

Original article

Wastewater Generation and Environmental Pathways in Libya: An Evidence-Based National Accounting Framework

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Abstract

Reliable national wastewater accounts are difficult to construct where direct flow measurements, treatment-plant records, and discharge inventories are incomplete. This study develops an evidence-aware accounting framework to estimate domestic wastewater generation and distinguish sewer-connected from non-networked sanitation pathways across Libya's 22 administrative areas. The analysis integrates official 2021 population estimates, MICS7 (2024–2025) sanitation-connectivity data, a peer-reviewed Sirte household water-consumption benchmark of 255 L/person/day, and a six-month General Company for Water and Wastewater (GCWW) bulk water-supply dataset. Applying a central wastewater-return factor of 0.90 yields a reference generation rate of 229.5 L/person/day and an estimated national domestic wastewater generation of 1.606 million m³/day (586.3 million m³/year). Approximately 0.903 million m³/day is associated with sewer-connected populations and 0.704 million m³/day with non-networked sanitation, while 0.588 million m³/day of the sewer-connected component occurs in the nine coastal administrative areas. Additional scaling scenarios produce higher quantities but are treated as diagnostic rather than empirical national discharge estimates. The principal finding is that Libya's major evidence gap is the absence of a harmonised accounting chain linking water supply, wastewater generation, collection, treatment, reuse, bypass, and discharge. The proposed framework provides a transparent baseline for monitoring, infrastructure planning, and future national wastewater inventories.

Keywords. Wastewater Generation, Sanitation Infrastructure, Sewer Connectivity, Water Accounting.

Introduction

Wastewater management is a core component of urban infrastructure, public sanitation, and environmental protection because failures in collection, treatment, reuse, and final discharge can affect water resources, receiving ecosystems, and public health [1]. In water-scarce settings, wastewater accounting is particularly important because wastewater can represent both a recoverable water and nutrient resource and a pathway for environmental contamination when poorly managed. Recent global assessments therefore distinguish wastewater production, collection, treatment, reuse, and final discharge rather than treating all generated wastewater as untreated discharge [2].

In Libya, wastewater services have deteriorated over several decades under the combined effects of ageing infrastructure, inadequate maintenance, operational and financial constraints, and rapid urban expansion [3]. These pressures occur within a highly uneven sanitation landscape across the country's 22 administrative areas, ranging from centralised sewer networks to on-site and other non-networked systems. The Libya Multiple Indicator Cluster Survey (MICS7), conducted in 2024–2025 across all 22 administrative areas, provides an important national baseline for household sanitation connectivity [4,5]. However, connectivity alone does not establish whether wastewater is effectively collected, treated, reused, bypassed, or safely discharged. Wastewater pollution has been recognised as a major environmental concern in Libya for decades. The First Libyan National Report on the State of the Environment identified municipal and industrial wastewater among the country's principal environmental challenges, while more recent institutional evidence has highlighted continuing infrastructure and operational constraints [6]. Site-specific wastewater investigations reinforce the environmental significance of these pressures. A wastewater treatment facility in Tobruk has been associated with low-efficiency secondary treatment and approximately 18,000 m³/day of discharge, together with measurable effects on receiving coastal water quality [8]. Earlier work near Zawia also linked unlined on-site sanitation to localised groundwater pollution [9]. In Tripoli, reliance on bottled water and concerns regarding the quality and reliability of supplied drinking water further illustrate broader pressures on urban water services [7]. Coastal Libya is also affected by seawater intrusion associated with groundwater overexploitation [10], which can compound the consequences of inadequately contained wastewater. Recent experimental work has likewise highlighted groundwater salinity problems and evaluated treatment approaches for improving saline-water quality [11].

Beyond conventional treatment and polishing, locally available biomass and waste materials may provide opportunities for resource recovery and circular environmental management in Libya. Recent research on native Libyan plant species has demonstrated the potential to extract value-added cellulose from locally available biomass, highlighting opportunities to transform waste resources into useful products and support more sustainable resource management [12]. Such approaches could be further investigated within integrated wastewater-management systems, particularly where locally available biomass can be evaluated for low-cost treatment and resource-recovery applications [12]. SEWAGE-TRACK was developed for the MENA region to spatially disaggregate wastewater generation and track potential pathways. Together, these studies demonstrate the value of separating generation from collection and treatment and of making uncertainty explicit [13]. This study therefore develops a transparent, assumption-explicit national accounting framework for Libya's

domestic wastewater generation and sanitation pathways. Rather than asserting a single measured volume of untreated national discharge, the framework separates observed inputs, derived domestic wastewater generation, sanitation pathways, scenario-based transformations, and unresolved final fates so that each quantity is interpreted according to its evidentiary basis. The objectives are to: (i) reconcile available water-supply, wastewater-generation, and sanitation-connectivity data while explicitly distinguishing water supply from wastewater discharge; (ii) estimate domestic wastewater generation across all 22 administrative areas and distinguish sewer-connected from non-networked pathways; (iii) evaluate a GCWW supply-side screening scenario and expose its assumptions; (iv) quantify sensitivity to the wastewater-return and consumption-benchmark assumptions; (v) assess potential environmental pathways using available peer-reviewed and institutional evidence; and (vi) identify the principal infrastructure, institutional, monitoring, and regulatory gaps that constrain effective wastewater management in Libya. The resulting framework provides a quantitative baseline for future field measurement, national wastewater-flow accounting, infrastructure rehabilitation, and improved environmental monitoring.

Methods

Study Design and Evidence Hierarchy

The analysis follows a mass-balance logic in which water supply, domestic use, wastewater generation, sanitation connectivity, collection, treatment, reuse, bypass, and final discharge are treated as distinct quantities rather than a single interchangeable flow. Evidence is explicitly classified as observed/official, survey-derived, literature-derived, model-derived, or scenario-assumed (Table 1), which prevents a scenario output from being presented as a measured national flow. (Figure 1) summarises the resulting accounting framework.

Table 1. Data sources and evidence classification used in this study

Parameter	Reference period	Source	Evidence type	Use in this study
Population	2021	Statistics and Census Authority [18]	Official population estimate	Input; high relative confidence
Sanitation connectivity	2024–2025	MICS7 / UNICEF [4,5]	Nationally representative household survey	Pathway allocation; high confidence
Domestic water consumption	Sirte, winter	Alharsha et al. [14]	Measured household/end-use study	Reference benchmark; medium confidence for national extrapolation
GCWW bulk water supply	Six months, 2026	GCWW administrative dataset [19]	Reported supply by source and region	Screening input; high confidence for reported supply
Treatment/discharge evidence	Site-specific	Peer-reviewed Libyan studies [8,9]	Facility- and site-level observations	Local evidence; not nationally scalable without further data

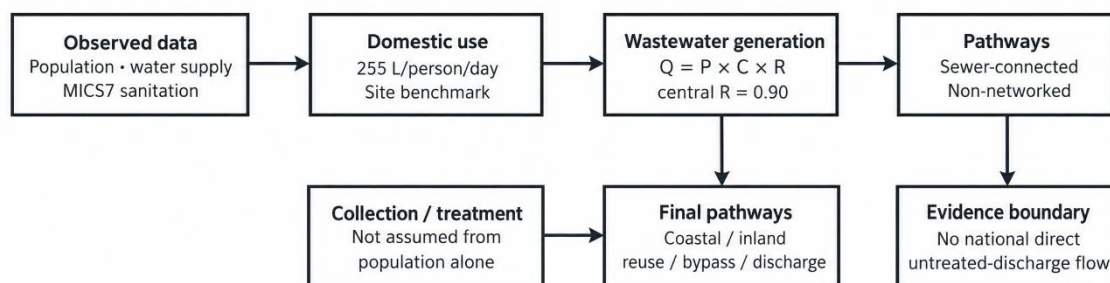


Figure 1. Evidence-aware National wastewater accounting framework used in this study

Population and Sanitation-Connectivity Baseline

The most recent full population census in Libya was conducted in 2006; the Statistics and Census Authority [17] subsequently published estimated district-level population counts for 2021, which are used here as the demographic baseline (Table 2). MICS7 sanitation-connectivity data [5], collected in 2024–2025 across all 22 administrative regions, are combined with this population baseline to allocate each region's population between sewer-connected and non-networked pathways (Table 2). At the national level, MICS7 reports 52% sewer connection and 47% septic-tank use, leaving

approximately 1% in other/unknown categories; for modelling purposes, the full non-networked share is therefore treated as the complement of the sewer-connected share (48% nationally), and the same convention is applied at the regional level.

Table 2. 2021 population estimates and MICS7 (2024–2025) sanitation connectivity by administrative area

Administrative area	Population (2021)	Sewer-connected (%)	Non-networked (%)
Ajdabiya–Al Wahat	217,592	95	5
Al Jabal Al Akhdar	254,518	91	9
Al Jabal Al Gharbi	381,662	51	49
Al Jafara	558,726	20	80
Al Jufra	61,662	85	15
Zawiya	357,631	12	88
Kufra	56,493	76	24
Al Marj	231,661	84	16
Al Marqab	541,810	12	88
Nuqat Al Khams	356,049	12	88
Benghazi	821,787	91	9
Derna	205,400	99	1
Sebha	158,504	92	8
Sirte	174,155	47	53
Tobruk	198,599	82	18
Tripoli	1,317,009	80	20
Ghat	28,214	54	46
Murzuq	95,777	36	64
Misrata	675,802	24	76
Nalut	115,934	34	66
Wadi Al Hayaa	93,401	48	52
Wadi Al Shatii	97,010	58	42
National total	6,999,396	52	48

Sources: Statistics and Census Authority [18]; Statistics and Census Authority & UNICEF [5].

GCWW Bulk Water-Supply Data

A six-month (2026) GCWW administrative dataset reports bulk water supply by source (river-system supply, seawater-desalination plants, groundwater wells and springs, and well-water desalination plants) for eight administrative groupings (Table 3) [19]. The dataset totals 493,374,709 m³ over six months, equivalent to 986.75 million m³/year or approximately 2.703 million m³/day (Table 4). Because this bulk figure aggregates agricultural, industrial, domestic, and other uses together with distribution losses — with agricultural use alone reported to account for roughly 78% of national water use it is not converted directly into a wastewater estimate; it is retained only as an independent screening input (Section 2.6).

Table 3. GCWW water-supply quantity by source and region, six months, 2026 (m³)

Region	River-water system	Seawater desalination	Groundwater (wells & springs)	Well-water desalination	Total (6 months)
Tripoli	36,000,000	—	39,823,200	—	75,823,200
Benghazi Plain	45,091,080	54,000	31,547,520	—	76,692,600
Jabal al-Akhdar	—	2,662,224	73,117,980	214,465	75,994,669
Eastern Central	44,303,760	—	10,762,200	—	55,065,960
Central	32,400,000	1,547,280	58,876,200	—	92,823,480
Western	—	2,578,500	35,781,480	180,000	38,539,980
Nafusa Mountains (Jabal al-Gharbi)	3,600,000	—	25,773,840	—	29,373,840
Southern	—	—	49,060,980	—	49,060,980
Total	161,394,840	6,842,004	324,743,400	394,465	493,374,709

Table 4. Calculated annual and daily GCWW water-supply equivalents by region

Region	Six-month total (m ³)	Annual (m ³ /year)	Average daily (m ³ /day)
Tripoli	75,823,200	151,646,400	415,469.6
Benghazi Plain	76,692,600	153,385,200	420,233.4
Jabal al-Akhdar	75,994,669	151,989,338	416,409.2
Eastern Central	55,065,960	110,131,920	301,731.3
Central	92,823,480	185,646,960	508,621.8
Western	38,539,980	77,079,960	211,178.0
Nafusa Mountains (Jabal al-Gharbi)	29,373,840	58,747,680	160,952.6
Southern	49,060,980	98,121,960	268,827.3
Total	493,374,709	986,749,418	2,703,423.1

Source: GCWW [18], unpublished six-month administrative water-supply dataset supplied for this study.

Domestic Wastewater Generation Model

A peer-reviewed field study in Sirte reported average household water consumption of 255 L/person/day during the winter season [14]. This study uses that value as a reference domestic-consumption benchmark rather than as a direct national measurement. Domestic wastewater generation for administrative area *i* is calculated as:

$$Q_{\text{dom},i} = P_i \times C \times R$$

where $Q_{\text{dom},i}$ is domestic wastewater generation (m³/day), P_i is the 2021 population of area *i*, C is domestic water consumption (m³/person/day), and R is the wastewater-return factor. In the central scenario, $C = 0.255$ m³/person/day and $R = 0.90$, giving $q_{\text{dom}} = 0.2295$ m³/person/day (229.5 L/person/day). In the sensitivity scenario, $R = 0.80$, giving $q_{\text{dom}} = 0.2040$ m³/person/day (204.0 L/person/day). The return factor is an explicit modelling assumption rather than a measured national coefficient; because region-specific consumption measurements are unavailable, the analysis reports scenario sensitivity rather than a formal statistical confidence interval.

Sanitation Pathways

MICS7 sanitation-connectivity percentages (Table 2) are combined with the domestic wastewater estimate for each administrative area to split it into sewer-connected and non-networked pathways:

$$Q_{\text{sewer},i} = Q_{\text{dom},i} \times f_{\text{sewer},i}$$

$$Q_{\text{nonnetwork},i} = Q_{\text{dom},i} \times (1 - f_{\text{sewer},i})$$

Non-networked sanitation is treated as a potential environmental-risk pathway rather than direct proof of groundwater contamination: actual contaminant transport depends on containment design, maintenance, overflow behaviour, soil properties, groundwater depth, hydraulic gradients, and local hydrogeology, consistent with the site-specific evidence reported near Zawiya [9] and the broader coastal groundwater vulnerability documented for the Tripoli area [10].

GCWW Supply-Side Screening Calculation

Because bulk water supply spans multiple uses, it is not used as the central wastewater-generation estimate. For comparability with earlier assessments of this dataset, a diagnostic calculation applies a 0.80 return factor to the full bulk supply of 2.703 million m³/day, giving 2.163 million m³/day; dividing this by a historical 0.54 planned-population-coverage assumption produces approximately 4.005 million m³/day. This figure is retained only as an upper-bound screening scenario, since it incorporates agricultural water, distribution losses, and a linear population-scaling assumption rather than measured domestic wastewater generation.

Scenario Transformation Retained From Earlier Assessments

Earlier assessments of this dataset used a 0.52 municipal-share factor to transform domestic wastewater into a combined municipal-and-industrial-equivalent quantity:

$$Q_{0.52} = Q_{\text{dom}} / 0.52$$

This transformation is retained here solely to allow reconciliation with earlier headline figures (Section 4.1). Because the 0.52 value is not an observed national industrial-wastewater fraction, $Q_{0.52}$ is not used as the central result of this study and is not described as measured industrial effluent or untreated discharge.

Coastal and Inland Classification

Nine administrative areas are classified as coastal for the pathway analysis: Tripoli, Benghazi, Misrata, Al Marqab, Zawiya, Nuqat Al Khams, Derna, Tobruk, and Sirte. Ajdabiya, Al Wahat and the remaining administrative areas are treated as inland under this simplified receiving-pathway classification. Sewer-connected flow in coastal areas is described as a potential coastal receiving-water pathway, not as directly measured sea discharge, because a complete national dataset separating collection, treatment, bypass, reuse, and final discharge at city level is not available.

Sensitivity Analysis

Sensitivity is evaluated first for the wastewater-return factor (0.80 versus 0.90) while holding the 255 L/person/day consumption benchmark constant. An additional stress-test matrix varies both the consumption benchmark and the return factor. The matrix is presented as an evidence-bounded scenario envelope rather than a probability distribution because the available Libyan data do not support defensible parameter-specific probability distributions. This approach is consistent with established wastewater-accounting literature, which emphasises separation of production, collection, treatment and reuse, spatial disaggregation, and explicit validation or uncertainty assessment where direct measurements are incomplete. Indirect flow-estimation studies further show that spatial data quality, population characteristics and temporal variability can materially affect reliability when direct measurements are unavailable [15,16]. Internal consistency checks are therefore used instead of claiming external validation: (i) national domestic wastewater equals sewer-connected plus non-networked pathways; (ii) regional estimates sum to the national total; (iii) daily estimates annualise consistently over 365 days; and (iv) GCWW source totals reconcile to the reported six-month total. These checks establish arithmetic consistency, not empirical accuracy. Sensitivity is evaluated first for the wastewater-return factor (0.80 versus 0.90) while holding the 255 L/person/day consumption benchmark constant. An additional scenario matrix varies both the consumption benchmark and the return factor to characterise the structural sensitivity of the model (Section 3.7). These are scenario ranges rather than statistical confidence intervals, since the supplied evidence base does not support a defensible probability distribution for either parameter.

Results

GCWW Bulk Water-Supply Screening Result

(Table 5) summarises the supply-side screening calculation. The approximately 4.005 million m³/day value is a diagnostic upper bound and is not carried forward as the national wastewater-generation estimate.

Table 5. GCWW bulk water-supply screening results

Metric	Value	Interpretation
Six-month reported bulk water supply	493,374,709 m ³	Observed GCWW administrative dataset
Annualised bulk water supply	986.75 million m ³ /year	Annualised from six-month total
Average bulk water supply	2.703 million m ³ /day	Supply, not wastewater
Diagnostic return-factor case ($\times 0.80$)	2.163 million m ³ /day	Screening only
Diagnostic 54%-coverage scaling case	4.005 million m ³ /day	Upper-bound screening scenario only

Central Domestic Wastewater Generation

Using the 2021 national population total of 6,999,396 and the central generation factor of 229.5 L/person/day, the model estimates 1.606 million m³/day (586.3 million m³/year) of domestic wastewater generation nationally (Table 6).

Table 6. Central-scenario domestic wastewater generation, national totals.

Component	Daily estimate (m ³ /day)	Annual estimate (million m ³ /year)
Domestic wastewater generated	1,606,361	586.3
Sewer-connected pathway	902,635	329.5
Non-networked pathway	703,727	256.9
Coastal sewer-connected pathway	588,056	214.6
Inland sewer-connected pathway	314,579	114.8

Regional Domestic Wastewater Pathways

(Table 7) presents the estimated domestic wastewater generation across the 22 administrative areas, disaggregated into sewer-connected and non-networked pathways. At the national level, total domestic wastewater generation was estimated at 1,606,361.4 m³/day, with 703,726.7 m³/day (43.8%) associated with non-networked pathways.

Table 7. Regional domestic wastewater pathways, central scenario (m³/day)

Administrative area	Population (2021)	Sewer connection (%)	Domestic wastewater (m ³ /day)	Sewer pathway (m ³ /day)	Non-networked pathway (m ³ /day)
Ajdabiya–AlWahat	217,592	95	49,937.4	47,440.5	2,496.9
Al Jabal Al Akhdar	254,518	91	58,411.9	53,154.8	5,257.1
Al Jabal Al Gharbi	381,662	51	87,591.4	44,671.6	42,919.8
Al Jafara	558,726	20	128,227.6	25,645.5	102,582.1
Al Jufra	61,662	85	14,151.4	12,028.7	2,122.7
Zawiya	357,631	12	82,076.3	9,849.2	72,227.2

Kufra	56,493	76	12,965.1	9,853.5	3,111.6
Al Marj	231,661	84	53,166.2	44,659.6	8,506.6
Al Marqab	541,810	12	124,345.4	14,921.5	109,424.0
Nuqat Al Khams	356,049	12	81,713.3	9,805.6	71,907.7
Benghazi	821,787	91	188,600.1	171,626.1	16,974.0
Derna	205,400	99	47,139.3	46,667.9	471.4
Sebha	158,504	92	36,376.7	33,466.5	2,910.1
Sirte	174,155	47	39,968.6	18,785.2	21,183.3
Tobruk	198,599	82	45,578.5	37,374.4	8,204.1
Tripoli	1,317,009	80	302,253.6	241,802.9	60,450.7
Ghat	28,214	54	6,475.1	3,496.6	2,978.5
Murzuq	95,777	36	21,980.8	7,913.1	14,067.7
Misrata	675,802	24	155,096.6	37,223.2	117,873.4
Nalut	115,934	34	26,606.9	9,046.3	17,560.5
Wadi Al Hayaa	93,401	48	21,435.5	10,289.1	11,146.5
Wadi Al Shatii	97,010	58	22,263.8	12,913.0	9,350.8
National total	6,999,396	52	1,606,361.4	902,634.7	703,726.7

As shown in (Figure 2), the largest non-networked volumes occur in Misrata (117,873.4 m³/day), Al Marqab (109,424.0 m³/day), and Al Jafara (102,582.1 m³/day), followed by Zawiya and Nuqat Al Khams. The ten areas shown in (Figure 2) collectively account for approximately 90% of the national non-networked volume, indicating a strong spatial concentration. The results further show that areas with low sewer-network coverage can generate substantial non-networked volumes, particularly where low coverage coincides with relatively large populations. These findings provide a basis for prioritising areas for more detailed assessment of wastewater collection, on-site sanitation, treatment, and potential discharge pathways.

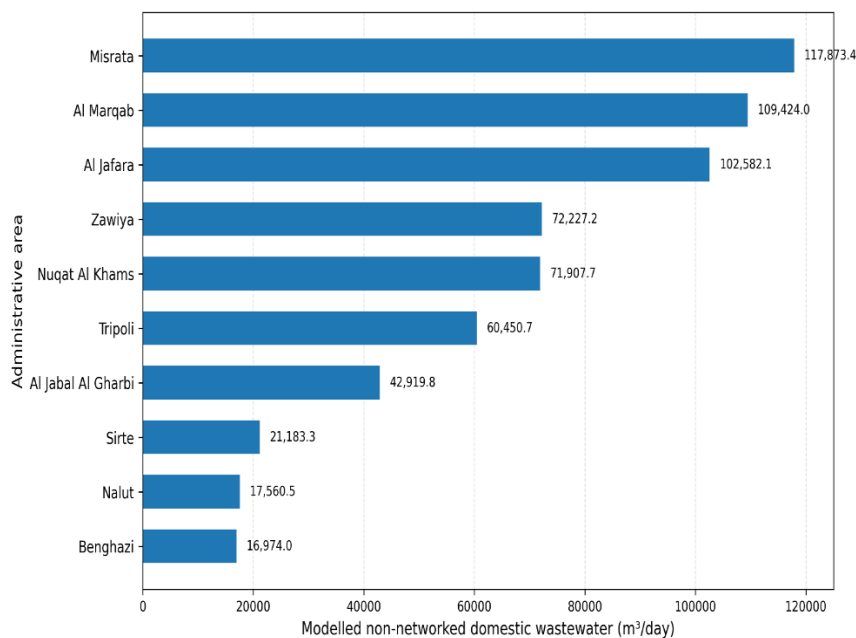


Figure 2. Administrative areas with the largest modelled non-networked domestic wastewater pathway volumes.

Coastal Receiving-Water Pathway

The nine coastal administrative areas account for 588,055.8 m³/day of modelled sewer-connected domestic wastewater under the central scenario (Table 8), and this is interpreted as a potential coastal receiving-water pathway rather than directly measured sea discharge, because a national dataset separating collection, treatment, bypass, reuse, and final discharge at city level is not available. Local treatment evidence reinforces the need for this distinction: in Tobruk, Elbagrmi et al. [8] reported secondary treatment with low operational efficiency and approximately 18,000 m³/day of discharge associated with measurable coastal water-quality impacts, demonstrating that treatment performance and final outfall flow must be measured directly rather than inferred from sewer connectivity alone.

Table 8. Modelled wastewater production in coastal administrative areas, central scenario

Coastal area	Population (2021)	Sewer network (%)	Sewer pathway (m ³ /day)	Non-networked (%)	Non-networked pathway (m ³ /day)
Tripoli	1,317,009	80	241,802.9	20	60,450.7
Benghazi	821,787	91	171,626.1	9	16,974.0
Misrata	675,802	24	37,223.2	76	117,873.4
Al Marqab	541,810	12	14,921.5	88	109,424.0
Zawiya	357,631	12	9,849.2	88	72,227.2
Nuqat Al Khams	356,049	12	9,805.6	88	71,907.7
Derna	205,400	99	46,667.9	1	471.4
Tobruk	198,599	82	37,374.4	18	8,204.1
Sirte	174,155	47	18,785.2	53	21,183.3
Total	4,648,242	55.1	588,055.8	44.9	478,715.7

Non-networked and Inland Pathways

The remaining thirteen (predominantly inland) administrative areas account for 314,578.9 m³/day of modelled sewer-connected pathway flow and 225,011.0 m³/day of non-networked pathway flow (Table 9). Nationally, the central model estimates 703,726.7 m³/day of domestic wastewater associated with non-networked sanitation; this volume identifies wastewater for which on-site containment, emptying, leakage, overflow, or infiltration must be resolved by field data — it is not, by itself, evidence of groundwater discharge.

Table 9. Modelled wastewater production in non-coastal (inland) administrative areas, central scenario

Inland area	Population (2021)	Sewer network (%)	Sewer pathway (m ³ /day)	Non-networked (%)	Non-networked pathway (m ³ /day)
Ajdabiya–Al Wahat	217,592	95	47,440.5	5	2,496.9
Al Jabal Al Akhdar	254,518	91	53,154.8	9	5,257.1
Al Jabal Al Gharbi	381,662	51	44,671.6	49	42,919.8
Al Marj	231,661	84	44,659.6	16	8,506.6
Al Jufra	61,662	85	12,028.7	15	2,122.7
Al Jafara	558,726	20	25,645.5	80	102,582.1
Kufra	56,493	76	9,853.5	24	3,111.6
Sebha	158,504	92	33,466.5	8	2,910.1
Nalut	115,934	34	9,046.3	66	17,560.5
Wadi Al Hayaa	93,401	48	10,289.1	52	11,146.5
Murzuq	95,777	36	7,913.1	64	14,067.7
Ghat	28,214	54	3,496.6	46	2,978.5
Wadi Al Shatii	97,010	58	12,913.0	42	9,350.8
Total	2,351,154	58.3	314,578.9	41.7	225,011.0

Diagnostic 0.52 Municipal-and-Industrial-Equivalent Scenario

(Table 10) reports the 0.52 scaling transformation (Section 2.7) applied to the central and sensitivity domestic wastewater estimates, alongside the original GCWW supply-side diagnostic, for reconciliation purposes only.

Table 10. Diagnostic scenario-scaled quantities (not used as the study's central result)

Quantity	Million m ³ /day	Status
Central domestic wastewater	1.606	Primary model result
0.52 scenario transformation (central)	3.089	Scenario-based; not empirically grounded
Sensitivity domestic wastewater (R = 0.80)	1.428	Sensitivity model result
0.52 scenario transformation (R = 0.80)	2.746	Scenario-based; not measured
GCWW supply-side diagnostic upper bound	4.005	Supply-side screening only

The scaled coastal municipal-and-industrial-equivalent pathway (588,055.8 / 0.52) is approximately 1,130,876.6 m³/day (413.7 million m³/year), and the scaled non-networked municipal-and-industrial-equivalent pathway (703,726.7 / 0.52) is approximately 1,353,320.6 m³/day (493.96 million m³/year), together giving a total scaled pathway of approximately 3,089,156.5 m³/day (1,127.54 million m³/year) under the central scenario and 2,745,916.9 m³/day (1,002.26 million m³/year) under the 0.80 return-factor sensitivity case. As emphasised throughout this study, these scaled figures should be read as scenario diagnostics that reconcile the present framework with earlier assessments of the same underlying dataset, not as measured national wastewater or discharge volumes.

Sensitivity Analysis

(Table 11) presents the full sensitivity matrix across plausible domestic-consumption and wastewater-return-factor combinations. At the reference consumption of 255 L/person/day, changing the return factor from 0.80 to 0.90 changes the national domestic wastewater-generation estimate from 1.428 to 1.606 million m³/day — a variation of roughly 12%, which illustrates that the central estimate is linearly sensitive to the return-factor assumption within its plausible range.

Table 11. Sensitivity of national domestic wastewater generation (million m³/day) to consumption benchmark and return factor.

Consumption (L/person/day)	R = 0.70	R = 0.80	R = 0.90	R = 0.95
200	0.980	1.120	1.260	1.330
225	1.102	1.260	1.417	1.496
255	1.249	1.428	1.606	1.696
285	1.396	1.596	1.795	1.895
300	1.470	1.680	1.890	1.995

Internal Accounting Consistency and Evidence Validation

The accounting identities close exactly at the model level: 1,606,361.4 m³/day of national domestic wastewater equals 902,634.7 m³/day of sewer-connected pathway flow plus 703,726.7 m³/day of non-networked pathway flow. The 22 regional estimates sum to the same national total, while the GCWW source totals reconcile to 493,374,709 m³ over six months and 986,749,418 m³/year after annualization. These checks verify numerical consistency within the model but do not independently validate the 229.5 L/person/day generation coefficient or the sanitation-connectivity estimates.

Discussion

Interpreting The National Wastewater Estimate Responsibly

The most defensible national quantitative result of this study is the central domestic wastewater-generation estimate of approximately 1.606 million m³/day, derived directly from an empirical Sirte consumption benchmark, a stated return-factor assumption, and official 2021 population estimates. It is a modelled generation estimate, not a direct national flow measurement. The 3.089 million m³/day value reported in Section 3.6 should not replace this central estimate. It is produced by dividing the domestic estimate by 0.52, where 0.52 is not an observed national industrial-wastewater share but a scaling assumption carried forward from earlier assessments of this dataset. The transformation is useful for tracing the origin of the earlier headline figure and for enabling direct comparison with that prior work, but it cannot support a claim that Libya generates or discharges 3.089 million m³/day of combined municipal and industrial wastewater. Likewise, the approximately 4.005 million m³/day GCWW-derived figure (Section 2.6) is a screening upper bound obtained by applying a return factor to total bulk water supply and then rescaling by a historical coverage assumption; it is not directly comparable to a domestic wastewater-generation estimate, because bulk supply includes agricultural water, industrial water, and distribution losses that do not map one-to-one onto municipal wastewater. The gap between the 1.606 million m³/day domestic estimate, the 3.089 million m³/day scenario-scaled figure, and the 4.005 million m³/day supply-side diagnostic is therefore a methodological artefact of three different accounting bases rather than evidence of a specific volume of infrastructure loss.

Closing this data gap by measuring, rather than inferring, the links between supply, generation, collection, treatment, and discharge is itself among the most important infrastructure-management priorities identified by this study. The methodological structure adopted here is consistent with established wastewater-accounting research. Jones et al. [2] constructed a global database by harmonising country-level information, estimating missing values, spatially downscaling results, and validating the estimates. developed SEWAGE-TRACK specifically for MENA and demonstrated that national wastewater totals can be spatially disaggregated into urban/rural and coastal/riparian/inland components and then classified by potential fate. The Libya framework is deliberately more conservative: it does not infer treatment or final discharge from sewer connection and does not substitute regional MENA averages for Libya-specific evidence. Two methodological studies retrieved through SciSpace reinforce this principle. Schilling and Tränckner [14] showed that wastewater discharge can be estimated from spatial building data when direct flow data are inaccessible, but highlighted commuting, building-use heterogeneity, and data quality as important limitations. Kanneganti et al. [15] demonstrated that sewage-flow estimation can also be supported by demographic and environmental predictors when direct sanitary-sewer measurements are not always feasible. These studies support indirect estimation in data-poor settings, but also strengthen the case for explicit sensitivity analysis and eventual validation against measured flows. Qadir et al. [16] further emphasised that wastewater reporting is constrained by inconsistent terminology and incomplete information on collection, treatment and reuse. This is directly relevant to Libya because the present framework prevents generated wastewater, collected wastewater, treated wastewater and environmental release from being treated as interchangeable quantities. The methodological structure adopted here is consistent with the direction of established international wastewater-accounting research. combined multiple country-level sources, statistical estimation, spatial downscaling, validation, and explicit uncertainty rather than relying on a single national water-supply figure, and applied an analogous, spatially explicit logic to separate wastewater generation from fate across the MENA region.

The present Libya-focused framework is less data-rich than either of these regional or global efforts, reflecting the country's current monitoring capacity, but it adopts the same conceptual principle: generation, collection, treatment, reuse, and environmental release are represented as distinct, separately evidenced stages rather than collapsed into a single “wastewater discharge” figure.

Comparing Environmental Pathway

The sewer-connected estimate identifies wastewater entering a networked sanitation pathway, not wastewater necessarily reaching the sea untreated; treatment, bypass, pumping failure, leakage, reuse, and final discharge must be measured separately at each facility. Similarly, the non-networked estimate identifies wastewater associated with on-site sanitation without establishing contaminant transport to groundwater. This distinction is particularly important in coastal Libya, where a sewer connection may ultimately lead to a marine outfall of variable treatment status as documented at Tobruk [8], while on-site systems in inland or peri-urban areas may create localised soil and groundwater risks, as documented near Zawiya [9], without producing a measurable surface-water discharge. Given that coastal aquifers in northern Libya are already under stress from overexploitation and seawater intrusion [10], uncontrolled non-networked sanitation represents a compounding rather than an isolated risk. These are different pathways with different risk profiles and monitoring requirements, and should not be aggregated into a single “untreated discharge” quantity.

Regional Limitations of the Baseline Consumption Figure

The Sirte study [14] provides a valuable empirical anchor, but its national extrapolation is the principal source of structural uncertainty in the current domestic wastewater estimate. Household water use varies with climate, household size, supply reliability, income, metering practice, and local service conditions, all of which differ across Libya's 22 administrative regions. A national inventory should therefore replace the single Sirte benchmark with region-specific measurements, or harmonised metered-use data, as these become available.

Infrastructure and Governance Implications

The results point to a monitoring problem that is at least as pressing as the underlying infrastructure problem. A defensible national wastewater balance requires a common reporting architecture in which GCWW and relevant environmental and municipal institutions report treatment-plant inflow and outflow, bypass events, pumping-station operation, network losses, sludge handling, reuse, and final discharge, linked to GIS locations and population-served estimates. The non-networked pathway also requires targeted monitoring: the administrative areas with the highest modelled non-networked volumes (Table 7; Figure 2) — notably Misrata, Al Marqab, Al Jafara, Zawiya, and Nuqat Al Khams — represent screening priorities for septic-system condition surveys, emptying-practice assessment, and groundwater vulnerability screening. Priority setting should, however, be based on measured vulnerability and environmental evidence rather than an assumption that all non-networked wastewater contaminates groundwater.

Evidence Boundaries and Limitations

Several limitations bound the interpretation of these results. First, the 255 L/person/day consumption value is measured in Sirte and extrapolated nationally as a benchmark (Section 4.4). Second, the 0.90 central return factor is an explicit scenario assumption rather than a measured national coefficient; 0.80 is retained as a sensitivity case. Third, population data are from 2021 while MICS7 sanitation data were collected in 2024–2025; this temporal harmonisation is necessary because the two datasets provide complementary information, but it introduces a time-alignment limitation given ongoing population change. Fourth, the 0.52 scaling factor has no sufficiently documented national empirical basis and is therefore excluded from the central estimate, being retained only as a diagnostic (Sections 2.7 and 3.6). Fifth, no complete national inventory of industrial wastewater generation, collection, treatment, or discharge is available in the evidence base used here. Sixth, the model estimates volumes but does not quantify pollutant loads, pathogen concentrations, groundwater contaminant concentrations, or epidemiological outcomes; claims concerning environmental and health impacts are therefore restricted to the risks and location-specific evidence documented in the cited literature. Finally, the model cannot distinguish, at national scale, between treated discharge, bypass, reuse, leakage, and direct untreated discharge; resolving this requires direct flow monitoring at treatment plants, pumping stations, outfalls, and representative on-site systems.

Validation Strategy for Future National Monitoring

The present analysis should be regarded as a baseline accounting model rather than a completed national flow-monitoring system. The most informative validation program would compile continuous flow measurements at representative treatment-plant influent and effluent points, pumping stations and selected sewer catchments, together with rainfall, served-population, water-consumption and treatment-operation data. A stratified design should include large coastal cities, smaller coastal settlements, inland cities and areas dominated by on-site sanitation. These measurements could be used to estimate region-specific return factors, calibrate consumption-to-wastewater relationships, and replace the present scenario envelope with empirical uncertainty distributions. This would convert the current screening framework into a validated national wastewater inventory.

Conclusions and Recommendations

This study develops an evidence-aware national accounting framework for domestic wastewater generation and sanitation pathways in Libya. Under the central scenario, the 22 administrative areas generate approximately 1.606 million m³/day (586.3 million m³/year) of domestic wastewater, of which approximately 0.903 million m³/day is associated with sewer-connected populations and 0.704 million m³/day with non-networked sanitation; approximately 0.588 million m³/day of the sewer-connected component occurs in the nine coastal administrative areas. The principal methodological conclusion is that Libya currently lacks the evidence required to report a single, defensible national volume of untreated wastewater discharge. The 3.089 million m³/day and approximately 4.005 million m³/day figures examined in this study can be retained only as scenario diagnostics with their assumptions fully exposed (Sections 3.6 and 4.1); they should not be presented, in this or future work, as measured national discharge. The overall wastewater challenge in Libya is therefore best understood not as a simple shortage of water, but as the fragmentation of water-supply, sanitation, treatment, and discharge systems and the absence of a unified national flow-monitoring framework. The principal methodological contribution of this framework is accordingly the explicit separation of water supplied, wastewater generated, wastewater entering sewer or on-site pathways, wastewater collected, wastewater treated, wastewater reused, and wastewater finally discharged, a structure consistent with modern international wastewater-accounting approaches and a foundation for future national monitoring.

Recommended National Monitoring Architecture

1. Establish a standardised GCWW wastewater-flow reporting protocol covering treatment-plant inflow/outflow, bypass events, pumping-station performance, network losses, sludge handling, reuse, and final discharge volumes.
2. Create a national geospatial WASH database linking population, sewer networks, treatment plants, pumping stations, outfalls, septic-service areas, groundwater vulnerability, and receiving environments.
3. Replace the single Sirte consumption benchmark with region-specific household consumption measurements and, where possible, metered domestic-use data.
4. Develop a national industrial-wastewater inventory by sector, including water use, effluent generation, treatment status, discharge location, and monitoring frequency.
5. Conduct targeted field monitoring of coastal outfalls and high-risk non-networked sanitation areas, including groundwater and receiving-water quality monitoring where hydrogeological conditions justify it.
6. Report national wastewater balances with explicit uncertainty ranges and with separate quantities for generation, collection, treatment, reuse, bypass, and final discharge.
7. Prioritise rehabilitation of treatment and pumping infrastructure using measured treatment performance and actual flow data, rather than nominal plant capacity alone.

Legislative and Environmental Enforcement

Environmental agencies should establish routine sampling and inspection programs for coastal outfalls, inland receiving environments, groundwater near high-risk on-site sanitation areas, and treatment plants, with legal and regulatory claims concerning penalties and prosecutions grounded in current primary legal documents and official enforcement records. An integrated national WASH surveying program — combining MICS, population statistics, GCWW supply records, wastewater-flow measurements, treatment-plant records, and GIS infrastructure mapping — should be funded, with international support where appropriate, to align bulk-supply models with actual point-of-discharge realities.

Technical and Infrastructure Interventions

Priority should be given to the rehabilitation of treatment and pumping infrastructure, expansion of sewer coverage in high-risk peri-urban areas identified in Table 7 and Figure 2, controlled emptying and containment of septic systems, and beneficial reuse of appropriately treated wastewater, with treatment objectives matched to intended end use and receiving environment and continuous monitoring of effluent quality. Low-cost, nature-based polishing steps also merit evaluation for resource-constrained coastal settings; for example, biosorption of organic pollutants using locally available seagrass biomass has been demonstrated at bench scale for methylene blue removal [19]. Recent research on native Libyan biomass and acid-activated Libyan bentonite highlights the potential of locally sourced materials for low-cost environmental applications, including supplementary treatment for improving effluent quality. While bentonite demonstrated enhanced adsorption performance for sulfur removal from model oil and commercial diesel, further evaluation is needed to determine its effectiveness for specific wastewater contaminants under realistic conditions [12, 20].

Statements

Data Availability

The analysis uses the supplied GCWW six-month administrative water-supply dataset, 2021 population estimates, MICS7 sanitation-connectivity data, and published peer-reviewed studies cited herein. Because some administrative datasets are not publicly archived, the underlying regional water-supply and wastewater-pathway data are provided in the tables of this manuscript; the full underlying dataset should be deposited in an institutional or public repository where permissions permit, to support independent verification and reuse.

Author contributions

R.F., O.S., and O.S. contributed to the conception and design of the study. R.F., O.S., and O.M.S. developed the accounting framework and model equations, performed data analysis, and prepared the initial draft of the manuscript. E.A.E. and A.M. contributed to the interpretation of results and critical revision of the manuscript, while A.A. contributed to the final refinement of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Ethical approval

This study used publicly reported and administratively supplied aggregate data; it did not involve human or animal subjects and did not require ethical approval.

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