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Advancing Sustainable Mining Through Inclusive Water Security Assessment: A Comparative Analysis in Colombia and Palestine

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Abstract

This study analyses the impact of mining activities on water scarcity in two contrasting mining regions: Zaragoza, Colombia, and Qabatiya, Palestine. Despite significant climatic and hydrological differences, both regions face substantial pressures on water resources and governance systems caused by mining. To assess these pressures on water security, the Water Poverty Index (WPI) has gained the attention as a holistic tool; however, its application in regions dominated by informal extractive economies presents a critical scientific gap; standard WPI methodologies rely heavily on low-resolution, macro-level secondary data, which inherently smooths out localized socio-environmental crises and creates a "compensation bias" in which temporary economic inflows mask severe ecological degradation. Furthermore, conventional frameworks fail to capture the dynamics of informal hydro-social governance, territorial conflicts, and non-conventional pollutants that characterize data-scarce extraction zones. To address this gap, this study applied four versions of the Water Poverty Index (WPI), Conventional, classic-inclusive, geometric, and arithmetic, to evaluate longitudinal changes between 2010 and 2025 under counterfactual baselines versus active extraction scenarios. The framework assessed six components: Resources, Access, Capacity, Use, Environment, and Cohesion, integrating both quantitative indicators and qualitative evidence. Results revealed that mining consistently reduced WPI performance in both localities, particularly within the Environment, Use, and Cohesion dimensions. Zaragoza exhibited a generalized decline across all WPI versions due to mercury contamination, institutional fragility, and social fragmentation associated with informal alluvial gold mining. At the same time, Qabatiya saw moderate infrastructure improvements, offset by groundwater depletion and environmental degradation from stone quarrying. The iWPI versions demonstrated superior sensitivity in capturing governance and socio-environmental degradation. The study concludes that water poverty in mining regions is multidimensional and driven by interconnected environmental, institutional, economic, and social pressures (as measured by the WPI), rather than by physical water scarcity alone.

Keywords: community based; inclusive water poverty index; SDG #6; sustainable mining

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1. Introduction

Mining activities exert profound and multifaceted pressure on hydrological systems, leading to the depletion of local freshwater supplies through intensive extraction and the chronic contamination of both surface and groundwater. Key impacts include the generation of corrosive acid mine drainage, the leaching of toxic heavy metals, and the permanent destabilization of natural hydrodynamics and sedimentation patterns [1,2]. However, conventional assessment frameworks that rely primarily on water quantity indicators, often comparing available flow against industrial demand, fail to reflect the comprehensive magnitude of these disruptions [3,4]. Such metrics frequently overlook the long-term degradation of water quality and the resulting loss of biodiversity, which can render remaining resources unfit for agricultural or domestic use and disenfranchise local communities. Consequently, there is an urgent need to develop and implement multidisciplinary tools that integrate hydrochemical, ecological, and socio-economic variables. Only through such a comprehensive stewardship approach can researchers and policymakers move beyond fragmented data to accurately capture the cumulative impact of mining on basin health and human well-being.

1.1. Gold Mining and Water Vulnerability in Colombia

As Colombia's leading mineral export, gold generated USD 3,886 million from January to November 2025—accounting for 39.9% of total mining exports—and supported 165,042 jobs nationwide [5]. Although the subsector is an economic cornerstone, it exhibits critical social dependency, with 45,151 registered subsistence miners in the Bajo Cauca Antioqueño district alone [6]. In Colombia, mining activities disrupts hydrological systems through wastewater, runoff, infiltration, and atmospheric pathways [7], with artisanal and small-scale gold mining (ASGM) acting as the primary driver of socio-environmental degradation [8].

Rudimentary mercury amalgamation pushes heavy metal levels past national and WHO thresholds [9–12], while alluvial extraction and absent WASH infrastructure introduce turbidity, suspended solids, and pathogens [4]. These combined pressures elevate health risks, impair drinking water, heighten perceived degradation, and erode traditional farming and fishing livelihoods [13–15].

From a consumption perspective, ASGM is water-intensive, requiring between 0.45 m^3 and 1.06 m^3 of water per gram of gold produced [4]. This demand is further aggravated by the structural absence of formal WASH infrastructure in mining communities [13].

While previous studies applied Water Footprint metrics [16], SARWIM models [17], and ethnographic approaches [11,18], governance relies on unadapted international guidelines [13]. Compounded by scarce baseline data [17,19], community mistrust, and scepticism [11,17], technical risk assessments remain detached from local socio-political vulnerabilities [18].

Existing evaluative frameworks fail to simultaneously integrate technical water indicators, local organoleptic perceptrons (e.g., turbidity, odour) [18], and the socioeconomic vulnerabilities of informal extraction into a single diagnostic tool. To resolve this gap, this study introduces and validates the Inclusive Water Poverty Index (iWPI) in Colombia, offering a multidimensional framework designed to translate baseline vulnerabilities into actionable state policy.

1.2. ASGM in Zaragoza, Colombia

The municipality of Zaragoza, located in Antioquia's Bajo Cauca subregion, covers 1077 km^2 with a population of 25,210 inhabitants (DANE census, 2018). Although agriculture and fishing offer alternative livelihoods, the local economy remains heavily gold-dependent, representing a historical core for artisanal and small-scale gold mining (ASGM) [20] that expanded rapidly after the late-2000s global price boom [9]. Between

2012 and 2023, Zaragoza produced 21,404,156 g of gold, accounting for 13% of the total output in the Bajo Cauca Mining District [6].

ASGM in Zaragoza (95.5%) is highly mechanized (76%, alongside 23% manual labour), utilizing an operational fleet of motor pumps (53%), mini-dredges (23%), heavy equipment (19%), and large-scale dredges (1%) [21]. The mining titles encompass 41.3% of the municipal territory (48,169.60 ha) [21].

The high level of extraction is predominantly driven by informal and small-scale operations, creating intense physical and socio-environmental pressures. These structural conditions establish the baseline needed to analyze the multidimensional water impacts documented across the territory.

1.3. Hydro-Climatic Profile and Water Vulnerabilities in Zaragoza

Zaragoza features a dense hydrological network fed by the Nechí, Porce, and Tiguí rivers, situated in a transitional zone of the lower Nechí River basin—the principal tributary of the Cauca River [22]. The area exhibits a humid tropical climate with mean temperatures of 28–30 °C and annual rainfall between 2000 and 4000 mm, underlain by both unconfined and confined aquifers [20].

Alluvial mining severely disrupts surface hydrology through altered runoff, heavy sedimentation, and artificial ponds. Compounded by global-peak per capita mercury contamination, evidenced by 47 urban processing sites (entables) in 2010 [23], this degradation exacerbates critical structural failures in drinking water and sanitation infrastructure, while deepening socio-political vulnerabilities like poverty, governance deficits, and armed conflict [20,24–26].

These baseline hydro-climatic and institutional constraints underscore the necessity of a comprehensive, multidimensional assessment of water impacts. Table 1 presents the multidimensional impacts of ASGM identified in the literature.

Table 1. Summary Table of Key Impacts of artisanal and small-scale mining.

Impact Category	Specific Effects	References
Environmental	Mercury in air, water, soils; high TSS; cyanide; wetland contamination; fish bioaccumulation.	[4,12,20,23,27]
Health	Neurological damage; respiratory illness; reproductive effects; occupational injuries.	[23,28–30]
Economic	Mixed poverty effects; low wages for miners; increased primary enrollment but lower college attendance.	[7,26,31]
Social/Conflict	Violence, massacres, forced displacement; illegal group control; human rights violations	[24,25,32]
Governance	Regulatory shortcomings; poor enforcement of the law; lack of information; environmental segregation; corruption.	[33,34]

Zaragoza and Qabatiya represent two global scenarios where economic dependence on mineral extraction comes into direct conflict with community water security. While in Colombia the challenge centres on multidimensional disruption caused by informal mining, in Palestine the pressure stems from water disruption due to pollution and high-water consumption in quarries; nevertheless, in both cases, social cohesion emerges as the critical asset that determines the territory's resilience, even in different climatic contexts. This similarity in human dynamics justifies a comparative analysis that seeks universal lessons on inclusive water management in areas influenced by mining.

1.4. Stone Quarrying and Water Vulnerability in Palestine

Ranking 12th globally, the Palestinian stone industry generates 600 million USD annually (4.8% of GDP) across 1361 facilities employing 25,000 workers [35]. Despite its economic weight, quarrying and processing exert severe environmental pressure, with quarries and crushers recording elevated impact scores of 756 and 751.2 out of 1000, respectively [36]. GIS-based spatial assessments confirm medium to high levels of physical damage across natural and built environments [36]. Operationally, the industry generates roughly 190,789 m^3 of dry, powdery waste annually, degrading air quality, land stability, water resources, and overall ecosystem health [36,37].

In terms of water balance, the sector incurs a high operational demand, consuming approximately 1,006,525 m^3 of water per year [37]. Water degradation is further critical as 40% of facilities discharge roughly 600,498 m^3 of untreated slurry water directly into the surrounding environment annually [37].

To mitigate these impacts, the literature emphasizes the urgent need for robust regulatory frameworks and spatial management [35–37]. Strategic recommendations focus on establishing a national spatial plan to govern facility siting, enforcing rigorous environmental licencing [35,37], and repurposing closed facilities into light industrial zones to preserve economic output while mitigating ecological decline [35–37].

While these spatial and policy recommendations target facility licencing and location, existing research lacks a comprehensive metric to assess how quarrying emissions and slurry discharges translate into localized water poverty. Applying the iWPI framework in Palestine addresses this gap by establishing an integrated assessment that links quarry-induced water stress directly to local hydro-social vulnerabilities.

1.5. Stone Cutting in Qabatiya Town

Situated 6 km south of Jenin in the northern West Bank, Qabatiya covers 50.5 km^2 (50,547 dunams) with a population rising from 19,197 in 2007 to 24,439 by 2017 (PCBS census, 2017). Traditionally agricultural, its territory now features fertile olive groves coexisting with a rapidly expanding stone industrial sector.

The stone industry represents the cornerstone of Qabatiya's local economy, occupying a physical footprint of approximately 0.94 Km^2 across 235 operational facilities, including 122 stone cutting workshops, 101 quarrying sites, and 12 crushing units.

The sector serves as the main driver of local employment, sustaining about 2800 permanent jobs (averaging 10 workers per establishment), with annual sales ranging from 1.2 million NIS for small facilities to 4.8 million NIS for large factories (1 USD = 3.0 NIS), and daily outputs reaching 100 m^2 for cutting and 1000 m^3 for crushing. However, the sector faces widespread regulatory informality, with only 75 of the 235 active establishments being formally registered. This unmonitored expansion generates significant hydro-environmental strain, setting the stage for a critical review of the multidimensional impacts reported in the regional literature.

1.6. Hydro-Climatic Profile and Water Vulnerabilities in Qabatiya

Qabatiya is situated in a semi-arid climatic zone receiving 460–565 mm of annual rainfall [38] and relies on a groundwater-dependent hydrological system. Domestic and agricultural demands are primarily supplied from the shallow Eocene aquifer via municipal and private wells, with rainwater cisterns playing a secondary role [39].

Although municipal network coverage is high [40], water delivery is severely restricted by ageing infrastructure, substantial distribution losses, and seasonal yield reductions, keeping consumption below demand [39]. These supply bottlenecks exacerbate baseline vulnerabilities—including groundwater contamination risks from cesspit leakage, mu-

nicipal wastewater, agricultural runoff, and stone industry discharges—amid broader geopolitical and institutional constraints [39,40].

These baseline constraints highlight the urgent need for an integrated, multidimensional evaluation of local water poverty. The impacts of quarrying and stone cutting on water resources are substantial and multifaceted; these are summarized in Table 2 below:

Table 2. Summary Table of Key Impacts of stone industry on water and environment.

Impact Category	Specific Effects	References
Water Quality	Contamination of surface and groundwater by slurry water, sediments, and quarry-related pollutants; deterioration of water quality for domestic and agricultural use.	[35,37] (SM—Annex1)
Water Use	High water consumption for stone cutting and washing, placing additional pressure on local water resources.	[37]
Water Resources	Altered hydrology, reduced aquifer recharge, increased sedimentation, and declining groundwater availability.	[35,37] (SM—Annex1)
Impact on Aquifer Recharge	The removal of surface layers can prevent rainfall from infiltrating the ground, leading to a decrease in groundwater levels and affecting water availability for agricultural and domestic use.	[35,37]
Health	Water contamination and dust emissions pose risks to community and occupational health.	[35,37]
Environment	Land degradation, erosion, dust pollution, and degradation of aquatic and terrestrial ecosystems.	[35,37] (SM—Annex1)

Mitigating these impacts is essential for advancing sustainability within the stone industry, preserving water resources, and protecting environmental health. Sustainable practices may include the recycling and reutilization of stone powder in the production of value-added materials.

2. Theoretical Framework

2.1. Water Poverty Index

The Water Poverty Index (WPI), originally developed by Sullivan [41], was formulated as a holistic and interdisciplinary management tool designed to link household welfare directly with water availability [42,43] across five core components: Resources, Access, Capacity, Use, and Environment [44–47]. This multidisciplinary nature allows for the assessment of complex interactions within the hydrosocial cycle, making it a highly appropriate instrument for tracking the multi-faceted impact of industrial activities such as mining on local water security [47,48]. By integrating physical water metrics with socio-economic drivers, this multidimensional framework captures complex hydrosocial dynamics, enabling a comprehensive assessment of how resource extraction simultaneously impacts local water security, adaptive capacity, and environmental integrity [42,47–49]. By integrating these diverse metrics into a single numerical value, the WPI provides a transparent framework for decision-makers to prioritize interventions and allocate resources based on the greatest social and physical needs [48–50].

2.2. Inclusive Water Poverty Index

The conventional WPI [41] relies on a strictly additive structure prone to "compensation bias," rendering it insensitive to ecological and social tipping points while masking localized suffering [48,51]. Because mining impacts extend far beyond biophysical metrics to reshape socio-economic and institutional dynamics, the Inclusive WPI (iWPI) overcomes these limitations by introducing a sixth component: Cohesion [51]. This dimension

measures community solidarity, local water subsidies, and vulnerable group representation [52]—critical social buffering assets that offset missing infrastructure in fragile, industrially stressed landscapes [50]. Ultimately, the iWPI provides decision-makers with a transparent framework to prioritize interventions and allocate resources according to acute physical and social needs [48–50].

2.3. Theoretical Alignment and Conceptual Limitations

By operationalizing local dynamics, the iWPI aligns with international debates on environmental justice—revealing the hidden socio-ecological burdens in mining areas [53,54]—and decentralized water governance [55] as a benchmark for community resilience. While its strength lies in translating adaptive capacity into actionable metrics for local decision-makers, a critical caveat remains: using the index as a single aggregated score without proper disaggregation or participatory validation risks obscuring the very inequalities it aims to expose [56].

3. Materials and Methods

3.1. Inclusive WPI (iWPI)

iWPI was measured in both Qabatiya, Palestine, and Zaragoza, Colombia. The methodology includes identifying subcomponents, measuring components, and then measuring the three versions of WPI using the inclusive version introduced by [52].

3.1.1. iWPI Components and Subcomponents

The inclusive WPI contains the original five components. These are: physical availability of water (Resources), extent and type of access to water (Access), community's capacity to provide and manage water services (Capacity), ways in which water is used (Use), and the environmental services/conditions that affect the extent of access to quality of water (Environment). Furthermore, in accordance with Kini [52], a sixth component was added. This component reflects the social forces that maintain community unity across socio-economic divides (Cohesion).

The selection and validation of the iWPI subcomponents followed a participatory and expert-informed approach. The six subcomponents were organized under the conventional WPI framework proposed by Lawrence [44]; the specific indicators were identified based on previous WPI applications (e.g., [44,51,57,58]), expert recommendations, and data availability constraints. A multidisciplinary panel reviewed the preliminary indicator set for each study site. In Qabatiya, for example, the panel included 10 experts representing academia, government institutions, the water and mining sectors, non-governmental organizations, and the United Nations WASH Cluster.

A second validation round was conducted with academic specialists in water resources, environmental sciences, socioeconomic development, and mining. In addition, a participatory approach was adopted throughout the assessment process through consultations with key local stakeholders, including farmers, municipal representatives, mining operators, Governmental Directors of environment, agriculture, and health departments, and local and international NGOs.

3.1.2. Scenario Construction and Counterfactual Modelling

To systematically isolate and quantify the multidimensional impacts of mining activities on water security, this study employs a longitudinal counterfactual research design. Two distinct socio-hydrological scenarios were constructed across the 2010–2025 timeline for both Zaragoza and Qabatiya: The Baseline Scenario (Without Mining) and the Active Extraction Scenario (With Mining).

The Active Extraction Scenario ($iWPI_{Mining}$) reflects the empirically observed historical trajectory of the territories. It integrates direct primary and secondary data streams that capture distortions by mining, including localized biophysical degradation (e.g., soil degradation, heavy metal and sediment concentrations under the Environment dimension), economic influxes (e.g., formal employment in the mining sector and the impact on fishing or agricultural revenues under the Capacity component), and socio-institutional shifts (e.g., altered social cohesion scores driven by territorial conflicts).

Conversely, the Baseline Scenario ($iWPI_{Baseline}$) represents the counterfactual condition, a mathematical estimation of how water poverty would have evolved in the absolute absence of the mining activities. Given that iWPI is aggregated using the subcomponents depicted in Table 3 below, and given that those subcomponents include indicators that are relevant to mining (e.g., water quality, income generation through mining, etc.) and others that are not relevant to mining (e.g., proportion of the population using safely managed sanitation services). Calculation of $iWPI_{Baseline}$ was done after either eliminating or recalculating the subcomponent, assuming no mining is taking place in the area. For example, Income generated through the stone cutting sector per capita was omitted from aggregation in the baseline calculations in Qabatiya. Please refer to the Supplementary Materials for more detailed calculations of the $iWPI_{Baseline}$.

Table 3. The subcomponents that will be used to measure iWPI.

Component	Data Used [44]	Zaragoza/Bajo Cauca/Antioquia/Colombia	Qabatiya/Jenin/West Bank/Palestine
Resources	Internal Freshwater Flows	Water Use Index (WUI)	Groundwater wells yield
		Water Vulnerability Index (HVI)—Aquifer	
		Water Scarcity Index (WSI)—Aquifer	
		Water Retention and Regulation Index (IRRH)	
	External Inflows	Population	Proportion of Water purchased from the Israeli side out of total water supply
	Population	**Perception of the loss of water reliability** **Perceived water security in mining population pressure context**	Population
Access	% population with access to clean water	Quality Risk Index (IRCA)	Proportion of population using safely managed drinking water services
		% Municipal Water System Coverage.	Proportion of water losses out of total water supply
		% Municipal Sewer System Coverage.	
	% population with access to sanitation	% of days HHs have access to water network.	Proportion of population using safely managed sanitation services
			% of area C according to Oslo accords
	% population with access to irrigation adjusted by per capita water resources	**Degree of perceived disruption to the water supply** **Perceived increase in informal sanitation systems**	Percentage of Irrigated Cultivated Land with Temporary and Permanent Crops from Total Cultivated Land
			% decrease in irrigated land in the affected area
Capacity	Gini coefficients of income distribution	%Multidimensional Poverty Index (MPI)	**Income generated through stone cutting sector per capita (% of GDP)**

Table 3. *Cont.*

Component	Data Used [44]	Zaragoza/Bajo Cauca/Antioquia/Colombia	Qabatiya/Jenin/West Bank/Palestine
	ppp per capita income	% of formally employed persons relative to the total population	Gross National Income per capita
		Population with unmet basic needs (NBI) **Extent of the impact on local economic autonomy (Fishing)**	Proportion of population living below the national poverty line
	Under-five mortality rates	% of population aged 25 and above completed secondary education	Mortality rate, infant (per 1000 live births)
		Infant Mortality Rate (children under 5 years of age)	Life expectancy/National Life expectancy
			Severity index on the respiratory system
	Education enrolment rates	% Literacy **Prioritizing mining over secondary and higher education** Average score on state tests (critical reading level)	Expected years of schooling
		Perceived barriers of the process vs. success % formalization **% Mining formalization**	
Use	Domestic water use in litres per day	% of domestic water use	Domestic Water consumption
		% of Agricultural water use	Quantity of water pumped from groundwater wells used for domestic purposes
	Share of water use by industry and agriculture adjusted by the sector's share of GDP	% of HH use water for industrial purposes (small/microincome generating projects)	**% of water diverted to stone industry**
		Degree of perceived tension between miners and the community over priority water use	Quantity of water pumped from groundwater wells used for agricultural purposes
			% decrease in crop yield
Environment	Water stress (pollution)	Water Pressure on Ecosystems Index (IPHE) Water Quality Index (ICA)	% of months per year where deficit in domestic water supply is experienced
		% of HH not connected to safe wastewater discharge system	**Proportion of stone cutting establishments with uncontrolled solid waste disposal to the environment**
			% of agricultural land affected by stone cutting
	Environmental regulation and management	**Water Quality Index (ICA) downstream of the mining activity (post-discharge).**	**% of stone establishments in compliance with the national standards**
		Potential Water Quality Impairment Index (IACAL)	
		% of alluvial gold mining (EVOA).	Population density

Table 3. *Cont.*

Component	Data Used [44]	Zaragoza/Bajo Cauca/Antioquia/Colombia	Qabatiya/Jenin/West Bank/Palestine
Cohesion	Internal solidarity	Armed Conflict Incidence Index	Proportion of population subjected to physical violence in the previous 12 months
		Number of village water systems managed by the community itself.	**% of population in Qabatiya southwestern cluster reported being affected by pollution**
	Solidarity towards the poor	Solidarity toward poor and vulnerable groups	Solidarity toward poor and vulnerable groups;
			General community solidarity and mutual assistance
	Subsidy of the poor's access to water and sanitation	Representation of poor and vulnerable groups	The existence of local funds to subsidize access to water and sanitation for the poorest
	Inclusiveness of the poor in decision-making	**Mining association focused on water and environmental justice**	Proportion of population who believe decision-making is NOT inclusive and responsive, by sex, age, disability and population group
		Degree of trust in mining and environmental authorities	The representation of poor and vulnerable groups in the management of such social funds.

The above subcomponents were aspired from the below sources: [45,52,57,58]. The **bolded** subcomponents are considered for tracking the impact of mining.

To ensure empirical validity, avoid arbitrary assumptions, and address severe data scarcity at the local scale, identification and validation of subcomponents affected by mining and the way how was affected were done with local experts in each area. Moreover, the timelines for both scenarios were the same to maintain comparability.

Due to the scarcity of instrumentation and continuous monitoring stations at the micro-watershed level in the study area, the evaluation of baseline water availability and physical quality relied on indicators from the immediately larger scale. For Zaragoza, some of the missing data were extracted from the National Water Study (ENA)—specifically the Water Risk Index (IRH), Water Use Index (IUA), Vulnerability to Water Scarcity Index (IVH), and Water Quality Index (ICA). These regional values were adopted as proxy variables for the environmental baseline and subsequently calibrated and triangulated to the local scale using primary data collected through qualitative methods, including Participatory Assessment of Development (PADev), Key Informant Interviews (KII), and Focus Group Discussions (FGD). The same procedure was used to impute missing data across the components.

In the absence of continuous annual records, a Linear-trend interpolation model was implemented to reconstruct the historical series of the index. Although these indicators do not capture the full spectrum of mining impacts, they provide context-specific proxy measures that facilitate the assessment of mining's contributions to water poverty.

As per Sullivan [41], WPI was developed collaboratively with its intended users and stakeholders, ensuring a more inclusive and contextually grounded framework. Furthermore, in light of Giné and Pérez-Foguet [59], the improved version of WPI and expert-based weighting were also considered as options for calculating iWPI. Moreover, to ensure the inclusion of poor and vulnerable populations in water and sanitation programmes [60], indicators of poverty and vulnerability were integrated. Such indicators are often underrepresented in conventional WPI formulations [41,44,55,56,59–62].

3.1.3. Data Collection and Analysis

Through this research, both qualitative and quantitative data were used. The qualitative data were collected mainly through primary sources, including focus group discussions (FGDs), observation, semi-structured interviews, and key informant interviews (KIIs). On the other hand, quantitative data were mainly acquired through secondary official sources. Examples of sources used in Palestine include the Palestinian Central Bureau of Statistics (PCBS), the Palestinian Water Authority (PWA), and the Office for the Coordination of Humanitarian Affairs (OCHA). On the other hand, examples of secondary data sources in Colombia include the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM), the National Administrative Department of Statistics (DANE), the Regional Autonomous Corporation of Central Antioquia (CORANTIOQUIA), the National Planning Department (DNP), and TerriData open data.

Key informants include representatives of local water providers, community-based organizations (CBOs), municipal authorities, social leaders, and members of user committees or water-related NGOs. FGDs are conducted separately with different social groups (e.g., stakeholders benefiting from mining work (workers, mining business owners, etc.), stakeholders negatively affected by mining such as farmers, owners of lands polluted by mining activities, etc.); wherever applicable, triangulation is done to confirm the accuracy of secondary data and eliminate spatial masking.

In both Colombia and the Occupied Palestinian Territories, 10 key informant interviews (KIIs) were conducted to ensure coverage of institutional, technical, and community perspectives. For FGDs, participants are recruited using a combination of purposive and snowball sampling to ensure inclusion of poor and vulnerable groups, as locally defined. In Palestine, three FGDs are held, with separate groups for (i) stakeholders including vulnerable groups who benefit from mining activities, (ii) stakeholders who are negatively affected by mining activities, and (iii) women or other relevant sub-groups, depending on context. This design enables the capture of both dominant narratives and marginal voices regarding cohesion around water and sanitation. On the Colombian side, one focus group is held to ensure the equitable participation of the three aforementioned stakeholder groups.

For qualitative data analysis, all interviews and FGDs are transcribed and coded thematically using a coding framework aligned with the six iWPI components. For cross-site comparison, component-specific qualitative indicators are constructed by synthesizing recurring patterns and assigning ordinal ratings (e.g., low–medium–high) for each site across the six components. Through this data analysis approach, contextual narratives were preserved. For quantitative data analysis, PCBS, MS Excel, and MS Paint were used for data analysis and visual representation.

Due to the scarcity of micro-level longitudinal data in the study area, the evaluation of water availability and physical quality relied on indicators from the immediate higher scale (sub-watershed, governorate, or regional level). These higher-scale values were adopted as proxy variables (environmental baseline) and subsequently calibrated/triangulated to the local scale of Qabatiya and Zaragoza using primary data collected through qualitative methods (e.g., KII and FGD), thus ensuring that the final iWPI reflected the point-source alterations of mining that regional averages usually render invisible. For detailed analysis of data, refer to Supplementary Materials S1–S3.

3.1.4. Normalization of Variables

In this study, the iWPI framework, as shown in Table 1, comprises six components and 32 subcomponents in Qabatiya and 26 in Zaragoza. Standardization of the variables, except those expressed as rates or percentages, was done to enable comparisons using various methods. Among several normalization methods, the minimum-maximum method was

used [44,58,63–65] to scale the data to a standard, comparable range of 0–100. It is also notable that the method is applied only when data are reported in various units and/or scales. Equations (1) and (2) are used when the subcomponent is correlated proportionally and inversely, respectively. Normalization is again based on the data available for subcomponents depicted in Table 3. Due to data scarcity at the micro level, some of these components' values are considered from the immediate next spatial level.

$$Subcomponent\ i = \frac{Xi - Xmin}{Xmax - Xmin} \times 100 \quad (1)$$

$$Subcomponent\ j = \frac{Xmax - Xj}{Xmax - Xmin} \times 100 \quad (2)$$

where X_i, X_{min}, and X_{max} are, respectively the current value of variable X for locality i before scaling, the lower and the upper thresholds of the variable X. In general, appropriate thresholds (or benchmarks) were initially selected as the maximum and minimum values when available. If such values were unavailable, the thresholds for the variables considered in this study were set to the maximum and minimum values.

3.1.5. Calculation of Subcomponents

a. Resources

A higher value of this component reflects a better water situation (i.e., abundant water resources with less variability).

b. Access

Ensuring adequate access to safe water sources and improved sanitation services enhances hygiene practices and contributes to eradicating extreme poverty [55].

c. Capacity

Capacity can be conceptualized in terms of physical, social, and economic dimensions that enable the secure provision of adequate quantities of safe water to meet fundamental needs sustainably [55].

d. Use

The Use component is the appropriate index that links the ways water is used for various purposes to its contribution to the overall economy. The domestic water use indicator represents the current state of resource use in daily household activities (e.g., cooking, hygiene, and laundry) [55,66]. This indicator is easily measured as daily water use per capita, normalized using a min-max approach [44,63,64,67,68]. According to WHO (2020), the lower threshold for essential water needs is 50 litres per capita per day (LPCD), and the optimal threshold (the maximum volume of water that fulfils all water needs) is 150 LPCD [65].

$$U1_i = \begin{Bmatrix} \frac{x_i}{50} \times 100,\ x_i \leq 50 \\ 100 - \frac{x_i - 50}{x_{max} - 50} \times 100,\ 50 < x_i \leq 150 \\ 100 - \frac{x_i - 50}{x_{max} - 150} \times 100,\ 150 < x_i \end{Bmatrix} \quad (3)$$

where X_i is the current value of the domestic water use variable in lpc.d in locality i, with X_{max} being the highest value of the variable in the whole country.

e. Environment

As recommended by Lawrence [44] and Sullivan [55], water quality is considered one of the main indicators of the environmental component in the WPI framework.

f. Cohesion

Cohesion (Co) was included to capture the "force" that maintains community unity despite differences in socioeconomic and professional categories, thereby addressing social, psychological, and cultural aspects of poverty. In alignment with Kini [52], cohesion was measured using six subcomponents. Please refer to Table 1.

i. Aggregation and weighting

The aggregation of the six components was done under the assumption of non-compensability, in which failure in one component cannot be offset by strong performance in another, ensuring that poor performance in any component is penalized more severely. To achieve this, a weighted multiplicative function is employed, as it is deemed the most suitable aggregation method for calculating the final index while accounting for non-compensability among the components [63,68–70].

A diverse range of experts determined the appropriate weighting scheme. This technique allows for objectively determining the set of weights that explain the largest variation in the original components [71]. The weighting process consisted of two main steps: selecting participant experts with deep experience in water and environmental fields, proven technical skills in water and mining, and experience working in the target areas. Secondly, the weight calculation was performed using the Analytic Hierarchy Process (AHP) for the six components. Bidaki [43] used the AHP tool and reported that it offers a robust scientific framework for addressing multidimensional water poverty. By synthesizing expert attitudes through hierarchical binary comparisons, AHP facilitates reliable decision-making. This method is highly efficient, as it requires minimal field data and leverages localized expert knowledge. The final weight of each component was determined as the average weight assigned by each expert using the AHP tool. Please refer to the Supplementary Materials to review the tool and method of calculating weights.

Then the final index can be formulated numerically as follows:

$$iWPIa = \sum_{i-R,A,C,U,E,\ Co} WiXi \quad (4)$$

$$iWPIg = \prod_{i=R,A,C,U,E,\ Co} X_i^{w_i} \quad (5)$$

where iWPIg/iWPIa are the final values of the index, Xi is the ith component, and wi is the weight assigned to that component.

ii. With and Without mining calculations

The above subcomponents were determined to measure the longitudinal impact of mining. However, the "without mining" scenario was developed as a counterfactual condition intended to estimate water poverty in the absence of mining activities while keeping all other environmental, social, and institutional factors unchanged. Counterfactual values were derived by recalculating mining-related indicators under expected conditions, without mining intervention, rather than through trend extrapolation. The adjustment method varied according to the nature of each subcomponent and involved removing mining-related pressures or restoring indicator values to conditions representative of a non-mining context. For example, the indicator reflecting the effect of stone quarrying on groundwater recharge was recalculated assuming no quarry-induced reduction in recharge. This approach allows the specific contribution of mining to individual iWPI components and to overall water poverty levels to be assessed by comparing observed conditions.

iii. Sensitivity analysis

To evaluate the robustness of the proposed index to weighting assumptions, a one-at-a-time (OAT) sensitivity analysis was performed for both the weighted arithmetic and geometric iWPI. Following commonly adopted procedures for composite indices, each iWPI's component weight was individually increased by 20% while the remaining component weights were proportionally adjusted to maintain a unitary sum. The weighted arithmetic and geometric iWPI values were subsequently recalculated for all years and scenarios (with and without mining) in Qabatiya and Zaragoza. Sensitivity was assessed by calculating the percentage deviation of the recalculated indices from the baseline values and by examining whether changes in weighting altered the relative ranking of scenarios or the observed longitudinal trends. Quantitative robustness thresholds were defined based on the percentage change between the original and perturbed iWPI values. An absolute change of <5% was considered low sensitivity (robust), changes between 5% and 10% were considered moderate sensitivity, and changes > 10% indicated high sensitivity to the weighting assumptions. This approach identified the most influential components and assessed the index's robustness to credible variations in expert-derived weighting factors.

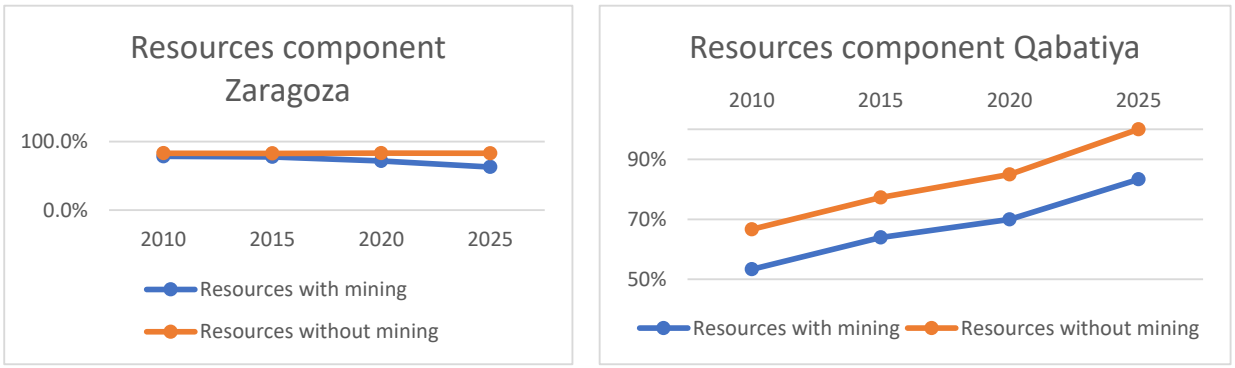
4. Results

4.1. WPI Components

Significant differences in WPI components and versions were observed at both sites when comparing the situations with and without mining. The following explores the results and their interpretation from the quantitative and qualitative assessments conducted in both localities, first regarding Colombia and then regarding Palestine.

4.1.1. Resources

Zaragoza maintains a robust hydrogeological baseline, backed by high surface and groundwater availability (Hydrological Regulation Index (HRI) of 0.77 and a Water Use Index (WUI) of 0.8%). However, uncontrolled informal well drilling by incoming miners and mining-driven riverbed alterations threaten long-term aquifer sustainability, underscoring systemic failures in territorial water governance. In Qabatiya, the Resources (R) component reflects severe mining pressures, where stone industry operations have reduced groundwater yield by 10–30%, and over 30% in the industrial zone, by impairing natural recharge (Figure 1). Paradoxically, official metrics mask this depletion through increased groundwater pumping, which excludes widespread unregistered private wells and poses a critical threat to long-term aquifer sustainability.

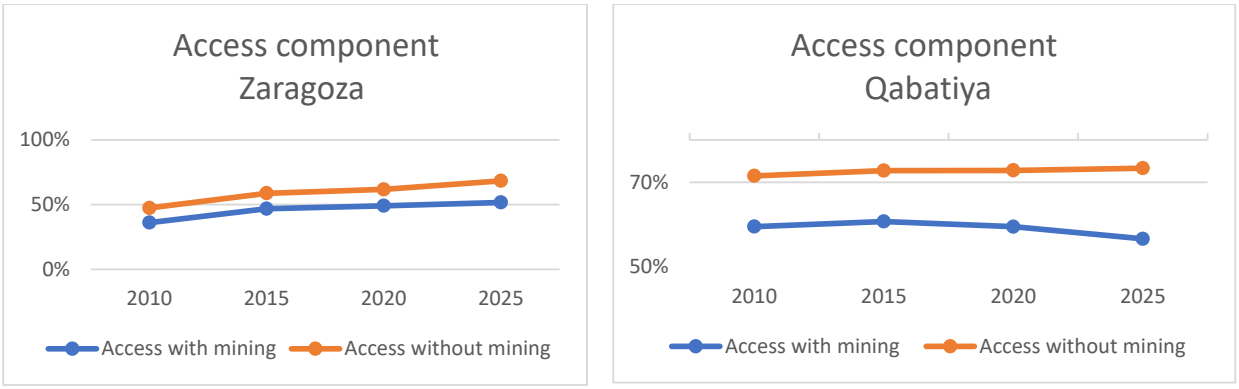


(**a**) (**b**)

Figure 1. The longitudinal values of Resources component for the years 2010 to 2025 with and without mining in Zaragoza (**a**) and the longitudinal values of Resources component for the years 2010 to 2025 with and without mining in Qabatiya (**b**).

4.1.2. Access

As presented in Figure 2, In Zaragoza, the Access (A) component reveals deep urban-rural disparities, intensified by a 35% demographic surge in informal settlements. The total lack of wastewater treatment (WWTP) drives direct untreated discharges, while persistent outages (3–5 days up to month-long failures) normalize "water conformism." Paradoxically, higher quantitative Access scores reflect informal water market expansion ("privatized resilience") rather than institutional progress, masking systemic infrastructure failure.



(**a**) (**b**)

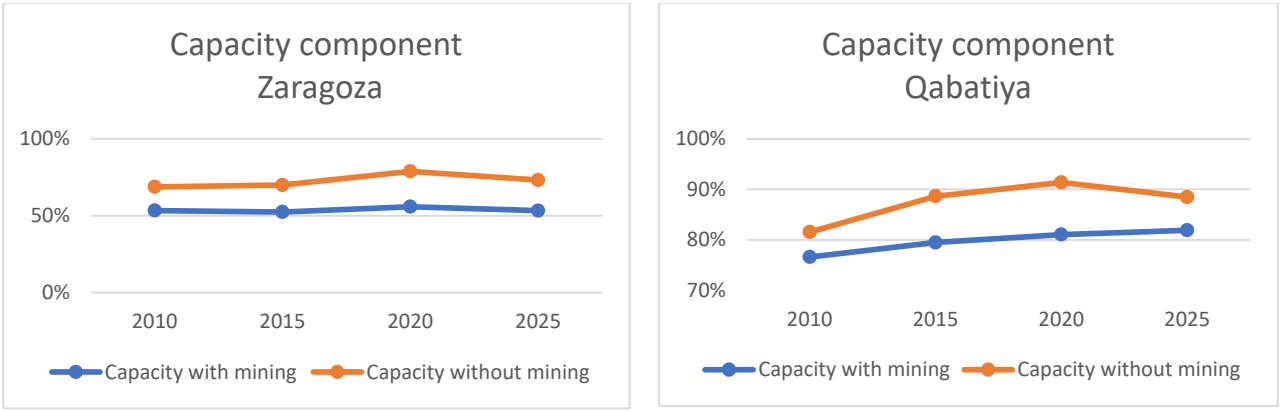
Figure 2. (**a**) The longitudinal values of the Access component for the years 2010 to 2025 with and without mining in Zaragoza and (**b**) the longitudinal values of the Access component for the years 2010 to 2025 with and without mining in Qabatiya.

In Qabatiya, the Access (A) component features near-universal domestic coverage (98% in 2023) alongside a complete absence of wastewater treatment. However, the stone industry introduces sharp economic disparities and pressure on irrigated lands: industrial reliance on private wells and tankers inflates supply costs to 7 NIS/m^3 versus 2.6–2.8 NIS/m^3 for domestic users, depressing overall Access scores despite high physical connectivity.

4.1.3. Capacity

The persistent gap between the scenarios in the Capacity component reflects a structural erosion of local adaptive capacities driven by extractive activities (Figure 3). Rather than relying on economic indicators, such as mining GDP or direct revenues, which are difficult to quantify in informal extraction settings, the framework evaluates the "with mining" scenario through the disruption of alternative livelihoods and the degradation of human capital. The lower Capacity scores under mining indicate that extractive activities undermine traditional economic sectors, particularly artisanal fishing, while exacerbating existing socioeconomic vulnerabilities. This is reflected in Zaragoza's high poverty rate (42.2%) and informal labour rate (91.1%), whereas the "without mining" scenario represents a trajectory in which livelihoods and human capabilities evolve without sustained extractive pressures.

Human capital is further constrained by short-term livelihood strategies, whereby young people (14–18 years) favour subsistence mining over the limited opportunities for post-secondary education. Although approximately 82.9% of Mining Production Units (UPMs) lacked formal environmental instruments in 2022, local authorities identified an emerging willingness to adopt more responsible practices. However, limited technical support and rigid formalization procedures continue to hinder this transition.



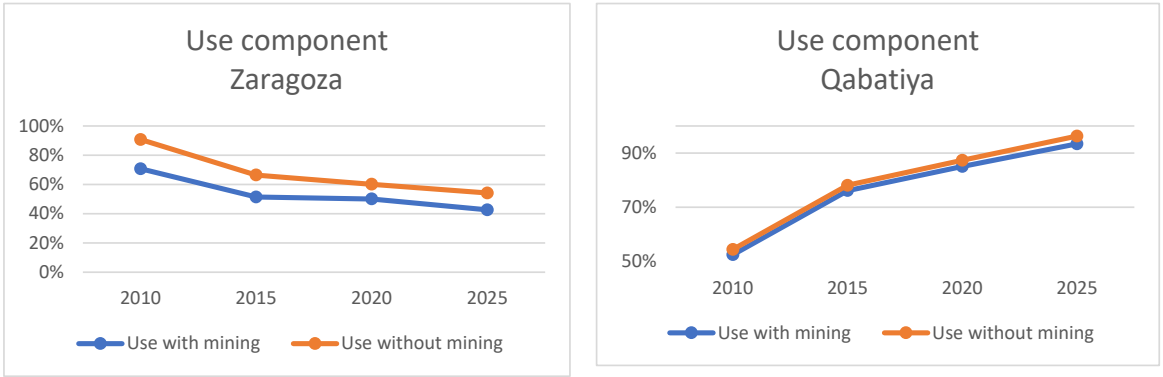
(**a**) (**b**)

Figure 3. (**a**) The longitudinal values of the Capacity component for the years 2010 to 2025 with and without mining in Zaragoza and (**b**) the longitudinal values of the Capacity component for the years 2010 to 2025 with and without mining in Qabatiya.

As for Qabatiya, the stone industry strengthens economic capacity by generating approximately 2800 permanent jobs and substantial annual revenues of up to 4.8 million NIS (around US$1.5 million) for large factories. Nevertheless, these economic benefits are offset by weak institutional capacity, characterized by insufficient law enforcement, limited environmental awareness, and inadequate regulation of mining-related impacts on water resources. Consequently, while mining contributes positively to financial capacity, it continues to constrain effective environmental governance. See Figure 3.

4.1.4. Use

The longitudinal assessment of the Use component reveals contrasting water-use dynamics between the baseline and "with mining" scenarios (Figure 4). In Zaragoza, the baseline decline is primarily associated with inefficient domestic water allocation and consumption, driven by deficiencies in the municipal distribution network and the absence of micro-metering. In contrast, agricultural water use remains relatively stable through traditional community-managed water supply systems. The lower scores under the "with mining" scenario result from the direct expansion of mining activities on critical water collection structures, increasing turbidity, restricting physical access to water, and generating sociopolitical tensions associated with territorial control by illegal actors. These factors collectively undermine equitable water distribution.



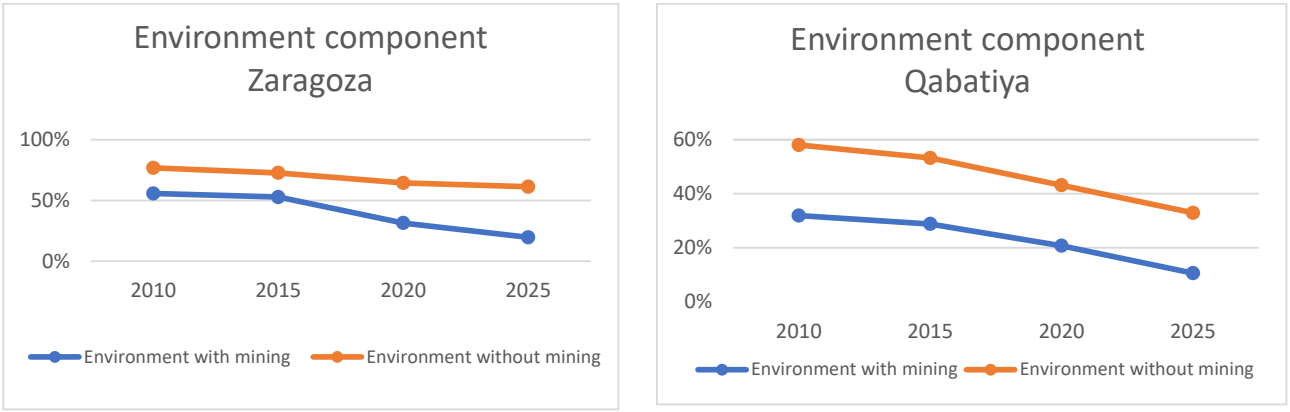
(**a**) (**b**)

Figure 4. (**a**) The longitudinal values of Use component for the years 2010 to 2025 with and without mining in Zaragoza; and (**b**) The longitudinal values of Use component for the years 2010 to 2025 with and without mining in Qabatiya.

In Qabatiya, water is primarily allocated to domestic and agricultural uses under the "without mining" scenario, with domestic consumption exceeding 933,000 m^3 annually. The "with mining" scenario introduces substantial industrial demand, with each stone-processing establishment consuming approximately 10 m^3 of water per day. Qualitative findings reveal inefficient water use due to the absence of water recycling and the discharge of wastewater into abandoned quarries instead of treatment and reuse. This practice intensifies competition with agriculture. Although improvements in water infrastructure, particularly the rehabilitation of the main groundwater well, have enhanced water availability over time, mining continues to reduce the Use component by diverting water to industrial activities and lowering agricultural productivity through dust deposition on open-field crops.

4.1.5. Environment

The longitudinal analysis of the Environment component highlights the substantial deterioration of hydro-environmental security in Zaragoza under the "with mining" scenario (Figure 5). KIIs and FGDs identified long-standing mining activity as the principal driver of watershed degradation through the accumulation of sediments, mercury, and cyanide in the Nechí River and the La Oca and Juan Vara creeks. Although conventional indicators, such as the ICA Water Quality Index, classify water quality as only moderately or slightly impaired, they fail to capture the environmental impacts of heavy metal contamination. Mining Production Units (UPMs) discharge mercury concentrations ranging from 0.091 to 0.549 mg/L, far exceeding the Colombian regulatory limit of 0.002 mg/L for human consumption.



(**a**) (**b**)

Figure 5. (**a**) The longitudinal values of the Environment component for the years 2010 to 2025 with and without mining in Zaragoza; and (**b**) the longitudinal values of the Environment component for the years 2010 to 2025 with and without mining in Qabatiya.

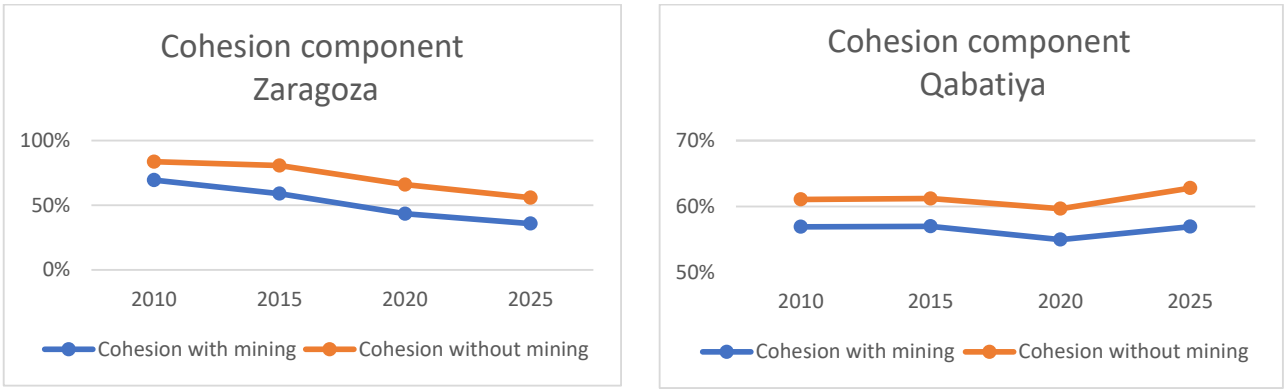
Environmental degradation is further reflected in the extensive loss of High Environmental Value Coverages (AVA) associated with Alluvial Gold Mining (EVOA). Between 2019 and 2020, Zaragoza lost 489 ha, representing 8% of the national total in this degradation category. More recently, mining activities have increasingly focused on reprocessing fine sediments (tailings), promoting the remobilisation of previously deposited mercury into river systems, a process intensified by rising global gold prices.

In Qabatiya, the Environment component also experienced substantial degradation due to the stone industry. According to FGDs and KIIs, water quality frequently exceeded WHO esthetic guidelines, with Total Dissolved Solids (TDS) reaching 1500 mg/L and turbidity up to 500 NTU. Experts further attributed mining activities to a 20% reduction in biodiversity and a 10–30% decline in agricultural productivity resulting from the use of dust- and sediment-contaminated water. Environmental conditions are further aggravated by the widespread use

of explosives, which experts rated as having a high impact on aquifers (4/5), together with increasing liquid and solid waste associated with population growth.

4.1.6. Cohesion

The Cohesion component addresses the social equity and conflict-resolution dimensions of water management. In Zaragoza, qualitative evidence indicates that community cohesion has progressively shifted towards a reactive, subsistence-oriented form under extractive pressures (Figure 6). In the baseline scenario, a clear distinction exists between rural and urban settings. Rural communities retain relatively strong local governance, self-managing 18 of the municipality's 21 water supply systems through Community Action Boards (Juntas de Acción Comunal), aqueduct committees, and indigenous reserves. In contrast, urban solidarity is largely confined to informal neighbour-to-neighbour support, with limited collective capacity to advocate for water rights, reflecting long-standing institutional neglect and the normalization of precarious living conditions.



(**a**) (**b**)

Figure 6. (**a**) The longitudinal values of the Cohesion component for the years 2010 to 2025 with and without mining in Zaragoza; and (**b**) the longitudinal values of the Cohesion component for the years 2010 to 2025 with and without mining in Qabatiya.

Mining further weakens social cohesion by promoting unstable, short-term economic relationships that fail to translate into collective environmental responsibility. The predominance of informal mining (approximately 96%), combined with the influence of illegal armed groups, intensifies socio-environmental conflicts, fragments community networks, and restricts safe access to water sources. This fragmentation is reinforced by a profound lack of trust in public institutions, as local government, the National Mining Agency (ANM), and law enforcement are perceived as absent or punitive rather than supportive actors. Consequently, community trust in environmental and mining authorities remains critically low (40/100).

As for Qabatiya, mining presents a mixed social outcome. Although the stone industry generates employment, it is also recognized as a major source of internal disputes and conflicts with neighbouring communities, particularly Zababdeh village. While solidarity towards vulnerable households remains moderate (57/100), their representation in managing social water funds is critically limited (20/100). The absence of a dedicated social responsibility fund from the stone industry further constrains inclusive water governance, allowing economic benefits to be overshadowed by social tensions and the marginalization of vulnerable groups in decision-making.

4.1.7. Comparison Between WPI Components' Performances

For the aforementioned six WPI components, both Qabatiya and Zaragoza demonstrate that mining creates a persistent trade-off between short-term economic gains and long-term deterioration in water security. However, the magnitude and mechanisms differ substantially between the two contexts. In both localities, the strongest negative impacts are concentrated in the Environment, Use, and Cohesion components, while Capacity shows partial improvement due to mining-related economic activity. However, Zaragoza exhibits a more severe systemic collapse across environmental and social dimensions due to the cumulative impacts of informal alluvial gold mining (ASGM), illegal governance structures, and toxic contamination. For example, mercury concentrations in Zaragoza mining discharges ranged from 0.091 to 0.549 mg/L, exceeding the Colombian regulatory limit for domestic consumption (0.002 mg/L) by 45–270 times, while the municipality lost 489 ha of High Environmental Value Coverages between 2019 and 2020 alone. On the other hand, Qabatiya's environmental degradation is more closely associated with quarry dust, sedimentation, and groundwater depletion, with TDS reaching 1500 mg/L and turbidity peaking at 500 NTU, accompanied by a reported 20% biodiversity loss and a 10–30% reduction in agricultural productivity. Both sites also showed declining Resources and Environment trends over time under mining conditions; however, the drivers differed.

In Zaragoza, apparent increases in the Resources component were linked to uncontrolled groundwater abstraction and informal wells associated with population influxes. In contrast, in Qabatiya, the decline was attributed mainly to reduced groundwater recharge and intensive abstraction by the stone industry. Access conditions also differed substantially: Qabatiya maintained nearly universal domestic water network coverage (98–100%), although mining introduced economic competition through expensive industrial water supply systems (2.3 US$S/m^3 compared with 0.84–0.90 US$/m^3 for domestic users). At the same time, Zaragoza experienced chronic institutional failure characterized by repeated supply interruptions lasting from several days to entire months. Despite these differences, both localities demonstrated a similar longitudinal pattern in which mining consistently suppressed WPI component scores, particularly in environmental sustainability and equitable water governance.

4.2. WPI Results

4.2.1. Longitudinal WPI Versions Results

The comparative analysis of the four WPI formulations differentiates the trajectories of water security in Zaragoza under the baseline and "with mining" scenarios (Figure 7). Even without mining, the baseline reflects accumulated structural deficiencies in water infrastructure and public resource management. The introduction of artisanal and small-scale gold mining (ASGM) results in a marked reduction in WPI scores across all index versions. Although favourable hydrological conditions and mining-related income partially improve the Capacity component, these gains are insufficient to compensate for the deterioration observed in the Environment, Use, Cohesion, and Access components.

The modified WPI versions (iWPI, iWPIg, and iWPIa) demonstrate greater methodological sensitivity than the conventional WPI by incorporating qualitative dimensions that are overlooked by traditional indices, including reduced social cohesion, informal governance by armed actors, and localized mercury contamination. Consequently, these indices better capture the multidimensional impacts of mining and prevent economic gains from masking the intensification of territorial water poverty.

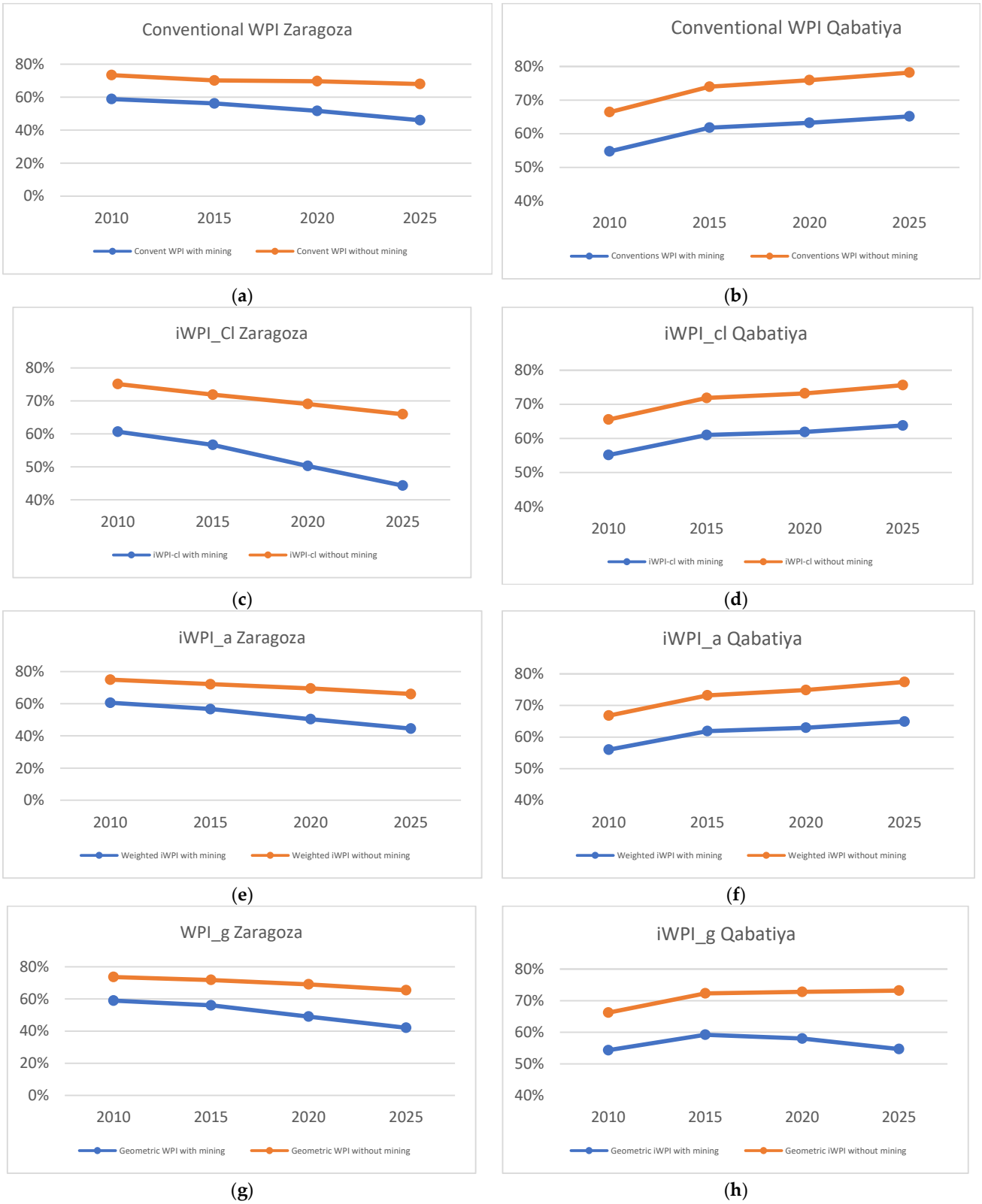


Figure 7. (**a**,**c**,**e**,**g**) The longitudinal values of the four versions of WPI for the years 2010 to 2025 with and without mining for Zaragoza; and (**b**,**d**,**f**,**h**) The longitudinal values of the four versions of WPI for the years 2010 to 2025 with and without mining for Qabatiya.

In Qabatiya, the baseline scenario reflects a community constrained by natural water scarcity and limited wastewater infrastructure despite maintaining high domestic water supply coverage. Mining substantially reduces WPI values across all four WPI versions.

While the stone industry improves the Capacity component through employment generation and tax revenues contributing approximately 16% of gross income, these benefits are outweighed by declining Environment, Use, Access, and Cohesion scores. This pattern is reinforced by the expert-derived weighting scheme, which assigns the highest importance to Access (0.23) and Resources (0.19), both of which are directly affected by untreated stone-cutting wastewater and intensive groundwater abstraction.

Overall, the inclusive WPI variants consistently provide a more comprehensive assessment of mining impacts than the conventional WPI by integrating both quantitative and qualitative dimensions of water security and factoring in the social cohesion dimension. Across both case studies, they demonstrate that the socioeconomic benefits associated with mining are insufficient to offset the cumulative environmental, institutional, and social costs imposed on water security.

4.2.2. Sensitivity Analysis

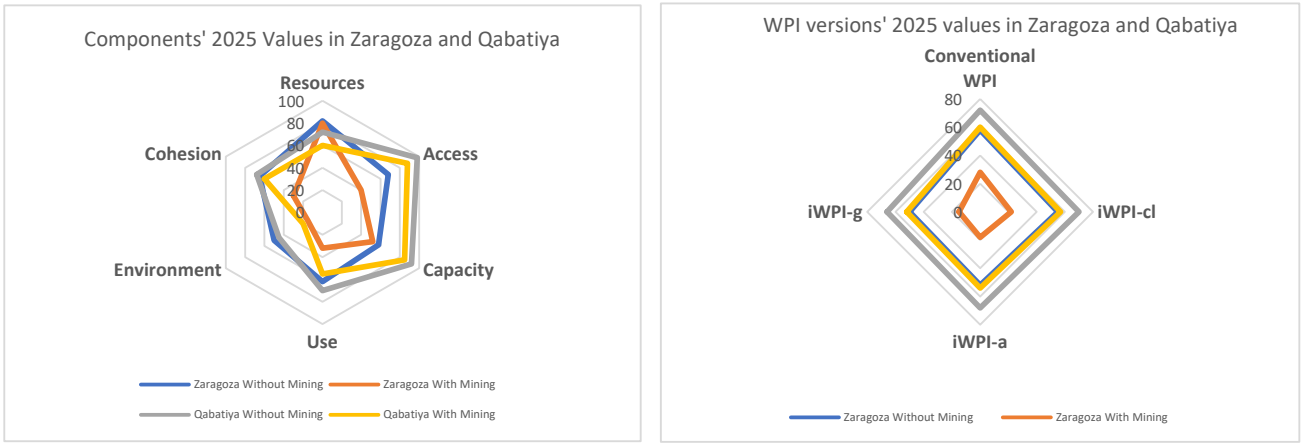
The sensitivity analysis demonstrated that the iWPIa and iWPIg were generally robust to moderate perturbations in component weights. In Qabatiya, the Environment component exerted the greatest influence on index values, followed by Capacity and Use, whereas Access and Cohesion contributed comparatively smaller variations. In Zaragoza, the sensitivity pattern reflected a locality-specific weighting structure, with Capacity and Cohesion expected to exert a stronger influence on the final index due to their higher expert-assigned weights. Across both study areas, variations in component weights did not alter the overall distinction between the with-mining and without-mining scenarios, nor did they affect the temporal trajectories observed between 2010 and 2025. These findings indicate that the principal conclusions of the study are not driven by the specific weighting configuration adopted and that the proposed iWPI framework is robust under plausible alternative weighting assumptions.

4.2.3. Comparative Review for WPI Performance in Both Localities

The four WPI versions further highlight both the commonalities and contrasts between Zaragoza and Qabatiya (Figure 8). In both localities, mining consistently reduced WPI scores relative to the baseline, demonstrating that the economic benefits of extractive activities were insufficient to offset their multidimensional impacts on water security.

In Zaragoza, mining was associated with a widespread deterioration across all WPI versions, reflecting the combined effects of environmental degradation, institutional fragility, and social fragmentation. The inclusive WPI variants (iWPI, iWPIg, and iWPIa) captured these impacts more effectively than the conventional WPI by incorporating qualitative dimensions, including informal governance, weakened social cohesion, and localized mercury contamination, which are not adequately represented by conventional water security indicators. In Qabatiya, improvements in water infrastructure, rehabilitation of the main groundwater well, and employment generated by the stone industry partially strengthened the Capacity component. However, these gains were offset by declining Environment, Use, Access, and Cohesion components, driven by untreated stone-cutting wastewater, intensive groundwater abstraction, and increasing pressure on water resources.

Overall, the comparison demonstrates two distinct hydro-social trajectories. Zaragoza represents a system experiencing accelerated hydro-social deterioration under ASGM, whereas Qabatiya reflects a comparatively more resilient water system in which the progressive expansion of the stone industry is increasingly compromising long-term water security. These findings confirm that the inclusive WPI variants provide a more comprehensive assessment of mining impacts than the conventional WPI by integrating environmental, institutional, and social dimensions into the evaluation of water poverty.



(**a**) (**b**)

Figure 8. Comparative illustration for (**a**) WPI versions and their components in Qabatiya for the year 2025 and (**b**) WPI versions and their components in Zaragoza for the year 2025. Refer to S3.

4.3. The Hydro-Social Resources Paradigm: Zaragoza and Qabatiya in the Context of the Extractive Economy of the Global South

The multidimensional dynamics captured by the iWPI in Zaragoza and Qabatiya reflect broader structural challenges characteristic of the expansion of artisanal and small-scale mining (ASM) frontiers in the Global South. Rather than framing ASM as inherently destructive, the index's performance highlights the complex trade-offs between immediate socioeconomic livelihoods and long-term hydro-environmental stability. The systemic pressure observed on Environment (E), Capacity (C), and Cohesion (Co) aligns with Martínez-Alier's "ecological distribution conflicts [72]," where localized extractive externalities impact vulnerable rural areas lacking institutional mechanisms to safeguard traditional livelihoods [73].

Addressing these systemic challenges and successfully transferring the iWPI framework to other Global South contexts hinges on five critical operational factors:

i. Sociotechnical engineering competencies: Professional capacity to concurrently address the intertwined social and technical drivers of water security [74,75].
ii. Robust intersectional lens: Integration of the key social factors that determine water vulnerability [76–78].
iii. Neutralizing institutional biases: Corrective focus to redirect diagnostic resources away from political centres toward remote, extraction-impacted peripheries [76,77].
iv. Fine-grained spatial disaggregation: Localized data collection at district or community scales to expose intra-regional inequities masked by aggregated averages [76,77].
v. Differentiated formalization pathways: Policy application aimed at guiding inclusive artisanal mining formalization [79].

Consequently, the iWPI provides an empirical roadmap for managing reconfigured "hydrosocial territories" [80] without penalizing the ASM sector—a vital local livelihood driver. Rather than relying on punitive enforcement, this framework equips policymakers across Latin America and the MENA region with a spatially explicit tool to guide differentiated formalization strategies [79], effectively balancing resource extraction with ecosystem restoration and long-term hydrosocial resilience. Despite the diagnostic potential of the iWPI, existing literature remains largely confined to conventional WPI applications at community, district, and watershed scales; to date, no prior studies have deployed this methodological framework within intensive mining contexts.

5. Conclusions

WPI provided an objective, transparent, and comprehensive measurement of the impact of mining. It showed the multifaceted impact of mining on water and sectors affecting the water situation. Despite the marked climatic, hydrological, and geographical disparities between Zaragoza (Colombia) and Qabatiya (Palestine), there is a convergence in the symptoms of water scarcity and water insecurity. Below are the main conclusions of this study:

- Convergence of man-made Stressors: Despite vastly different climatic and geographical contexts, both Qabatiya and Zaragoza demonstrate that mining-related man-made pressures emerged as major drivers of water insecurity that, in many cases, outweighed the influence of natural hydroclimatic constraints.
- Economic-Environmental Paradox: While mining provides a significant economic boost—generating substantial annual incomes—these gains are mathematically offset by sharp declines in the Environment, Use, and Access dimensions of the iWPI in Qabatiya and the Environment, Use, and Social Cohesion components in Zaragoza.
- Superior Sensitivity of iWPI Variants: The inclusive WPI approaches (iWPI, iWPIg, and iWPIa) demonstrated greater sensitivity than the conventional WPI by incorporating social indicators that prevented economic gains from masking severe multidimensional water insecurity.
- Institutional Normalization of Water Insecurity: In both case studies, institutional adaptation to chronic environmental degradation has led to the social normalization of water precariousness—a severe symptom of social fragmentation where prolonged service disruptions and illegal extraction are accepted as standard realities rather than addressed as governance failures.
- Methodological relevance and policy implications: By capturing the divergence between baseline and active mining scenarios, the iWPI proves essential for navigating complex socio-ecological dynamics. Consequently, mitigating water poverty requires moving beyond isolated regulations toward comprehensive, multi-stakeholder governance. While cross-sector collaboration is vital, leadership must explicitly rest with the State as the primary guarantor to orchestrate landscape restoration, strengthen local water governance, and drive territorial livelihood diversification.

6. Recommendations

The respective main recommendations of this study are depicted as follows:

- Upscale the Utilization of iWPI for Comprehensive Monitoring: This study proved that WPI in general and iWPI in specific provide comprehensive, multidisciplinary, easy-to-measure indices to help assess the impact of mining on water conditions. Proper application and monitoring should be based on the factors outlined in Section 4.3.
- Evolve Assessment Frameworks: Adopt an enhanced "Inclusive WPI" that includes a seventh dimension for "Institutional Governance" to specifically track transparency, state presence, regulatory compliance, and institutional effectiveness. The experience of the Household Water Security Index from [81] can help inspire this upgrade.
- Strengthen Local Information Systems: Departments of Statistics and water authorities in both countries are advised to monitor mining-related indicators to support the calculation of more accurate iWPI values and facilitate evidence-based decision-making. This would support the transition from reactive to preventive water governance.
- Integration of sociotechnical competencies: Strengthen local mining and environmental departments by embedding multidisciplinary professionals skilled in sociotechnical diagnosis, conflict mediation, and policy design.

- Facilitate Mining Formalization: Simplify the legal and financial requirements for traditional and small-scale miners to enter the formal sector while providing technical assistance to improve environmental compliance and reduce illegal practices.
- Foster Social Responsibility Funds: Establish dedicated social responsibility funds financed by mining businesses to subsidize water and sanitation access for vulnerable community members and strengthen local social cohesion.
- Integrated Multi-Agency Monitoring: Improve coordination between Water Authorities, Ministries of Agriculture, Environmental Authorities, and Public Health institutions to conduct regular joint inspections and eliminate illegal use or encroachments on water bodies. Furthermore, it is recommended that the iWPI framework be adapted and applied at the watershed scale across the six municipalities of the Bajo Cauca mining district to establish a multidimensional monitoring system capable of supporting context-specific public water management policies rather than generalized one-size-fits-all approaches.
- Institutionalize Corporate Social Responsibility (CSR) frameworks: by mandating that mining and stone-cutting enterprises establish dedicated funds to mitigate localized environmental externalities and subsidize water access for vulnerable populations, thereby addressing the current absence of formal social responsibility mechanisms and rebuilding institutional trust in extractive territories.

7. Limitations

The following are the limitations of the study.

- Financial and logistical constraints: Budgetary limitations restricted operational team size and focus group frequency; expanding sample sizes in future research would refine localized vulnerability perceptions.
- Data scarcity as a diagnostic metric: While the lack of systematic monitoring limited continuous baselines, this data gap inherently reflects low institutional capacity and failed governance.
- Cross-sectional scope: The study provides a static baseline, highlighting the need for longitudinal tracking to capture dynamic, seasonal hydro-social fluctuations.
- Spatial scale misalignment: Disparities between municipal administrative boundaries and hydrological sub-basin limits can compromise indicator precision in anthropocentric frameworks like the iWPI.
- Factoring in climate change impact: While this research isolated mining-specific impacts via counterfactual analysis, the independent role of climate change remains a recognized gap outside the study's current scope. Future iWPI applications should integrate regional climate-risk indices to evaluate how extractive activities function as an accelerating catalyst within hydroclimatically stressed territories.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/mining6040096/s1.: S1: Compiled Needs Assessment report-Qabatiya; S2: List of subcomponents and their Values for Qabatiya and Zaragoza; S3: Radar graphs.

Author Contributions: Conceptualization, A.I., Z.G.-R. and H.J.; methodology, A.I., Z.G.-R. and H.J.; software, H.J.; validation, H.J.; formal analysis, A.I. and Z.G.-R.; investigation, A.I. and Z.G.-R.; data curation, A.I. and Z.G.-R.; writing—original draft preparation, A.I. and Z.G.-R.; writing—review and editing, J.M.M.-A., O.J.R.-B. and H.J.; visualization, A.I. and Z.G.-R.; supervision, J.M.M.-A., O.J.R.-B. and H.J.; project administration, J.M.M.-A. and O.J.R.-B. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and formal approval were not required for this study in accordance with national and institutional legislation, as the study involved anonymous survey data and non-invasive procedures carrying minimal risk to participants. Prior to data collection, institutional permissions and authorisations were obtained from the relevant official bodies in Palestine and Colombia. The study was non-interventional and involved qualitative data collection through KIIs and FGDs. No private, sensitive, or personally identifying information was requested from or collected from participants. Participants were informed about the purpose of the research, the voluntary nature of their participation, how the information would be used, and the measures taken to ensure the confidentiality and anonymity of their contributions. Participants were also informed that they could decline to answer any question or withdraw from the discussion or interview at any time without consequence. Verbal informed consent was obtained from all participants prior to data collection.

Informed Consent Statement: Verbal informed consent was obtained from the participants. Verbal consent was obtained rather than written because, within the local cultural and community context, requesting written signatures was considered potentially intrusive and could create discomfort or mistrust among participants. Before each interview or questionnaire, the researcher explained the purpose of the study, what participation would involve, the voluntary nature of participation, and the measures taken to ensure confidentiality and anonymity. Participants were informed that they could decline to answer any question or withdraw from the study at any time without any consequences. They were given the opportunity to ask questions and seek clarification, after which verbal consent was obtained before data collection began.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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