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Article

Megacity Wastewater Poured into a Nearby Basin: Looking for Sustainable Scenarios in a Case Study

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Abstract: The megacities´ sewage creates socioeconomic dependence related to water availability in the nearby zones, especially in countries with hydric stress. The present paper studies the water balance progression of realistic scenarios from 2005 to 2050 in the Mezquital Valley, the receptor of Mexico City untreated sewage since 1886, allowing agriculture irrigation in unsustainable conditions. WEAP model calculated the water demand and supply. Validation was performed with outflows data of the Tula River and simulated three scenarios: 1st) Steady-state based on inertial growth rates, 2nd) Transient scenario concerned climate change outcomes, with minor influence in surface water and hydric stress in 2050; 3rd) Transient scenario perturbed with a planned reduction of 36% in the imported wastewater and the start-up of a massive Water Treatment Plant, allowing drip and sprinkler irrigation since 2030. In the 2005-2017 period, 59% of the agriculture depended on the flood irrigation with megacity sewage. The water balance scenarios evaluated the sectorial supply of the ground and superficial water. Drip irrigation would reduce 42% of agriculture demands, but still does not grant the downflow hydroelectric requirements, aggravated by the lack of wastewater supply since 2030. This research alerts about how present policies compromise future Valley demands.

Keywords: water demand; megacity wastewater; hydrological balance scenarios

1. Introduction

Megacities are considered Global Risk Areas and a sink of natural resources. Their sewage flows outside in huge volumes, and sustainable use mitigates water scarceness in the neighboring areas [1]. In the Middle East, Asian, and African regions with water scarcity, megacities are boosting, the agriculture sector increasingly demands water volumes, and water resources planning is a challenge to guarantee economic and social development [2]. The freshwater demands exceed 15-20% of the supplies, and the 2025 trends predict severe water shortages for two-thirds of the world´s population [3]. On a basin scale, water management needs multi-disciplinary integration [4].

Megacities water supply and management have been a research interest of policy scientists since recent years because of the challenge of securing water and sanitation services. In emerging countries, cities' growth rates are still increasing, and water management gets worse [5, 6]. However, the impact that large cities have on their proximity areas has had less attention. Megacities´ sewage is commonly used without treatment for agriculture irrigation despite the health risks and environmental damage [7, 8]. Although wastewater irrigation raises organic carbon and nutrients for improving crops, it promotes serious contamination risks to the groundwater and soil [9]. The World Health Organization [10] advice about the high concentration of pathogens and chemicals accumulation in soils, but still is a widespread practice in developing countries [11]. Water reuse applications have been accepted solutions with substantial challenges concerning water treatment technologies selection [12].

The hydrological models are useful tools for calculating water balances in case study scenarios. They are widely employed to understand and predict the local water cycle (occurrence, circulation, and distribution) and the future behavior of demand/supply issues based on realistic or hypothetical conditions as proposal adaptation actions. The results are relevant to water management and planning [13], and the model selection depends on the mathematical approaches, the available data, and the appropriate system representation. A comprehensive review of the most relevant hydrological models and features was published recently [14].

Climate change adds uncertainty modeling results due to lowering precipitation and rising temperatures, intensified in semi-arid regions [15]. Precipitation is the primary supplier in the water cycle, and the most affected by global change, causing rain intensity differences, floods, and droughts [4]. Rain infiltration and surface flows contribute to evapotranspiration output, whose proper calculation is essential for an accurate hydrological balance [3].

The Water Evaluation and Planning System (WEAP) is one of the most versatile predictive models for analyzing federal programs related to water scenarios. It integrates technical parameters such as demand, supply, infiltration, runoff, crop requirements, flows, storage, discharges, ecological issues [16], and the results allow the analysis of political actions. The web page displays plenty of papers and reports uploaded from the WEAP world community members [17].

The purposes of this work are i) to quantify how much the lack of suitable policy led to unsustainable management of megacity sewage, which supported the agriculture development in a nearby valley but caused enormous environmental damage. Water-depended neighboring areas are at the risk of been suppressed from the resources at the moment the governing board returns its treated wastewater as most cities do. ii) To achieve the hydrological balance of a case study, the Mezquital Valley and evaluate the dependence of the sewage received due to Mexico megacity proximity considering the basin complexity in terms of clean and wastewater, the sectorial water-supplier to industries, population, agriculture irrigation, services, the internal returns, and the final outflow that supports an hydroelectric dam. iii) To give a more in-depth insight into the past, current, and future balance scenarios based on local climate changes, planned events, and irrigation alternatives (2005, 2017, 2030 and 2050). This work will contribute to the understanding of the megacities assessment towards their immediate environment concerning their wastewater management. The impact is not equal in all countries, nor all cities. Its findings are the main contribution of this paper.

2. Materials and Methods

2.1. Study case

Mexico City is the 11th global biggest megacities in the world, located in the Mexican Central Plateau. It has a 20.8 million population [18] whose water infrastructure supply and sewage discharge systems were described in detail by [19, 20]. In the past hundred years, Mexico megacity untreated wastewaters are drained to the semiarid Mezquital Valley, becoming one of the most environmental impaired regions in the country. It is situated at 50 km north of Mexico City in the southwest part of Hidalgo State, between 19º45′ and 20º 40′N and 98º 44′and 99 º 36′W at 1910 - 2150 masl (meters above sea level). See Figure 1.

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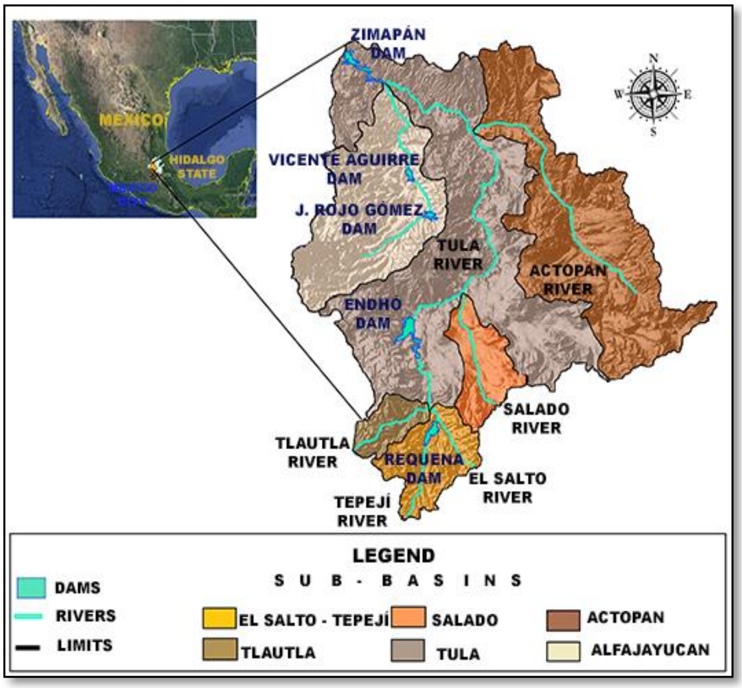

Figure 1. Mezquital Valley Basin located in the Central Mexican Plateau. Major rivers, dams, and six sub-basins delimited by the runoff criteria from the elevations map.

The Megacity proximity promoted the local economic development but caused environmental damages due to the unmanaged wastewater. In 2005, 711,450 inhabitants lived in 5,045 km^2 valley area, and 1663 Mm^3/y of untreated wastewater was supplied for agricultural flood irrigation [7].

Figure 2 shows the interaction of the valley with Mexico Megacity and the primary sewage supply sources. Three main flows convey the wastewater to the valley: a) The Great Sewage Channel (Gran Canal), constructed in the XIX century, affected by subsidence. So, wastewaters are pumped to the valley. It was improved in 1950 and expanded in the 2000 year. b) The Deep Sewerage Tunnel (Emisor Profundo) constructed in 1975 (153 km at 200 m deep) operates at 200-340 m^3/s with significant operational and maintenance problems. c) The 62 km underground East Transmitter 7 m diameter Tunnel (Emisor Poniente) start-up since the 60´s decade, renovated and enlarged in the last ten years. Also, the Tequisquiac and the Nochistongo Tagus tunnels join the Salado and El Salto Rivers, respectively [21]. A channel is constructing to connect El Salto River with El Salado River, to allow the water treatment of the later.

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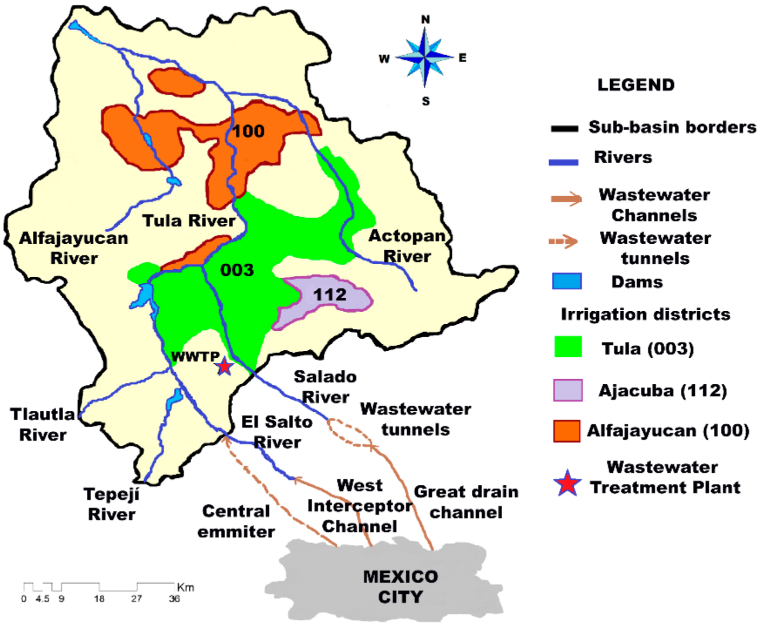

Figure 2. Schematic representation of the interaction between the Mezquital Valley and Mexico Megacity and the location of the irrigation districts in orange, green, and grey. The Central Emitter, West Interceptor, and Great Canal are the wastewater entrance. Note that Actopan and Alfajayucan Rivers are not linked with the Megacity, but receive the local wastewaters, poured without treatment. Adapted from free online [23]

Tula River is the mainstream of the valley, whose effluents El Salto and El Salado flow into it carrying the megacity wastewaters. The main rivers collect the rain runoff and local sewage from other secondary streams, supplying the water to the irrigation districts of the valley, and finally, the basin outflow heads towards the Zimapan hydroelectric dam [22]. El Salado River crosses the Mezquital Valley and merges with El Salto in the Requena Dam, creating the Tula River, which pours into the Mexican most significant Endho wastewater reservoir (200 Mm^3). It acts as a regulating/supply vase for the agriculture irrigation districts: Tula, Ajacuba, and Alfajayucan, through channel networks [23].

The irrigation permeates the soil and modifies the natural groundwater recharge. The reported irrigation rates range from 1500 to 2200 mm/y depending on crop and soil type [24](González-Méndez et al., 2014). Agricultural consumption reduces the final output, which flows to the Zimapan Hydroelectric dam, affecting its generation capacity.

There are many reports about the Mezquital Valley environmental damage, such as water pollution [25, 26, 27, 28, 29]; agriculture emissions [24]; health risks [7, 30]; soil degradation [31] and pollution [32, 33, 34]; unsustainable agricultural practices [35, 36, 37, 38], among others.

Recently, the Federal Government fulfilled the construction of a large wastewater treatment plant (WWTP) in Atotonilco de Tula, just at the entrance of the Valley, in the sewage input. Its lowest capacity is 23 m^3/s for the dry season, with an additional 12 m3/s unit for rainy times. The WWTP started operation at 30% capacity since 2017 (300 m^3/y) and would be 100% in 2020 [39, 40, 21]. The water balance studies in the Mezquital Valley has been focused on groundwater, with unusual shallow aquifer replenishment due to unmanaged recharge [41, 23]. There are no reports about the internal fluxes and interactions in the water cycle, as well as prospective analysis of water use.

2.2. WEAP Model

The Water Evaluation and Planning System (WEAP) is considered a conceptual model for the physical system and the character of the models used for describing the hydrological processes. The natural and technical components of the system are represented in a network-like scheme with inter-connected model elements. The WEAP model allows user-defined demand priorities, preferences

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and environmental requirements for the various nodes. The water allocation problem is solved using linear programming on a daily or monthly basis. For estimate evapotranspiration, runoff, interflow, baseflow and percolation the model uses empirical equations [42].

2.2.1 Assumptions for the baseline scenario (2005)

- The valley is considered as a basin which compiles a set of six adjacent sub-basins. Figure 1 shows the elevation map of the area, which delimits sub-basins. The GIS layer depicts six sub-basins: three small ones at the southern part (Tlautla, Tepeji-El Salto, and El Salado Rivers) and three bigger ones at the center and north (Actopan, Alfajayucan, and Tula Rivers).
- The superficial wastewater importation from Mexico City enters in the southern part, through the El Salto and El Salado Rivers. Both flows will merge as a one-point entrance by the connecting channel between them.
- - The startup of WWTP in Atotonilco de Tula occurred in 2017 with a 30% capacity and will be 100% since 2020. It treats about 60% of the imported sewage at its maximum capacity.
- There are shallow and deep aquifers. The last ones are not contaminated by the internal wastewater returns from the surface (rivers, channels, and irrigation), as reported by [23, 28]. Sewage infiltrates the shallow aquifers which supply agriculture demands in areas outside the irrigation districts.
- The model considers six aquifers based on the orography, which determines the catchment zones. It does not assume the political division criteria reported by [23].
- The value of consumptive water for each irrigation districts was distributed and divided by the area, based on the official reports [43]. The consumptive water use for individual crops was considered the same.
- Since 2020, the wastewater importation from Mexico City will be allocated in 31% to the Mexico State. Scenario # 3 considers this sharp reduction as a realistic transient scenario.

The WEAP program provides the mathematical expressions which best fit with the conceptual model assumptions and aims.

2.2.2 Schematic model

The WEAP module "schematic" allowed to draw the model diagram, representing the mainstream Tula River in a south-north flow direction, secondary streams, water importations, water supply sources, reservoirs, demands, and their interactions [16].

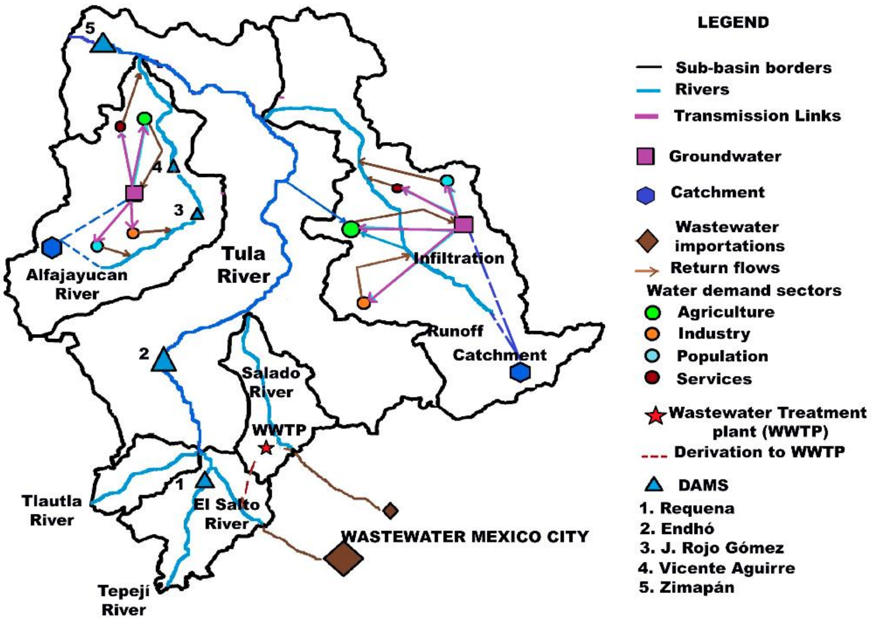

Figure 3. Basin conceptual model drawing by WEAP "Schematic" module.

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2.2.3 Data Model

Module "data" required the following input information: water supply and demand sites for surface and groundwater (domestic, agriculture, industrial, and service sectors) [43]; cover vegetation, land use [44], crop coefficient (Kc) [45, 46]; monthly precipitation and temperature [47]. Evapotranspiration (Eto), runoff, and infiltration were calculated to simulate the hydrological process by the "rainfall-runoff" module in the WEAP simulation platform [48].

Tables 1S, 2S, 3S, and 4S (Appendix A) show the input data used for the calculation with the mathematical tools of WEAP.

Water Supply Sources. The groundwater recharge considered the rainwater infiltration and irrigation water returns. The total surface water included the rain runoff, imports from the megacity, and domestic wastewater generation.

Cover Vegetation. The vectorial shapes of land use information [49, 44] were classified and quantified by the Quantum GIS program. Table 1S shows the data of urban sprawl, water bodies, and vegetation areas in each sub-basin and the whole Mezquital Valley. The agricultural areas are predominant (42.6%), followed by forest (29%), pastureland (17.6%), and urban areas (10.7%).

Runoff and infiltration coefficients estimation. Equation 1 calculates the infiltration coefficients (Ci) [50].

$$Ci = (Kp + Kv + Kfc) \tag{1}$$

Where Kp, Kfc, and Kv are the infiltration fractions corresponding to the slope, soil type, and vegetation cover, respectively. See Tables 1S, 2S, and 3S.

The runoff coefficient (Ce) was calculated by Equation 2 [51]. See table 4S.

$$Ce = 1.0 – Ci, \tag{2}$$

Climate data: Precipitation, temperature, and evapotranspiration (ETo). Eleven meteorological stations located in the valley provided the climate information, by the ERIC Fast Data Extraction Program [52]. Low precipitation occurred from May to October (450 to 550 mm/y). Mean temperatures range between 15 to 19°C.

Evapotranspiration (ETo). It was calculated monthly in the base year (2005) with the standardized Penman-Monteith method [53] (Equation 3), considered the best daily and monthly estimation for ETo [54].

$$ETo = \{[0.0408\Delta+(\gamma*(900/(T+273))*u2*(es-ea)]/[\Delta+ \gamma*(1+0.34u2)]\} \tag{3}$$

The Equation 3 includes parameters related to the energy exchange and the heat flow under different vegetation areas, such as solar radiation (Ra, Rn), air temperature (T), vapor pressure (ea, es), wind speed (u2) and psychrometric constant (γ) [55].

Mezquital Valley Crops. The principal crops are maize (Zea mays), alfalfa (Medicago sativa), and bean (Phaseolus vulgaris) [56]. The crop coefficient (Kc parameter) considers the harvest period for each crop whose maximal yield values were calculated in kg/ha, considering the growing periods and water requirements [57] for oat [58], wheat [59], bean [60], barley and corn [45]. Alfalfa presents the highest yield [61, 62]. Table 2S shows monthly Kc values and crop yields [46].

Water Demand. CONAGUA's official website allowed the 2005 information of the water demand database [43]. Data was workup by sectors and divided into groundwater (GW) and surface water (SW) for each sub-basin, producing the input demand data shown in Table 5S.

Validation was performed by plotting the 2005 - 2010 period calculated (WEAP) Tula River annual output vs. experimental Tula River outflows data assessed in the Ixmiquilpan Hydrometric Station, near the output of the basin [21]. See Figure 1S.

2.2.4 Scenarios: steady-state and transient conditions

The hydrological balance scenarios were simulated for 2017, 2030, and 2050 by the WEAP model:

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(#1) Steady-State Scenario. It simulates the inertial tendency (BAU, Business as usual), even though it includes the WWTP start-up since 2017. Table S2 shows the population projections data [63]. The industrial growth rates were from Mexican Business Information System [64]: chemical 0.45 %; textile3%; food 3.7%; metallurgical 3.7%; lime and cement 2.5%. The irrigated areas expansion was assumed to equal to the crop annual growth rates (maize 1.7%; beans 0.88%; alfalfa, forages, and vegetables 1.27%) [45].

(#2) Climate Change Scenario. It considers Scenario #1 + climate change perturbation. The average temperature would increase 2°C from 2005 to 2050 [65], and precipitation would decrease by 6.5% from 2000 to 2030 (0.06% per year) [66].

(#3) Adaptation Scenarios. The perturbations are related to irrigation alternatives and sewage import reduction. It considers Scenario #2 + decreased wastewater imports + each irrigation technology. It is the most likely scenario, with a 36% decrease in wastewater imports since 2020 due to five sewage treatment plants start-up, and Mexico State will catch 606 Mm^3/y. Also, the imported surface water will fit the quality requirements for sprinkling and drip irrigation technologies that will be analyzed separately since 2020, instead of the current flood irrigation with water savings of 25% and 43%, respectively [67].

3. Results and discussion

3.1 Model validation

The Tula River calculated outflows (WEAP) show a significant linear correlation with the experimental data (R^2 = 0.9525) with 95% confidence (Figure 1S in Supplementary Material). Experimental outflow data were the official reported values for each year in the same period (2005 – 2010) [21]. The outflow values have been slowing down along the time due to the rising temperature, lowering precipitation, unsustainable and uncontrolled flood irrigation, and agriculture development.

3.2 Model boundaries result in the base year 2005 (baseline)

Water supply sources and inflows. Figure 4 shows the primary data for each sub-basins of the Valley. The infiltration values were 10 - 14.6% of total precipitation, and the runoff ranged between 7.3 and 10.5%. The rainwater evaporation results matched with the reported 76% for the Mexico Basin [43]. The rainwater infiltration and the irrigation water returns add into the natural groundwater recharges. The Tula and Salado River sub-basins encompass the most extensive irrigation areas, and their water returns collect 35% total recharge. The surface water included the rainwater runoff, the local sub-watersheds sewage, and the imported wastewater from Mexico Megacity (main contribution, 1,536 Mm^3). The baseline depicts unsustainable agriculture, with untreated wastewater flood irrigation.

Water demand and outflows. The surface outflows were the evapotranspiration, and the waters conveying to the Zimapán Dam. The primary internal consumptions occurred by the agriculture irrigation districts, fulfilled by domestic sewage and the imported wastewater (59%, 831 Mm^3). Watersheds imported water consumption were Tula 36%, Actopan 9%, Salado 8%, and Alfajayucan 6%). Figure 3 shows the balance results.

The surface outflow pours downstream into the Zimapán hydroelectric dam (839 Mm^3). The result is comparable to the annual concessioned volume (851.2 Mm^3) for electric generation in 2005 [43]. The difference might be due to losses in evaporation calculation.

El Salado sub-basin groundwater presented strong overexploitation (-60 Mm^3), whose withdrawals are 330% higher than the groundwater recharge; because of the industrial sector and population. Tepeji-El Salto aquifer was in equilibrium, despite the Tula-Tepejí manufacturing region, whose population and industries withdrawal 95% of the total groundwater recharge. The remainder aquifers presented sustainable management with a low withdrawal/recharge ratio: 10% Alfajayucan, 27% Tlautla, 43% Tula, and 53% Actopan (Figure 4).

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Freshwater availabilities. The rain infiltration accounted for 473 Mm3 for 711,450 people in the Mezquital Valley. El Salto - Tepejí and Salado sub-watersheds presented absolute scarcity (< 500 m3/pers/y), based on the Falkenmark indicator. The Tula and Actopan River sub-basins were in stress condition (<1700 m3/pers/y). The other sub-basins were without stress as they are sparsely populated. The average freshwater availability for the Mezquital Valley was 952 m3/pers/y, in stress condition.

Those results lead to the following considerations:

- A sub-basin analysis is needed for management policies as their characteristics are not the same.
- Freshwater caption and its contamination prevention should be underlined in special programs for sub-basins El Salto – Tepeji and Salado.
- 59% of the imported untreated wastewater supports the agriculture irrigation of four sub-basins. So, the soil recuperating programs and remediation technologies, with particular emphasis on the Tula sub-basin.
- There is a misleading thought that rain is the first water input and support of valley agriculture because of the unsuitable evaluation of evapotranspiration.
- Despite the giant WWTP started the water remediation, the Actopan and Alfajayucan sub-basins are not benefited, and they need different local policy plans.

3.3 Transient conditions results

3.3.1 Scenario # 1. Steady-state (reference)

The scenario considers the same unsustainable 2005 conditions, worsened by the inertial growth in the industrial, residential, and agriculture sectors. Although it includes the WWTP start-up in Atotonilco de Tula, it does not affect the quantitative results but allows a gradual improvement in the surface water quality for agriculture irrigation since 2017. Figure 4 shows the trends of demands, inflows, and outflows for superficial and groundwater. Table 1 depicts the calculated values for the years 2030 and 2050.

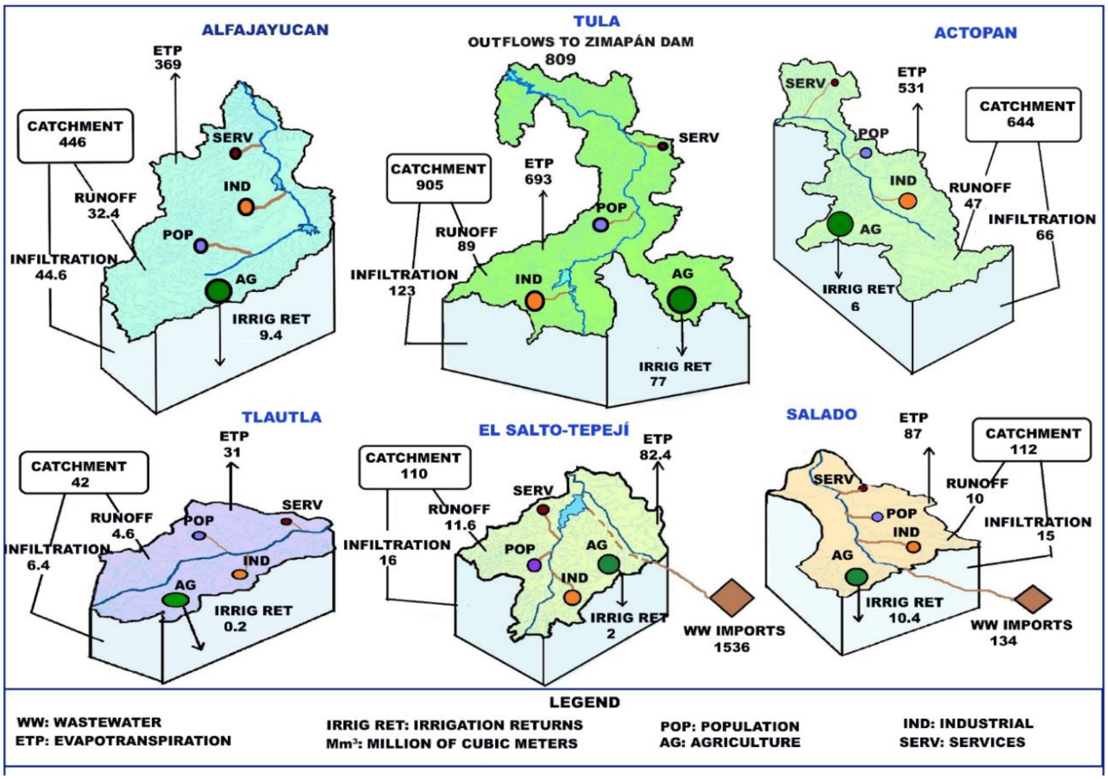

Figure 4. Calculated results in the sub-basins of Mezquital Valley in the baseline year 2005. Values in Mm³.

Table 1. Results of Transient Condition Scenarios. Water inflows and outflows in the Mezquital Valley (Mm^3/y)

Scenario	Name	Description	Source	2017		2030		2050	
				Inflow	Out-flow	Inflow	Out-flow	Inflow	Out-flow
1	Steady-state	Population, industrial and irrigation growth rates lead the water demands	Ground water	391.6	267	408.6	313	431	403
			Surface water	1925	1294	1931	1524	1944	**1966**
2	Reference + Climate Change effect	Rain infiltration and runoff gradually decrease up to 6.5% in 2050.	Ground water	371	267	363	313	353	**403**
			Surface water	1914	1294	1908	1524	1900	**1966**
3	Wastewater splits to other state + new irrigation technologies	Wastewater inflow falls 31% in 2020 and irrigation demand gradually decreases up to 45% in 2050	Ground water	341	267	350	310	350	**370**
			Surface water	1670	1294	1338	830	1338	667

In bold: The water demands (outflows) surpass the availability (inflows: water inlets + groundwater recharge)

Groundwater. Inertial demands will grow by 37% in 2030 and 76.5% in 2050. The population and agriculture needs will increase by 52% while the industrial, the most demanding sector, will rise by 60% (Figure 5a). In 2050, El Salado and Tula sub-basins would be the most water-consuming in the valley (38% and 35% respectively), as they are the most populated and industrial developed, followed by Actopan and El Salto (15% and 8%). The four sub-basins compile 96% of the valley demands. The Alfajayucan and Tlautla River groundwater use is low (< 5%) due to the minor population. Figure 5b shows El Salado sub-basin as the strongest overexploited groundwater since 2017, becoming worse in subsequent years. The Mezquital Valley impaired water management endangers the aquifers, and urgent plans should guarantee the sustainable use of groundwater resources.

Surface water. Agriculture irrigation is the most demanding in the Valley. Figure 5c shows the sector growth demand from 2005 to 76% in 2050. The irrigation districts in the Tula and Actopan sub-watersheds will consume 72% of total surface water demand. In contrast, the Alfajayucan district consumption is merely 12%. The irrigation areas expansion would increase the imported wastewater demand by 75% in 2030 and 100% in 2050, reducing the Tula River outflows, so that the Mezquital Valley would have deficit circumstances (Figure 5d).

The inertial scenario demonstrates the needs of action programs leading to sustainability and rational use of the water. The demands would be unmet.

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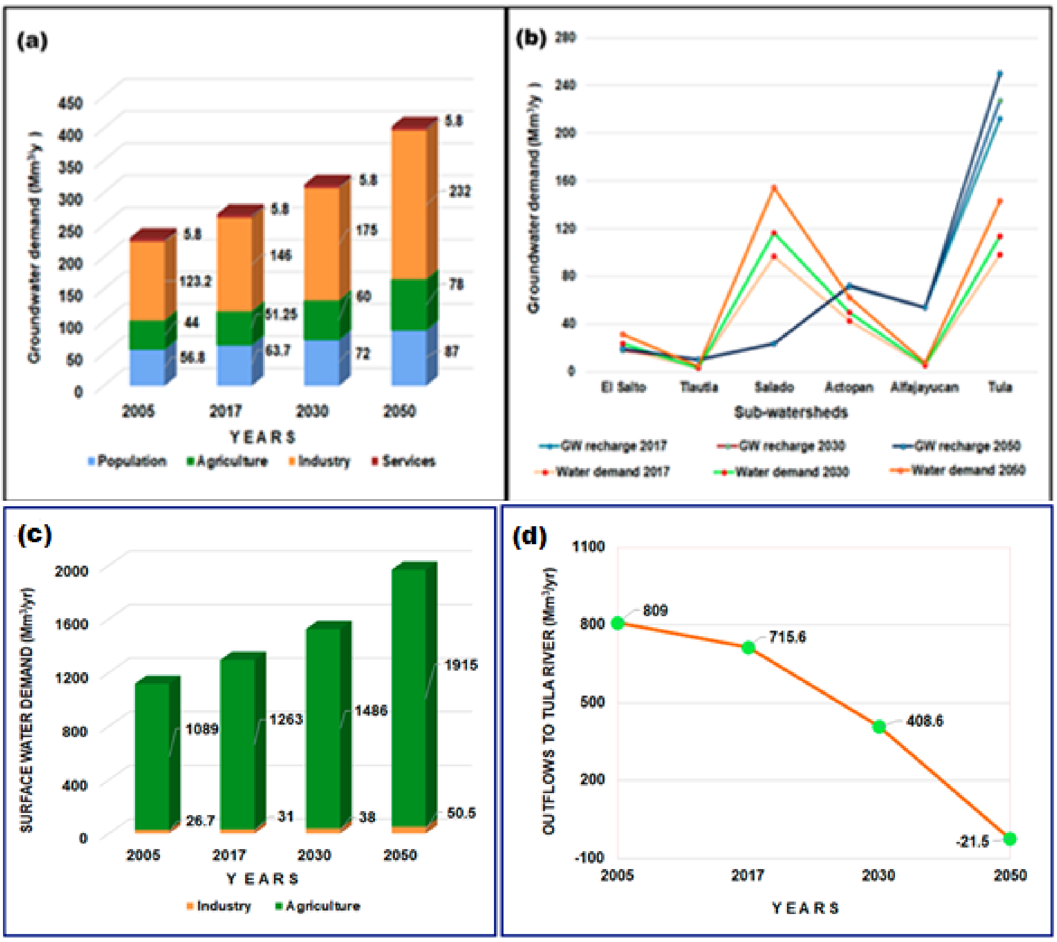

Figure 5. Scenario 1, Steady-state. Calculated results in the Mezquital Valley. Values in Mm³/y. a) Sectorial groundwater demands, with industry relevance. b) Yearly recharges vs. demands for each sub-basin, where El Salado presents the highest hydric stress. c) Sectorial water surface demands dominated by agriculture. d) Tula River calculated outflow presents a sharp decline after 2017.

3.3.2. Scenario # 2. Climate Change perturbations

The scenario considers the same conditions as scenario 1, worsened by climate change overcast. The analysis is focused on the natural freshwater availability impacted by the predicted local climate conditions in the Mezquital Valley, a 2°C temperature rise and a 6.5% precipitation drop in 2050 [65]. Table 1 shows the calculated inflows and outflows for each year.

El Salto, Tula, El Salado, and Actopan sub-basins show the highest water scarcity. The freshwater availability decreases along the timeline, and the Alfajayucan and Tlautla sub-basins turn to hydric stress after 2030 availability decay. See Figure 2S.

Groundwater. So, the calculated annual rainwater in the region would fall from 2290 Mm³/y in 2005 to 2140 Mm³/y in 2050 and, consequently, 10% runoff and infiltration reduction in 2050. Although evapotranspiration would rise 1% due to a higher temperature, its values decrease because of the precipitation decay. The runoff and infiltration reduce the groundwater recharge, the surface water inlets, and, therefore, the water supply and the outflow.

Surface water. The calculated surface volumes for agriculture irrigation surpass the potential supply, as well as Scenario 1. The influence of climate change in the surface water would not be so significant as long as the sewage importation continues. Generally, semidesert and desert zones bias climate change effects, due to the already existing hydric stress, such as the scenario results [68].

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3.3.3. Scenario # 3. Imported wastewater reduction and adaptation actions perturbations. Sparkling and drip irrigation technologies.

Scenario #3 is the most realistic. It considers the same conditions as the previous scenario, including the 593 and 606 Mm^3/y reductions of the imported wastewater from Mexico City. The volumes split towards new WWTP in Mexico State since 2020 with aggravating water lacking. As in China, centralized water management integrated the wastewater claims into a water resource allocation agreement by the Federal Government [69].

Two irrigation strategies implementation were calculated separately (sprinkling and drip), allowing water savings. Table 1 displays the calculated inflows and outflows for 2030 and 2050. Figure 6 shows the irrigation reductions of the surface water demand (sprinkler 227 Mm^3/y and drip 473 Mm^3/y). Drip irrigation resulted in more efficient than the sprinkler one, reducing 42% of demand requirements.

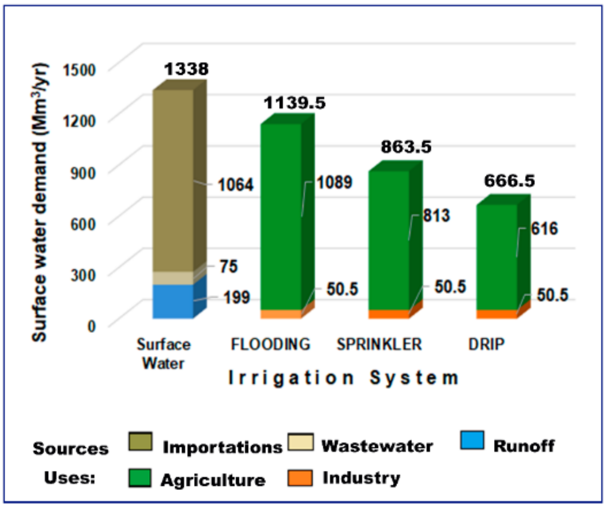

Figure 6. Scenario 3 calculated results for the 2050 year. Wastewater importation from Mexico City reduced 660 Mm3/y, and adaptation actions are the irrigation alternatives in the Mezquital Valley. The importation is the primary source of surface water, and the domestic wastewater is near 1%. Drip irrigation appears to be the most efficient.

The drip irrigation might fulfill the surface water demand for agricultural activities in 2030, but the volume delivered to the Zimapán hydroelectric dam would not. So, it would be not enough, and decisionmakers should program sustainable intensive agricultural practices.

3.4 Mezquital Valley hydrological balance scenarios. Flow diagrams.

Figure 7 shows the hydrological balance flows in Sankey diagrams for the baseline and the 2050 prospective scenarios.

Baseline. In 2005 (Figure 7a), water supplies and untreated wastewater importations were sufficient to fulfill the volume engaged to the Zimapán hydroelectric dam (606 Mm^3). Agriculture irrigation is the primary internal flow, and evapotranspiration is the most significant outflow. Precipitation does not fulfill the surface water demands, so the wastewater importation guarantees the agriculture development, in unsustainable conditions. The groundwater balance computes a net 149 Mm^3/y recharge.

Steady State, 2050. The hydrological balance (Figure 7b) predicts a surface water lack due to the inertial growth. The agriculture irrigation demands 98.5% of the total surface water, and the outflow to the Zimapan dam might fade away with -21.5 Mm^3 deficit, jeopardizing the hydroelectric production. The groundwater balance is almost in equilibrium, but the lack of surface water results in overexploitation risk.

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Climate change, 2050. The balance (Figure 7c) forecasts a precipitation drop, lowering the rainwater inflow and depleting 7% of water supply. So, agriculture would consume 99,5% water surface and total lack of supply for the hydroelectric production (outflow deficit: -40.5 Mm^3). The groundwater balance results in mild overexploitation of -17 Mm^3/y.

Drip irrigation, 2050. It includes a wastewater inflow reduction due to a 36% withdrawal from new treatment plants in Mexico State, worsening the scene. The balance (Figure 6).

d) includes drip irrigation to lower agriculture needs, the most water demanding sector, but the committed water for Zimapán Hydroelectric Power Plant (989.2 Mm^3) [70] would not be fulfilled (177 Mm^3). The surface impairment menaces the groundwater (overexploitation -12 Mm^3), and the scenario state an alert for the policymakers to focus on intensive agriculture.

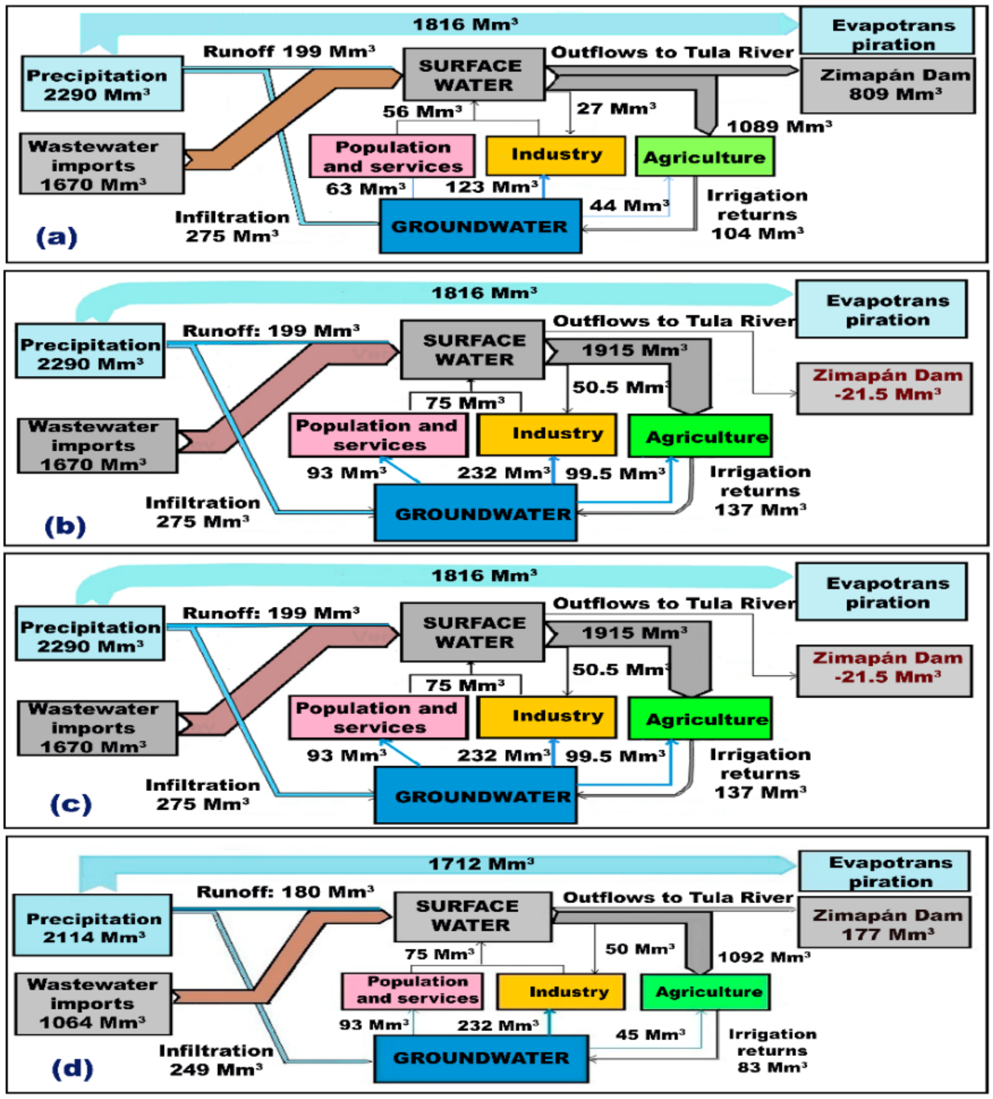

Figure 7. Flux diagrams for hydrological balance scenarios in Mezquital Valley. Surface and groundwater annual fluxes (Mm3/y). a) Baseline, 2005. b) Scenario 1: Steady-state reference, 2050. c) Scenario 2: Climate change, 2050. d) Scenario 3: Climate effects and drip irrigation, 2050.

4. Conclusions

The paper illustrates the environmental damage of big cities wastewaters to the surrounding areas when the sewage is managed in unsustainable conditions.

This work studies a basin next to Mexico City as a case study. It calculates the water balance in simulated outcome scenarios, separating waste and freshwater use and disposal for the industrial, agriculture irrigation, and population/services sectors. The conceptual model disaggregates the valley in sub-basins, which were calculated by the WEAP model, with suitable calibration, even though the complicated basin outlook. Flow diagrams could be depicted for the 2005 baseline and future scenarios, considering internal returns and external inflows and outflows. The results were revealing and warned about the urgent need for efficient irrigation, modern agriculture techniques, and the internal recycling of industrial water.

A recognized paradox is demonstrated and quantified. The principal source of surface water is the wastewater importation from Mexico Megacity and not the runoff because the evapotranspiration represents 79.2 % of the total precipitation. Rising demands of surface water would cause the insufficient hydroelectric power plant requirements since 2030. The agriculture irrigation is the most demanding sector, as much as 58% of sewage waters in 2005, while in 2050, it would not be enough despite the introduction of efficient irrigation technologies.

Climate change will increase the hydric stress, but the effect on the surface water is negligible. In contrast, the Wastewater Treatment Plants in Mexico State subtraction of the imported surface water worsens its availability. Moderate groundwater overexploitation is predicted to 2050 (-12.5 to -38.5 Mm3/y), but the forecast surface water deficit would be a risk to the deep aquifers, leading to more intense overexploitation.

The unsustainable conditions and lacking political practices caused environmental damage for more than one hundred years. Although adaptation programs are designing for water management and ecosystem restoration, this research alerts about future unsolving demands based on predictive scenarios of water balance modeling. This paper contributes to the knowledge of the environmental damage in the megacity´s near surroundings due to the unsustainable sewage management.

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Appendix A

Table 1S. Water bodies, urban and vegetation cover areas (%) in the sub-watersheds of the Mezquital Valley Basin.

Sub-Watersheds rivers	Area (km^2)	%					
		Water bodies	Urban	Temporal agriculture	Irrigation agriculture	Pasture land	Forest & scrub
Tlautla	172	0.0	9.0	14	23	33	21
El Salto-Tepejí	260	1.15	8.5	13	23	33.5	21
Salado	275	0.0	21	38	15	5.5	20.5
Alfajayucan	850	0.8	1.2	12	22	25	39
Actopan	1320	0.0	7	11	27	8.0	47
Tula	2168	1.0	16	29	20	12	21
Mezquital Valley Basin	5045	0.1%	10.7%	42.6%		17.6%	29%

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Table 2S. Parameters used for the Infiltration coefficients Kfc and Kp calculation

River sub-basin	Texture soil			Kfc	slope (%)	Kp
	Sandy	Silty	Clay			
El Salto-Tepejí	35	60	5	0.315	22.3	0.15
Tlautla	28	68	4	0.33	18.66	0.2
Salado	30	67	3	0.33	10.02	0.2
Actopan	35	62	3	0.32	16.57	0.2
Alfajayucan	45	53	2	0.30	14.07	0.2
Tula	32	66	2	0.33	18.75	0.15

Table 3S. Parameters used for Kv determination

River sub-basin	Urban areas	Agriculture	Pastureland	Forest &scrub	Water bodies	Kv
El Salto-Tepejí	8.50	36.00	33.50	21	1.15	0.12
Tlautla	9.00	37.00	33.00	21	0.00	0.12
Salado	21.00	53.00	5.50	21	0.00	0.09
Actopan	7.00	38.00	8.00	47	0.00	0.11
Alfajayucan	1.20	34.00	25.00	39	0.80	0.11
Tula	16.00	49.00	12.00	21	1.00	0.10

Table 4S. Ci and Ce values of Mezquital Valley sub-basins

River sub-basin	Kfc	Kp	Kv	Ci	Ce
El Salto-Tepejí	0.315	0.15	0.12	0.59	0.42
Tlautla	0.33	0.2	0.12	0.65	0.35
Salado	0.33	0.2	0.09	0.62	0.38
Actopan	0.32	0.2	0.11	0.63	0.37
Alfajayucan	0.30	0.2	0.11	0.61	0.39
Tula	0.33	0.15	0.10	0.58	0.42

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Table 5S. Groundwater and surface demand in the Mezquital Valley sub-basins for the year 2005.

River sub-basin	Groundwater demand (Mm³/y)					Surface water demand (Mm³/y)		
	Population	Agriculture	Industrial	Services	Total	Agriculture	Industrial	Total
El Salto-Tepejí	6.3	2	8.4	0.4	17.1	18.4	3.3	21.7
Tlautla	1.1	0.3	1.5	0.1	3	5.5	0.8	6.3
Salado	6.9	4.6	69.5	0.8	81.8	125	0.5	125.5
Actopan	13.8	20.8	2.2	0.6	37.4	175	0.1	175.1
Alfajayucan	3	1.7	0.3	0.1	5.1	135	1.6	136.6
Tula	25.7	14.8	41.4	4	83	630.1	20.7	645
Total	56.8	44.2	123.3	6	230.3	1089	27	1116

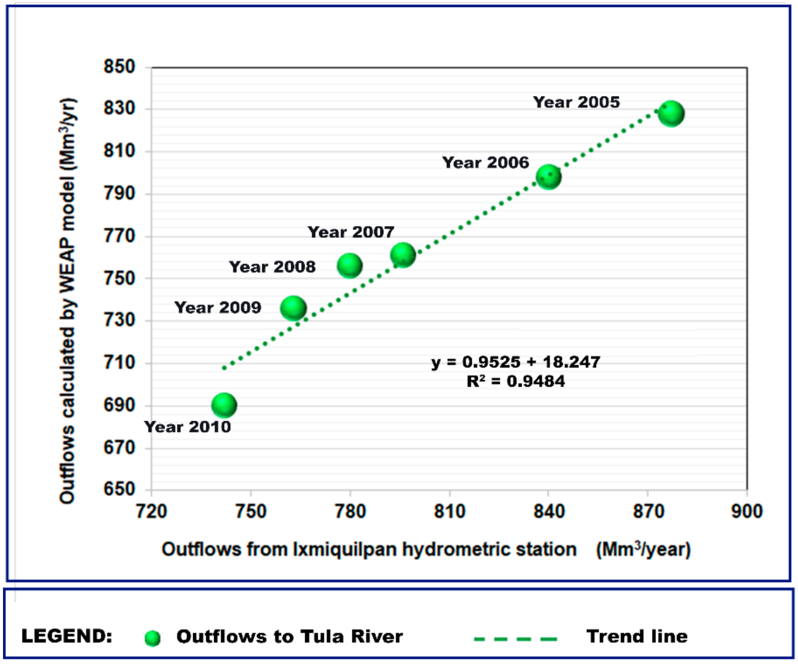

Figure 1S. WEAP model validation. Comparison between model outflows in Tula River vs. experimental data assessed in the Ixmiquilpan Hydrometric Station in the 2005 – 2010 period.

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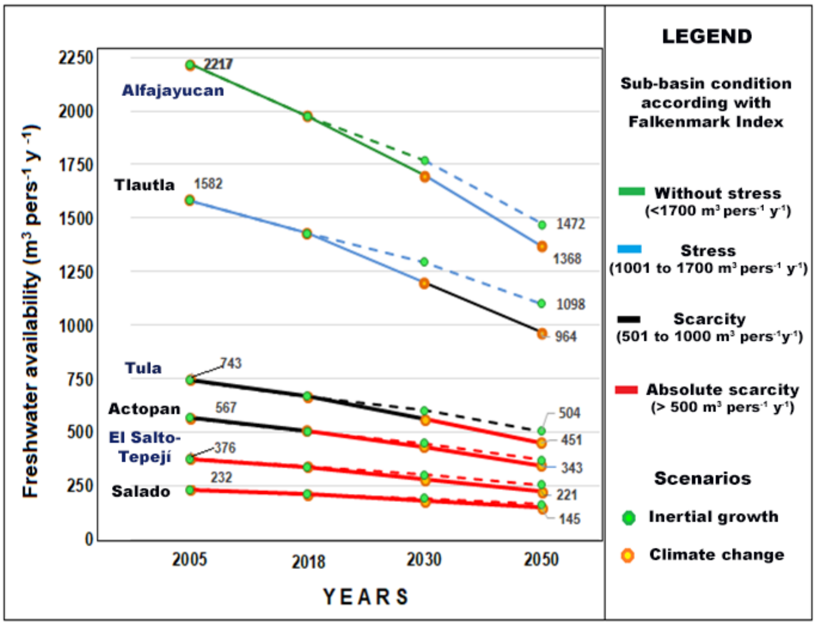

Figure 2S. Freshwater availabilities in Mezquital Valley sub-basins in the 2005 - 2050 period. Dashed lines only concern inertial growth rates (Scenario 1). Continuous lines consider inertial growth rates plus climate change conditions (Scenario 2)

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