row, and each correction is documented in the calculator's source sheet.

5.6. Limitations

Six limitations bound the claims. (i) The subregional surface-water allocation for the Bravo-Conchos system is an area-based assumption, not a published balance; it affects 41 municipalities and is flagged per municipality in the output. (ii) Municipalities are closed accounts: return flows and downstream reuse between municipalities are not represented, so municipal overdrafts cannot be netted against downstream space. (iii) Agriculture is frozen at the 2018–2022 pattern; the model measures the sustainability of the current cropping system, not of an optimized one, and represents no behavioural response to scarcity. (iv) Mining intensities mix concentrate-basis and refined-metal-basis coefficients (Northey et al., 2016), and gold's refined-basis coefficient applied to mine output likely overstates its water use — a conservative bias for our state-scale conclusion (mining smaller still) but a caution for the local shares. (v) Water quality is not represented, although arsenic in the central-valley aquifers effectively reduces usable supply below the accounted ceiling (Bencomo-Calderón et al., 2024). (vi) The climate signal enters only as a smooth multiplier on availability at a single horizon; interannual variability and extremes are outside the frame. None of these limitations touches the direction of the three robust findings; several — (iv), (v) — make them conservative.

6. Conclusions

Bringing the safe and just operating space down to the scale at which water is actually allocated changes what the analysis is about. At national or basin scale, Chihuahua's water question looks like scarcity under uncertain futures; at municipal scale, under every future in a 324-combination envelope, it resolves into three decided facts and one open number. The decided facts: fifteen municipalities — the irrigated heart of the state — are past their renewable space under all assumptions, by about a fifth of the state's renewable water; mining can never register at state scale yet is the dominant water user in Sierra municipalities; and those municipalities are precisely where the legally required allocation instrument, a delimited aquifer, has never existed. The open number is the minimum vital: whether Mexico's enforceable floor settles at 50, 100 or 150 L per person per day will do more to determine the accounted water future of Ciudad Juárez and the state capital than climate, demography and mining together. The state's water future, in other words, will be decided in concession registries and courtrooms rather than in the scenario space — and a municipal account with both bounds drawn from the country's own law is the instrument that makes that legible. The calculator, its manual and its full source documentation are released with this paper so that the account can be re-run, contested and extended by the authorities, communities and companies whose water it counts.

CRediT authorship contribution statement

Isabel Rodriguez Peña: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Katya Pérez-Guzmán: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Jordi Vera Cartas: Conceptualization, Methodology, Data curation

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The calculator (Excel workbook with all data, parameters, sources and formulas), its user manual, and the scenario-sweep replication code are available as supplementary material / in a public repository [REPOSITORY LINK TO BE ADDED]. All input data are from public official sources cited in the text and documented row by row in the calculator's source sheet.

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