

Societal and Economic Developments Leading to Water Resources Deterioration versus Mitigation Measures in Semi-Arid Areas—Case Study: Jordan, Where Do We Stand?

Elias Salameh¹, Tino Rödiger^{2,3}, Christian Siebert^{2,3}

¹Department of Geology, University of Jordan, Amman, Jordan

²Department of Catchment Hydrology, Helmholtz-Centre for Environmental Research UFZ, Halle (Saale), Germany

³H3 GmbH, Jena, Germany

Email: salameli@ju.edu.jo

How to cite this paper: Salameh, E., Rödiger, T. and Siebert, C. (2025) Societal and Economic Developments Leading to Water Resources Deterioration versus Mitigation Measures in Semi-Arid Areas—Case Study: Jordan, Where Do We Stand? *Journal of Water Resource and Protection*, 17, 611-635.

<https://doi.org/10.4236/jwarp.2025.178032>

Received: July 21, 2025

Accepted: August 23, 2025

Published: August 26, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution-NonCommercial International License (CC BY-NC 4.0).

<http://creativecommons.org/licenses/by-nc/4.0/>



Open Access

Abstract

During the last few decades, countries in the arid and semiarid climate zones have witnessed increases in socio-economic development. This development has been challenged, on the one hand, by scarce water resources and water quality deterioration, and on the other by the mitigation measures and programs to balance between the negative water development impacts and the mitigation measures. These issues were additionally complicated by unevenly distributed water resources within the territory of countries and with limited relation to water demand centers, which complicated the utilization of the resources and increased the efforts and cost of their development and of their mitigation measures. In the current study, the water sector situation of Jordan as a semi-arid country is taken as an example of socio-economic development and its quantitative and qualitative impacts on the main surface water resources. For that purpose, the policies, programs, and action plans, which have been adopted to minimize the stresses and damages inflicted throughout the last 6 decades, are discussed. The study illustrates the very positive role of dams in saving good quality floodwater, for the downstream water users, and in improving the water quality in the downstream areas. At the same time, urbanization and other human activities added pollutants to the dams' water, a situation which was counteracted by the construction of household and industrial wastewater treatment plants, and the safe disposal of solid wastes. The study concludes that the undertaken mitigation measures to protect the surface water resources in quantity and quality have been successful, and that they

should be enhanced by increasing and improving these measures in order to address the present and future challenges facing the surface water sector in the country. Highlighted here is the urgency and importance of increasing the share of Jordanians in household water supply, which is expected to better reflect on the wastewater quality and on the quality of wastewater treatment effluents. For Jordan, the only viable and secure solution to increase its water resources is by resorting to seawater desalination.

Keywords

Socioeconomic Development, Water Resources Deterioration, Mitigation Measures, Environmental Balances, Jordan

1. Introduction

Jordan is a country of about 89,000 km² with a prevailing semi-arid climate where precipitation average annual rates range from 30 mm/yr in the southeastern parts of the country to 550 mm/yr in the northwestern highlands (Figure 1), and potential evaporation rates range from 4000 to 1600 mm/yr, respectively (Figure 2). This results in average renewable surface and groundwater resources of around 700 MCM/yr, indicating the scarcity of water resources in the country [1]-[3].

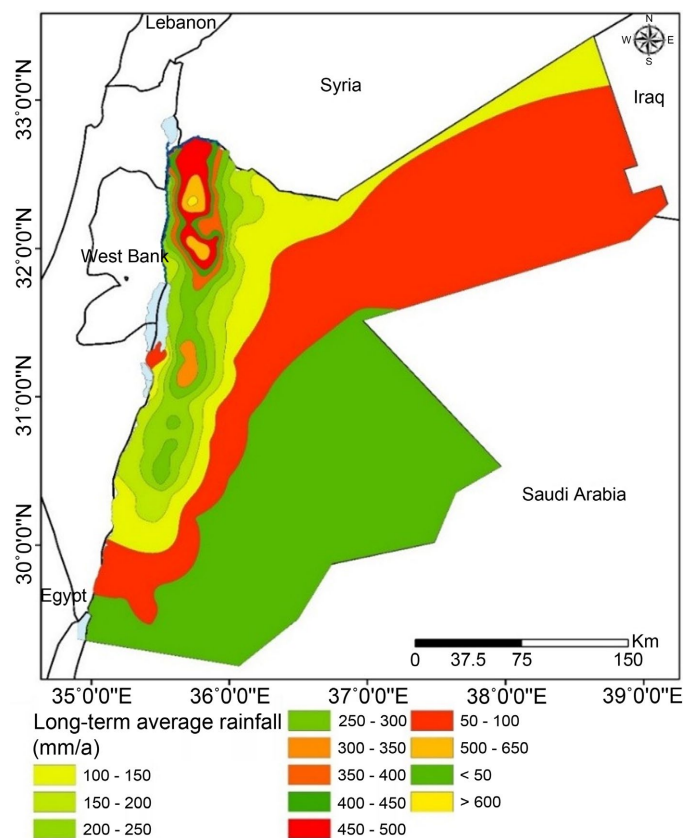


Figure 1. Average long-term precipitation over Jordan (mm/yr) [1].

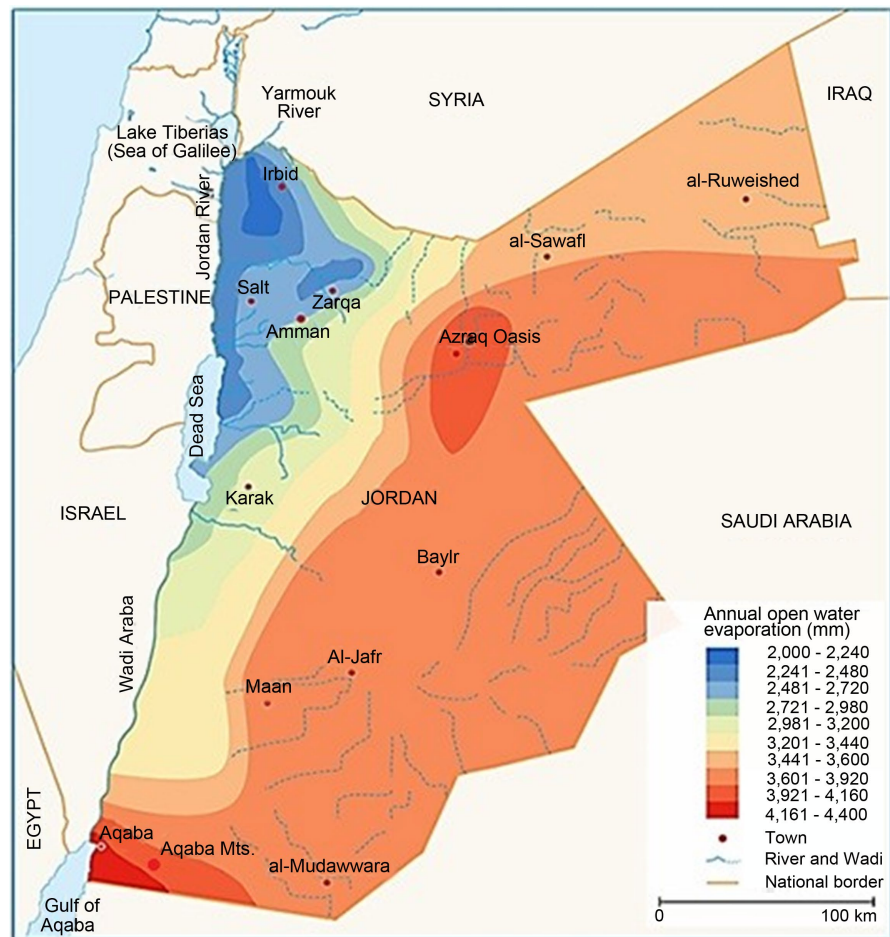


Figure 2. Distribution of potential evaporation rates in Jordan (mm/yr) [1].

Historically, mankind in Jordan settled near perennial water sources such as springs, the Jordan River and its few perennial side wadis, in addition to historic oases and lakes along the highlands [4] [5], of which the Azraq Oasis was the last existing and finally dried out in the 1980s due to overexploitation (Figure 3).

Jordan's population growth (from around 240 thousand inhabitants during the 1940s to more than 11 million at present), as a result of natural multiplication and huge refugee waves, industrialization, agricultural development, and improving living standards, has gradually put increasing pressure on the very limited water resources of the country. Accompanying this development, the increasing production of household and industrial wastewater, irrigation return flows, solid waste disposal, extraction and overexploitation of water resources, and some neighbors' transgressions on Jordan's shares in the transboundary waters have put increasing stresses on the water situation of the country [1] [3].

To counteract the quantitative and qualitative stresses on the water resources of the country, demand management, manifested in more efficient irrigation techniques, installation of water-saving devices, water recycling, wastewater treatment and reuse, and increasing the availability of water by developing water harvesting programs, was applied.

Balancing the deterioration in water resources against the undertaken mitigation measures indicates that some water sources regained their original status, others were rehabilitated to a certain degree but did not regain their original status, and some others are still increasingly suffering from deterioration. On the quantitative side, the water resources are still suffering from overexploitation, and they will continue their decreasing trends until the country develops new sources, which in the case of Jordan has become possible only through seawater desalination.

The discussion in this article is about how these natural systems have been changed by development, urbanization, and agricultural activities, and what actions have been undertaken to combat the impacts of these activities. In addition, the article discusses the present situations of the major watercourses of Jordan and the actions needed to remediate the damage.

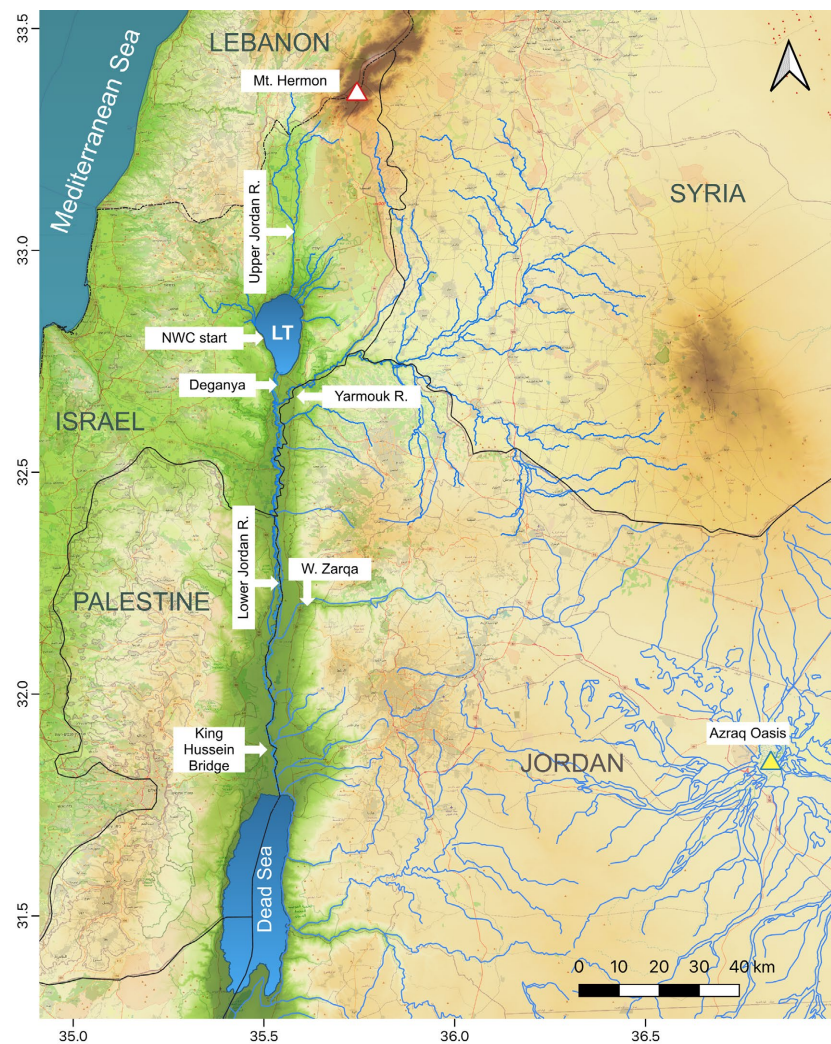


Figure 3. Map of northwestern Jordan, showing the Jordan River, the Yarmouk as the only remaining perennial water flows, Lake Tiberias, and the Dead Sea. Furthermore, the dry Azraq Oasis is shown (LT = Lake Tiberias). Based on “SRTM Digital Elevation Model”, drawn by Dr. Christian Siebert.

2. Methodology

Literature, referring back to about 9 decades, on the water quality and quantity of the discussed sites, has been collected from published and unpublished scientific reports, articles, books, and from files of governmental agencies and has been analyzed for their evolution. Because of the scarcity of data, especially in the 20th Century, there were no discrepancies in the data and analyses. The mitigation measures, which have been undertaken to conserve the water resources and to improve their qualities, are discussed, and a balance between developmental activities and their environmental consequences and mitigation measures has been drawn for each of the discussed watercourses.

3. Results on Historical Water Quality, Recent Deterioration, and Undertaken Measures to Improve

3.1. The Jordan River and Lake Tiberias

In the pre-development era before the 1960s, the Jordan River, which drains a catchment of around 43,000 km² extending into Jordan, Syria, Lebanon, Palestine, and Israel, used to discharge into the Dead Sea an average amount of water of 1,400 MCM/yr [6]-[8]. Due to water resources development in its catchment area, the flow of the Jordan River gradually decreased to around 150 MCM/yr at present. The flow is mainly composed of saline springs diverted from the surroundings of Lake Tiberias, saline groundwater seepages, treated and untreated wastewater, irrigation return flow, drainage from fishponds, and, to a small extent, floodwater, which can be controlled and extracted at very high unaffordable costs.

Table 1 shows the declining annual discharges of the Jordan River at two stations: Degania Bridge (ca. 4 km south of Lake Tiberias) and King Hussein Bridge or Allenby Bridge (ca. 10 km north of the Dead Sea or 90 km south of Lake Tiberias) (**Figure 3**) during the last 7 decades of the 20th century (1928-1998). A first significant drop in the discharge at Degania Bridge took place in the 1960s and 1970s when Israel started to divert an annual average of 540 MCM from Lake Tiberias headwater through the National Water Carrier (NWC) outside the Dead Sea Basin. This deprived the Lower Jordan River of its flow at Degania Bridge at the southern end of Lake Tiberias and caused a decrease in the discharge at King Hussein Bridge to less than its former half. Briefly afterwards, dams built in the Syrian headwaters of the Yarmouk River, the main perennial tributary of the Jordan River, reduced its flow by 300 MCM/yr., depriving the Yarmouk and the Jordan Rivers of another major part of their flows. In addition, Jordan, Israel, and Palestine have built water extraction facilities (dams, weirs and pumping stations) and diverted almost all the flood and base flows of the Lower Jordan side wadis. These activities gradually led to Jordan River flow averaging 150 MCM/yr into the Dead Sea since the end of the 20th century [1] [8].

The natural water table of Lake Tiberias is controlled by the discharge of the Upper Jordan River, which emerges on the foothills of Mt. Hermon and feeds the Lake with fresh water. Depending on the wetness of the rainy season, its discharge

varies, while simultaneously saline springs discharge on the lake floor, releasing diluted brines into the reservoir. The interplay between both leads to variable natural salinities (615 - 1210 $\mu\text{S}/\text{cm}$) in the Lake, which is the origin of the Lower Jordan River (LJR).

Table 1. 10-year average discharges of the Jordan River from 1928 to 1998 at Degania and King Hussein (Allenby) Bridges in MCM/yr. After 1998, the river discharge dwindled dramatically to around 150 MCM/yr [8].

Period	Degania (MCM/yr)	KHB (Allenby) (MCM/yr)
1928/29-37/38	487.6	1289.5
1938/39-47/48	518.0	1117.6
1948/49-57/58	531.6	1043
1958/59-67/68	292.3	846.3
1968/69-77/78	170.4	480
1978/79-87/88	61.5	582
1988/89-97/98	98.0	530

With the introduction of the NWC during the 1960s, the tangible saline springs discharging along the shorelines of Lake Tiberias were collected in a saline water diversion channel (SDC) and released into the LJR downstream of Degania. Due to the limited dilution by freshwater, that saline water (8600 $\mu\text{S}/\text{cm}$) is one of the major factors responsible for the water quality deterioration of the LJR, manifested in its strong salinization (6,680 $\mu\text{S}/\text{cm}$) shortly before the Yarmouk River confluence (Table 2). Analyses of the river water composition, before and after the 1960s [6]-[16], indicate that the water quality of the LJR has deteriorated with time and is now characterized by enhanced concentrations of major ions and nutrients (NO_3 , P) (Table 3).

Table 2. Evolution of the water composition of the lower Jordan Valley (from Lake Tiberias to the Dead Sea) during the last 8 decades (EC in $\mu\text{S}/\text{cm}$, all others in mg/l).

Author/Parameter	TDS	EC	pH	TC ⁰	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	NO ₃	TH
Lake Tiberias outlet													
[6]	720 - 800								300 - 316				22 - 28
[11]		615				55	110	21	360		67		
[10]		818.5			62	26	176.5		300	67	187		
[12]		1210	7.8	30.6	42	33	138	7.2	258	57	124	0.3	
SDC—Salt water diverted from Lake Tiberias and its surroundings into the Jordan River													
[12]		8600	7.5	20.8	494	126	1185	55.0	2775	184	349	3.4	

Continued

Jordan River: Mixture of Tiberias, salt, and other water sources north of the confluence of the Yarmouk River into the Jordan River												
[12]		6680	7.90	32.5	374	138	1025	58.2	2295	284	325	3.6
Jordan River: Mixture of Yarmouk and Jordan River waters (Sheikh Hussein Bridge)												
[13]	1991	5300	7.56	31.3	98.0	85.0	724.5	38.8	1246	436	416.6	18.0
[12]		6750	7.4	21.4	349	129	908	47.0	1889	300	383	13.1
[13]	2022	5840	7.92	28.6	255	140	805	32	1550	380	356	18.2
Jordan River, Zarqa River, and other water sources at Prince Mohammad (Damya or Adam) Bridge												
[12]		5388	7.70	30.2	183	191	765	53.2	1450	611	303	29.9
[13]	1991	3920	7.74	22.0	204	156.8	567	24.0	962.9	653.8	338.5	35.7
[13]	2022	7456	7.86	28.9	280	220	990	92	2155	436	436	36.8
Jordan River at King Hussein (Allenby) Bridge, ca. 12 km north of the Dead Sea												
[13]	1991	5540	7.95	30.2	240	145	825.7	25.6	1495	419	360.5	39.0
[13]	2022	8450	8.05	29.6	312	301	1112	75	2580	784	465	38.5
Jordan River at King Abdullah Bridge, ca. 5 km north of the Dead Sea												
Irwin	1925				77.1	62.4	117	10.0	316	6.1		
[6]	852 - 960		7.9		81.8				292 - 332	98		33.4 - 38.4
[12]	1681	2102	7.9		5.11	7.86	15.71		21.66	3.35	3.58	
[12]		10600	6.9	28.8	280	396	1330	102	2800	1040	259	19.0
[15]		9360	8.0		303	304	1220	86	2521	838	334	35.1
[13]	2022	9530	8.0	30.2	352	308	1190	78	2760	843	440	42.0

Table 3. Evolution of pollution parameter concentrations in the waters along the Lower Jordan River (in mg/l).

Author/Parameter	NO ₃	PO ₄	NH ₄	DO	COD	BOD ₅	TOC
Lake Tiberias outlet							
[12]	0.3			8.2			
Lake Tiberias and saltwater diversion into the Jordan River							
[12]	3.4	4.3	12.0				
Jordan River: Mixture of Tiberias, salt, and other water sources north of the confluence of the Yarmouk R. into the Jordan R.							
[12]	3.6	4.8	13	3.2			
Jordan River and Yarmouk River waters							
[13]	1991	18.0	1.29		8.6	14.8	32.6
[12]		13.1	8.3	2.0	7.5		

Continued

Jordan River, Zarqa River, and other water sources at Prince Mohammad (Damya or Adam) Bridge							
[13] 1991	33.6	6.64			33.6	12.6	31.59
[12]	22.0		13.0	2.94	4.0		
Jordan River at King Hussein (Allenby) Bridge, approximately 12 km north of the Dead Sea							
[13] 1991	40.3	4.9		10.2	86.2	2.8	4.88
[13] 2022	38.5	7.3	4.2	9.6	65.9	4.6	6.1
Jordan River King Abdullah Bridge, ca. 5 km north of the Dead Sea							
[12]	19.0			5.47			9.3
[13] 2012	35.1		0.14				
[13] 2022	38.9	7.2	4.9	8.9	56.8	9.6	10.5

Present status and required actions

Until now, no effective measures have been undertaken to adequately rehabilitate the Lower Jordan River, and the riparian countries sharing its catchment area are still using the river as a disposal stream for a variety of wastewaters, salt water (natural and desalination), and as a sink for irrigation return flow water. Rehabilitation of the Jordan River is a multinational undertaking due to the fact that its water-feeding streams originate, flow, and are affected by activities in the riparian countries. Trilateral projects by Jordan, Palestine, and Israel have been prepared to rehabilitate the Jordan River, but their implementation depends greatly on political and financial obstacles.

There is an urgent necessity to start the rehabilitation of the Jordan River due to its present catastrophic quantitative and qualitative situation and their negative impacts on humans and the environment, and due to its vital role in enhancing tourism to the river surroundings and to the Dead Sea area as a human heritage site.

3.2. The Yarmouk River

The Yarmouk River currently forms the borderline between Jordan and Syria, and in its most western part, between Jordan and the Israeli-occupied Golan Heights. Its catchment area is about 6790 km² and spans from Lebanon and Syria over Jordan. It receives an average amount of precipitation of 2500 MCM/yr. Historically, the river used to discharge an amount of flood and base flow water generally ranging from 400 to 500 MCM/yr into the Jordan River [7]. Due to water resources development by the riparian countries Jordan, Syria, and Israel, particularly the construction of tens of dams and weirs on the river's headwaters in Syria and the Al Wahda Dam (Figure 3), the flow of the river dwindled to a few tens of million cubic meters per year, mainly composed of flood flow, some base flow, and groundwater extracted from the area's aquifers, which are added to the river flow.

Most villages and settlements within the catchment area dispose of their wastewater into cesspools with varying degrees of self-purification, allowing it to infiltrate from there into the shallow aquifer of the area and eventually reach springs discharging into the Yarmouk River. In addition, in Jordan, various wastewater treatment plants have been constructed within the catchment area of the river (**Table 4**). Although their effluents are used for irrigation, some untreated or semi-treated wastewater still finds its way to the river, especially during flood events, when part of the river water diverted into King Abdullah Canal cannot be used as a drinking water source because of the floodwater turbidity.

Table 4. Pollution parameters' concentrations in the effluents of the waste and solid disposals flushed into the Yarmouk headwater during floods (mg/l).

WWTP	T-N	PO ₄	NO ₃	NH ₄	TDS	TSS	COD	BOD ₅	pH
Shallala	73.6	30.5	14.4	80.3	963	48	112	29	7.74
Ramtha	31.2	12.9	3.6	25.6	1255	173	78	6	7.89
Akhider	168.4	33.8	7.8	154	1992	306	762	86	8.1

Although the groundwater, which is extracted and discharged into the river, originates from a deep confined aquifer and is free of contamination, the socio-economic development within the catchment area is gradually being reflected in the deteriorating water quality of the Yarmouk River.

About 25 km to the east of the river entrance into the Jordan Valley, Al Wahda Dam was built on the river in 2007, collecting the high-quality water of headwater floods and base flow. Building Al Wahda Dam in an upstream area improved the quality of the Yarmouk River water in summertime (**Table 5**). At the same time, urbanization of the catchment area and its accompanying waste production as well as irrigation return flow resulted in worsening the surface water quality during the past decades. The drilling of mainly artesian groundwater wells in the Mukheibeh area, close to the Jordan Valley, and allowing their high-quality water to join the flow of the Yarmouk River counteracted the negative anthropogenic effects to a certain degree by dilution. However, that should not deter the responsible agencies from rehabilitating the environmental system within the catchment area in order to protect the river water from depletion and deterioration.

Present status and required actions

The Yarmouk River water at present does not represent its original water sources, neither in quality nor in quantity, which had prevailed during the pre-developmental era. Strong abstractions from its base and flood flows have been taking place in Syria, Israel, and Jordan, and Mukheiba wells' water has been extracted from the areas' main aquifers and added to the river flow. In addition, some parts of the river course are used as disposal sites for solid and liquid household wastes. Because the river water is shared by three countries and no consensus has been reached and no plans have been developed to rehabilitate it, the river is

suffering from the “tragedy of the commons,” loaded by hostilities among the riparian states.

If no river rehabilitation agreements among the basin countries are developed and implemented, the situation of the river will worsen, its quality will deteriorate, and its quantities will reduce with time.

Table 5. Yarmouk River water composition at the entrance of the King Abdullah Canal tunnel in Adasiya Dam (**Figure 4**) (in mg/l, EC in $\mu\text{S/cm}$).

Parameter/year	EC	pH	T	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	NO ₃	PO ₄	BOD ₅	COD
1991	830	8.87	28	53.2	20.4	78.9	5.6	100	85.9	206	12	0.11	1.0	8.3
2002	1035	8.60	25.5	75.4	50.2	79.8	4.0	93.1	95.4	298.8	14.6	0.82	2.0	8.89
2007	1019	8.11	22.5	46.6	32.6	109.9	6.0	119.7	72.0	244	30.5	0.29	12	18
2021	1135	8.6	23.5	85.3	31.8	103.5	6.7	125.3	81.6	322	13.2	0.22	20	43
2022	1030	7.25	26.5	57.0	35.0	92	7.0	144	109	275	7.0	0.33	21	44

3.3. King Abdullah Canal

King Abdullah Canal (KAC), formerly called East Ghor Canal, extends along the eastern side of the Lower Jordan Valley from the Yarmouk River in the north to the Dead Sea in the south. The canal water results from the diversion of Yarmouk water at the Adasiya Weir (**Figure 4**), and its main purpose is to supply irrigation water for the farmlands lying between the canal in the east and the Jordan River in the west by gravity flow. At the beginning, the canal water originated from directing part of the Yarmouk River water at Adasiya into the canal. Later on, groundwater from the Mukheibeh wells drilled along the lower reaches of the Yarmouk River between 1981 and 2024 was added to the river flow. At the beginning, their artesian groundwater was released to feed King Abdullah Canal water, but later on, it was diverted to join the Yarmouk River and from there the King Abdullah Canal. Since the Jordanian-Israeli Peace Treaty in 1994, the canal water has been further supplemented by water originating from Lake Tiberias. Due to drinking water shortages in the highland areas of Jordan, part of the canal water was diverted in 1985 from Deir Alla area, north of Wadi Zarqa and its inflow into the Jordan Valley, to enhance the drinking water sources of the highland areas. In 2007, the Al Wahda Dam, constructed on the Yarmouk River between Jordan and Syria, around 25 km east of the river entrance into the Jordan Valley, started collecting dwindling amounts of flood and base flow from the Yarmouk’s headwaters. This has also contributed to the changes affecting the quality and quantity of the Yarmouk River and King Abdullah Canal waters, mainly from the flood and base flows of the Yarmouk River, followed in later stages by water release from Wadi Al-Arab and Ziglab dams [17]. Due to decreasing flows of the Yarmouk River

These anthropogenic developments result in the fact that neither the discharge dynamics nor the water composition of both the Yarmouk River and, conse-

quently, the King Abdullah Canal water, reflect the original quality and quantity of the river anymore (**Table 6**).



Figure 4. Map of NW Jordan, indicating the locations of dams and wastewater treatment plants (LT = Lake Tiberias; KAC = King Abdullah Canal). Based on “SRTM Digital Elevation Model”, drawn by Dr. Christian Siebert.

Table 6. Evolution of King Abdullah Canal water composition over the last 3 decades (EC in $\mu\text{S}/\text{cm}$, all others in mg/l).

Parameter/year	EC	pH	T	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	NO ₃	PO ₄	BOD ₅	COD	TOC
KAC entrance 1991	830	8.87	28	53.2	20.4	78.9	5.6	100	85.9	206	12	0.11	5.6	12.3	35
Yarmouk and Mukheiba 1999	1027	8.35	24.5	65.3	31.8	96	6.6	125.4	72.6	284	28.0	0.29	4.8	17	42
From Israel 1999	1106	8.32	28.4	58.6	64.7	90	8.0	231	18	114.1	2.0	0.56	nd	nd	4.2
Yarmouk 2021	1135	8.6	23.5	85.3	31.8	103	6.7	125.3	81.6	322	13.2	0.22	20	43	
From Israel 2022	1030	7.25	26.5	57.0	35.0	92	7.0	144	109	275	7.0	0.33	21	44	

Continued

KAC Deir Alla	1991	810	8.58	27.5	53.0	29.6	80.5	4.6	94.5	67.5	205	9.6	0.05	5.2	9.7	8.5
	1999	1118	8.33	26.8	64.0	24	81.9	9.6	190	56.2	163	2.0	0.42	6.8	18.5	3.0
	2022	1150	8.22	25.6	54.0	33.0	102	12	210	70	186	2.9	0.44	7.2	17.2	4.5

Present status and required actions

The primary source of King Abdullah Canal water originates from the Yarmouk, which is partly diverted at Adesiya Weir into the KAC. It is mainly composed of Yarmouk flow from Al Wahda Dam, surface flow from Syria, such as the Ruqqad stream, and artesian groundwater extracted in the Mukheibeh well field. As a consequence of the treaty between Jordan and Israel, during periods of high flow, water from the Yarmouk is temporarily pumped via the Yarmoukhim reservoir in Israel into Lake Tiberias, while it returns through a pipeline into the KAC during periods of low flow to maintain the flow in the KAC high (Figure 5). Further south, water collected in Wadi Al-Arab and Ziglab Dams, and groundwater pumped from the Jordan Valley aquifers, join the KAC water according to water demands in the canal downstream area. Hence, depending on the individual composition of each source, the chemical characteristic of the canal water varies.

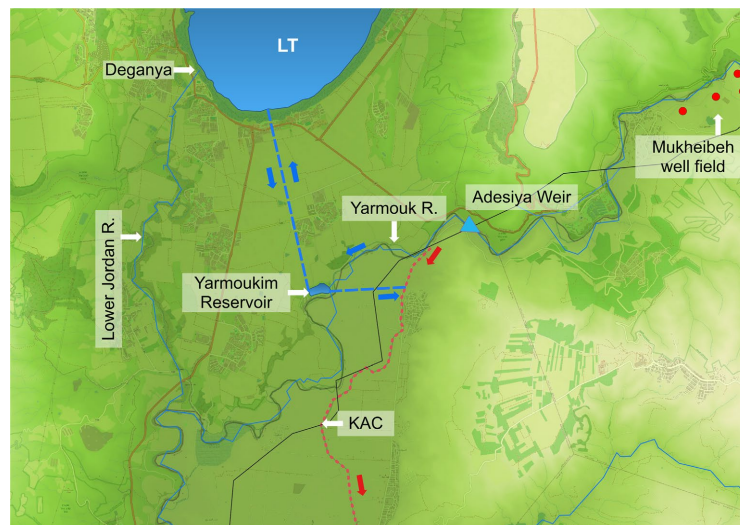


Figure 5. Map of the “water-triangle” south of Lake Tiberias (LT), showing the Yarmouk River with the Mukheibeh well field as a contributor to the flow to Adesiya Weir and the Yarmoukhim Reservoir, which is the relay between Lake Tiberias and the King Abdullah Canal (KAC). Arrows indicate artificial water transfer. Based on “SRTM Digital Elevation Model”, drawn by Dr. Christian Siebert.

As long as the quantities of the water sources and their qualities are maintained, the Canal will function as a source for irrigation and drinking water. The water quality and quantity along the Canal are monitored through sophisticated system control devices, allowing early warnings and adaptation of treatment in the Zai Purification Plant to deal with the changing raw water quality.

3.4. Zarqa River

Zarqa River is the largest perennial water stream in Jordan, not shared with other countries like the cases of the Jordan and Yarmouk Rivers. It drains a catchment area of around 4000 km² (Figure 4), receiving an average amount of precipitation of 565 MCM/yr. During the pre-development era, in the 1960s and 1970s, the river used to discharge into the Jordan River an average amount of 94.8 MCM/y. That water was composed of equal amounts of flood and base flows [2] [18]-[20]. After that, the river witnessed different phases of changes in quantity and quality because of human activities, e.g., construction of King Talal Dam on the river, construction of wastewater treatment plants within its catchment area and allowing their effluents to join the river, rapid urbanization, industrialization, and mining activities within the river catchment area. These activities resulted, on the one hand, in water quality deterioration and decreasing flow of the river counteracted, on the other hand, by domestic and industrial wastewater treatment. Changes in the annual river flow took place gradually during the last 5 decades. In the downstream area of King Talal Dam (Figure 3), the river flow was regulated by the dam since its construction in 1977. Changes in the river and dam water quality took place stepwise depending on the construction of wastewater treatment plants and hence the treatment of parts of the water reaching the Zarqa River and KTD. In the downstream area of the dam, the river water quality depends much on the amount of water released from the dam and the amount of river base flows.

Amman city, occupying the upper catchment area of the river, was provided in 1961 with a wastewater treatment plant (Ain Ghazal) to treat about 20,000 m³ of household wastewater. However, due to the huge increase in its population as a result of the 1967 Six-Day War between the Arab countries and Israel and the migration of hundreds of thousands of Palestinians to Jordan, that treatment plant became rapidly overloaded and incapable of treating the amounts of wastewater reaching it. This led to the release of semi-treated wastewater into the Zarqa River, causing deterioration in its quality and detriments to human health.

In 1977, King Talal Dam was constructed on the Zarqa River. It received, at that time, in addition to the river's flood and base flows, the semi-treated effluent of the Ain Ghazal treatment plant and therefore, from the first impoundment of the dam, its water quality suffered from pollution by the semi-treated wastewater and from eutrophication processes with all their consequences [20]-[24].

In 1984, the Khirbet es Samra wastewater treatment plant serving the area of Amman and Zarqa was commissioned. The treatment depended on stabilization pond principles, which is a natural treatment process. However, due to many factors and conditions, the new treatment plant did not function properly, and its effluents resembled semi-treated wastewater, resulting in further water quality deterioration of both Zarqa River and King Talal Dam [13] [24]-[26] (Table 7). After that, and with the passage of time, the water quality of both Zarqa River and King Talal Dam deteriorated more and more, so that the use of their water in irrigation became questionable (Table 8).

Table 7. Recent (2020-2022) and old (1993) pollution and other parameters of wastewater treatment plants in the Zarqa River catchment area (mg/l).

2022									
WWTP	T-N	PO ₄	NO ₃	NH ₄	TDS	TSS	COD	BOD ₅	pH
Samra	32.8	11.4	8.75	32	722	19	67	17	7.7
Abu Nusseir	14.9	10.6	45.3	1.7	951	10	43	6	7.76
Baqa'a	61.5	11.5	4.8	44.2	950	68	230	51	7.88
Jarash East	10.8	14.4	6.3	9.6	1304	14	55	11	7.6
1993									
WWTP	T-N	PO ₄	NO ₃	NH ₄	TDS	TSS	COD	BOD ₅	pH
Samra	90.0	20.5	1.3	78.1	1262	678	360	140.2	7.0
Abu Nusseir	na	na	na	na	792	22	80	22	na
Baqa'a	na	na	na	na	996	201	785	404	7.0
Jarash East	17.4	ma	8.0	9.0	1056	22	74	10	7.3

Table 8. Zarqa River at Jarash Bridge (Inlet) and KTD outlet (EC μ S/cm, all others in mg/l).

Parameter/Site	EC	pH	TC ^o	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	NO ₃	COD	NH ₄	BOD ₅	PO ₄	
KTD inlet	1988	1899	7.78	26.8	122	51.6	188	26.4	385	130	356	77.5	na	na	na	32.4
	1993	2300	8.20	30.2	110	48.1	253	37.6	410	59.5	631	25.4	92.5	32.2	29.6	24.86
	2012	2270	7.88	nm	124	68.3	255	33.6	420	74.4	515	86.0	65.9	na	26.1	0.14
	2021	1836	7.80	24.3	111	38	195	28.8	318	168	304	16.5	52	12.2	28.4	2.4
KTD out let	1988	1672	8.20	26	98.4	42.0	163.3	21.5	252	142	332	54	20.2	10.4	6.2	9.9
	1993	2120	8.02	27.3	140	50.4	244	32.8	376	2.86	446	83.6	167	27.7	4.5	3.35
	2012	2380	8.4	23.6	146	64.8	237	34.4	419	270	310	90.3	50	na	21.6	0.26
	2021	1900	8.32	26.2	103	22	270	39	322	212	276	10.55	46	14.5	19.5	2.66

The construction of a new mechanical wastewater treatment in the Khirbet es Samra area in 2007 has resulted in radically improved effluent quality (Table 8), which has had very positive impacts on the water quality of both Zarqa River and King Talal Dam, and the river course and the dam lake started a rapid rehabilitation process.

Present status and required actions

Throughout the last six decades, the Zarqa River has witnessed major changes in its water quality and the sources of its water. From the 1960s until 1983, the river water was composed of flood and base flow water with small amounts of treated and untreated wastewater, but the water salinity and the different water

components were low for a water source used in irrigation. Major deterioration in the river water quality started in 1984, when a new wastewater treatment plant of the stabilization ponds type was built in the Khirbet es Samra area, ca. 25 km northeast of Amman, and directly discharged the semi-treated wastewater of the Amman and Zarqa areas along the river course [26] [27]. The water flowing along the wadi and collected in King Talal Dam was loaded with pollutants such as NO₃, PO₄, COD, BOD₅, and high salinity resulting from evaporation from the treatment stabilization ponds with retention times of up to 60 days [12].

Until 2004, the river water quality had deteriorated due to discharges of semi-treated household and industrial wastewater into the river. Improved water treatment at Khirbet es Samra wastewater treatment plant serving Amman and Zarqa cities and improved industrial wastewater treatment in the catchment area of Zarqa River have resulted in a gradual improvement in the river and dam water qualities, making that water suitable for irrigating most crops grown in the Jordan Valley area.

The ministries of water and irrigation and the ministry of environment have developed different programs to improve the environmental conditions within the Zarqa River catchment, such as more connections of household wastewaters to wastewater treatment plants, improving treatment in existing wastewater treatment plants, and control and disposal of solid wastes, etc. However, additional programs have become necessary, including lessening the siltation rate in the King Talal, improved governance of pharmaceutical residues, and enhanced separation of runoff water canalization from sewerage systems.

3.5. Mujib River

Mujib River drains an area of 6596 km², extending from the Plateau area in the east to the Dead Sea in the west (Figure 6), receiving an average amount of rainfall of 790 MCM/yr. The river has a main northern branch, Wadi Wala, that joins the Mujib at about one km before its entrance into the Dead Sea. In the pre-developmental era, the river used to discharge an average amount of 74 MCM/yr into the Dead Sea, composed of 42 MCM/yr base and 31.8 MCM/yr flood flows (NWMP 1977 and updates).

Within its catchment area, two main dams have been established, namely Mujib and Wala dams, with capacities of 30 and 25 MCM, respectively.

The catchment area of the river was historically very sparsely inhabited, but during the last two decades urban centers have expanded and some industries, including mining of phosphate, gypsum, and trial mining of oil shale, have been established.

Both Mujib and Wala Dams (Figure 6) collect flood flow water, which has low salinity (<300 µS/cm Table 9), especially during the rainy season and the early dry months from April to July. After that, water-sediment interactions start to affect the dams' water, but the water remains of low salinity (~600 µS/cm) and very low concentrations of pollution parameters such as nitrates, phosphates, and ammonia (Table 9).

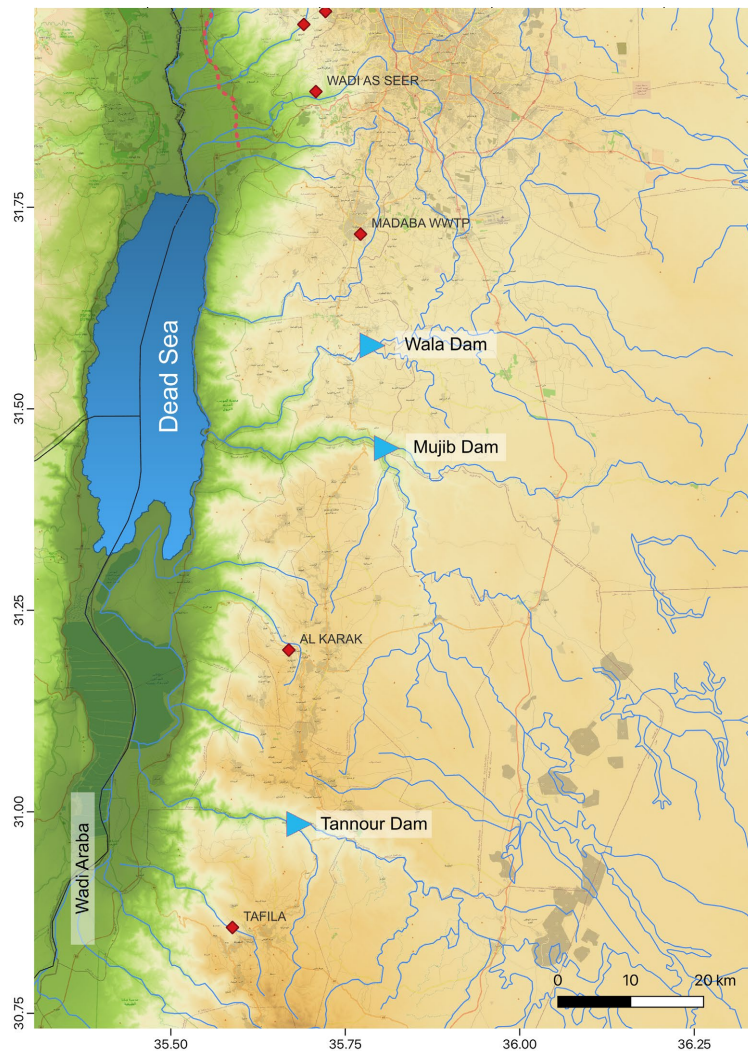


Figure 6. Map of SW Jordan, showing locations of dams reducing discharge towards the Dead Sea. Based on “SRTM Digital Elevation Model”, drawn by Dr. Christian Siebert.

Table 9. Water composition of flood flows of Mujib and Wala Wadis and Dams and their base flow in the Dead Sea area (EC in $\mu\text{S/cm}$, all others in mg/l).

Site/Parameter	EC	pH	T	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	NO ₃	NH ₄	PO ₄
Mujib Dam (Av.)	400 - 600	7.9 - 8.8	20 - 28	40 - 53	4 - 14	27 - 50	4 - 8	34 - 56	50 - 90	100 - 144	1 - 4	0.872 - 0.18	0.03
Wala Dam (Springtime)	410	8.0	24	31	5.79	37	9.5	31.9	4.83	152.5	7.1	0.35	0.13
Base flow DS area	1455	8.45	30	96	56.4	149.5	6.0	224	244.8	257	18.1	na	0.29
Flood of Mujib into DS	377	8.23	10.3	32	15.6	25.3	4.0	32.6	38.4	161.9	4.8	na	0.17
Wala flood upstream of the confluence into Mujib	279	7.86	10.6	42	5.5	14.5	9.2	26.6	27.4	135.8	6.8	na	1.3

Both Mujib and Wala form one river in the downstream area a few kilometers before discharging into the Dead Sea.

Before the construction of the dams, the good quality floodwater used to discharge into the Dead Sea, and during the summer months, the base flow of the wadis, consisting mainly of groundwater emerging from the deep sandstone aquifer containing water with a salinity of around 1700 $\mu\text{S}/\text{cm}$, flowed in the Wadi.

The released low salinity water from the dams during the summer months resulted in a major dilution of the river's base flow constituents in the downstream area, depending on the mixing ratios of the dam's water and base flow water.

As counter-measures, to alleviate the impacts of human activities on the water quality of the river, different household and industrial wastewater treatment plants have been constructed within the catchment area during the last two decades, thereby contributing to the improvement of the water quality of the river (mg/l).

Present status and required actions

The Wadis Mujib and Wala are regulated by the Mujib and Wala Dams, which collect floodwater from a sparsely populated area with very limited industrial and agricultural activities compared to their extended catchment areas. Along the wadi courses in the downstream area of the dams, intensive irrigated agriculture has developed using base flow water and water released from the dams, where different sources of pollutants are found, such as irrigation return flows, agricultural solid and liquid wastes, and some untreated household wastewater. The self-cleaning capacity of the river and the flash floods remove much of the pollution substances, but these mechanisms have their upper limits. The collection and release of the good quality water of the dams along their respective wadis have improved the environmental situation in the dam's downstream areas. In addition, since the water of the Mujib River at its entrance into the Dead Sea is captured and pumped for use in household purposes, the Mujib and Wala Dams can be considered a major rehabilitation project of their catchment areas and a secure household water supply. However, it deserves due consideration to minimize the inputs of pollutants within the catchment area of the river, especially in the dams' downstream areas. In addition, it is time to study pumping the drinking water needs from the Mujib and Wala dams directly into the drinking water supply network instead of allowing the water to flow down to the shores of the Dead Sea and pumping it from there. Of course, that should take place with provision for irrigational needs along the downstream areas of the dam.

3.6. Wadi Shueib

Wadi Shueib catchment area measures around 180 km², extending from the Salt and Suweileh highlands in the west with elevations of about 1,150 masl down to the Jordan Valley area at an elevation of 380 mbsl in the west, receiving average precipitation rates of 500 mm/year in the high mountains to 150 mm in the Jordan Valley area. In the pre-developmental era, the wadi used to discharge an average amount of water of 5.7 MCM/year, consisting of 1.8 MCM/year flood flows and 3.9 MCM/year of base flows. The perennial water of the wadi was composed of the many springs issuing from the upper reaches of its catchment, in the Salt and Fuheis-Mahis areas and along its course. Originally, the wadi flow consisted of base

and floodwaters. In 1945, Salt city was provided with a wastewater treatment plant (the first in Jordan), whose effluents joined the wadi flow in the upstream area of its catchment. The wastewater treatment plant had, at that time, functioned properly, and its small effluent quantity, of up to a few hundred cubic meters per day, represented only a small contribution to the flow of the wadi and was dealt with qualitatively by the self-cleaning mechanisms along the wadi course of around 25 km.

Population growth and the strong urbanization of the catchment area, and their accompanying increase in the use of cesspools, despite the existence of a sewerage system, resulted in the contamination of the springs' water feeding the base flow of the wadi and led to its water quality deterioration.

In 1968, a dam with a capacity of 2.3 MCM was built on the wadi before its entrance into the Jordan Valley area with the aim of using its water for irrigation. The dam's water consisted of base flow, flood flow, and effluents from the wastewater treatment plant.

With the passage of time, the wastewater treatment plant became overloaded several times compared to its design capacity, forcing its expansion and upgrading with time. Nonetheless, the increasing wastewater effluents added more pollutants to the wadi course, represented by increasing concentrations of BOD, COD, NO₃, PO₄, and others. Accordingly, the dam and wadi water quality allows its use only for irrigation (Tables 10-12).

Table 10. Average concentration of pollution parameters in Salt and Fuheis/Mahis wastewater treatment effluents (mg/l).

WWTP	T-N	PO ₄	NO ₃	NH ₄	TDS	TSS	COD	BOD ₅	pH
Salt	37.2	13.1	2.3	33.1	794	31	82	26	7.62
Fuheis/Mahis	23.6	7.3	9	16	784	60	177	21	7.76

Table 11. Average composition of Shueib and Kafraïn Dams' water in 1993 and 2021.

Source/Parameter	EC	pH	T	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	NO ₃	PO ₄	NH ₄	BOD ₅	COD	
Shueib Dam	1993	830	8.41	23.8	54.1	24.7	52.2	6.8	98	46.1	238.1	26.6	0.75	1.0	7.4	32.4
	2021	1230	8.63		76	51.8	103	13	161	138.6	280.6	5.7	0.71	0.34	12.6	35.6
Kafraïn Dam	1993	950	8.56	26.9	45.2	48.1	82.3	5.6	138	111	221	7.8	0.22	1.5	8.6	22.7
	2021	1170	8.05		57	52.8	94	11.3	198.1	195.6	195.2	4.34	0.08	0.68	13.1	32.6

Table 12. Average concentration of pollution parameters in Shueib and Kafraïn Dams' water (mg/l).

Pollution parameter/Site	PO ₄	NO ₃	NH ₄	BOD ₅	COD	pH						
Shueib Dam 1992/93	0.34 - 2.6	Av. 1.32	28 - 50	Av.36.8	0.13 - 1.92	Av. 1.0	7.5 - 8.7	AV.11.7	15.2 - 22.8	AV. 18.4	7.5 - 9.2	Av.8.4
Kafraïn Dam 1992/93	0.09 - 0.46	0.012	21.7 - 29.8	23.6	0.15 - 0.20	0.17	5.5 - 11.8	9.5	12.2 - 22.5	17.8	7.07 - 8.22	7.98
Shueib Dam 2021	0.71	5.7	0.34	12.6	35.6	8.63						
Kafraïn 2021	0.08	4.34	0.68	13.1	32.6	8.05						

Wadi Shueib water has witnessed several stages of water quality situations during the last 8 decades. Originally, the water quality was of low salinity and very low content of pollution parameters (Table 13, Table 14), with only a few thousand inhabitants residing in a scattered way in its catchment area. The strong urbanization of the catchment area, such as Salt City, Fuheis, and Mahis towns, led to increased wastewater production and pollution along the wadi course. The provision of a wastewater treatment plant for Salt in 1945 led to improved water quality of Wadi Shueib, but that improvement did not last long because of the increasing population and, hence, production of liquid wastes; therefore, the wastewater treatment plant became overloaded. Upgrading that treatment plant improved the water quality of Wadi Shueib, but added many nutrients, COD, and BOD to the water, leading to the eutrophication of its water and causing changes in the floral and faunal species living in it. At its headwater springs, the water quality has deteriorated because of urbanization. Further downstream, when the treated wastewater effluents join the wadi water, the water becomes loaded with nutrients and pollution parameters and can only be used in irrigation. Shueib Dam has become silted and holds highly eutrophic water only for a few months after the rainy season.

Table 13. Average concentration of pollution parameters in Wadi es Sir wastewater effluents (mg/l).

WWTP	T-N	PO ₄	NO ₃	NH ₄	TDS	TSS	COD	BOD ₅ ^{u0623}	pH
Wadi Sir	52.9	11.6	14.6	43.2	769	54	170	15	7.77

Table 14. Pollution parameters of El-Hasa WWTP (mg/l).

Parameter	PO ₄	NO ₃	COD	BOD ₅
Concentration mg/l	7.85	1.83	460	168

The water quality along Wadi Shueib and its tributary wadis and in Shueib Dam cannot be rehabilitated and can only be protected from further deterioration. The feeding springs' water quality in the upper reaches of the catchment area, such as Hizzir, Gadour, Baqquriya, Fuheis, Mahis, among others, can be additionally protected by more connections of wastewater sources to the treatment plants and through the rehabilitation of the catchment area.

3.7. Wadi Kafraïn

Wadi Kafraïn drains a catchment area of 189 km², extending from elevations of 1200 masl in the northwestern part of Amman down to the Jordan Valley area at 350 mbsl.

Precipitation in the highland of the catchment averages 550 mm/year, decreasing westward to reach only 140 mm/year in the Jordan Valley area.

The original average natural discharge of Wadi Kafraïn during the pre-devel-

opmental era in the 1960s totaled 6.4 MCM/year (1.6 MCM/year flood flow and 4.8 MCM/year of base flow). The headsprings of the wadi, in the Wadi Sir area, with a very sparse population around them, served as a source of drinking water for all settlements along the wadi. In 1968, a small dam with a capacity of 3.8 MCM was constructed at the entrance of Wadi Kafraïn into the Jordan Valley to collect flood and base flow water for use in irrigation in the Jordan Valley area. The dam was raised in 2007 to accommodate 7.5 MCM of flood, base, and effluent waters from the wastewater treatment plants within the wadi catchment area. King Hussein Medical City wastewater treatment plant used to discharge its treated effluents in the upstream area of the springs, leading to the contamination of the headsprings. However, that has changed and the City's wastewater has been diverted into and treated in the Wadi Sir Wastewater Treatment Plant, in the downstream area of the wadi near its entrance into Kafraïn Dam (Table 13). The dam currently collects flood water, some base flow water, treated effluents of Wadi Sir wastewater treatment plant, irrigation return flows, and water pumped from the area's aquifers. The mixture of these different waters has restricted its use to irrigation in the dam's downstream area.

Present status and required actions

Wadi Kafraïn water has been exposed to several phases of development. From the 1960s until the mid-1980s, the wadi discharged flood and base flow water in addition to limited amounts of irrigation return flows, almost free of nutrients and biocides. After that, wastewater treatment plants were constructed to treat Wadi es Sir and King Hussein Medical Center wastewaters. The effluents joined the wadi flow. Upon that, the water became rich in nutrients and, although the self-purification along the wadi course during the 1990s coped with the pollution parameters, the increasing concentration of these parameters exceeded the self-purification capacity of the wadi course. Therefore, the water reaching the dam reservoir was highly charged with nutrients, leading to eutrophication processes in that reservoir and rendering its water only suitable for irrigational uses (Table 13). Expanding urbanization, industrialization, and irrigation activities within the catchment area will certainly not allow major improvements in the wadi and dam's water quality.

Here, separation of storage of treated wastewater from the good quality flood and base flow waters along the different branches of the wadi is highly recommended.

3.8. Wadi El-Hasa

Wadi El-Hasa drains an area of 2,520 km², extending from the Dead Sea in the west to the eastern highlands of Jordan about 100 km east of the Dead Sea. Wadi El-Hasa is a perennial stream fed by many springs issuing along its upper reaches from Upper Cretaceous formations and along the lower reaches from the older underlying sandstone formations.

The catchment area of the river receives an average amount of precipitation of

146.8 MCM/yr, resulting in 4.86 MCM of flood flow and 36.4 MCM of base flow. Tannour Dam (Figure 5) was constructed on the upper reaches of the river mainly to collect floodwater. In addition, a weir, with a capacity of a few hundred thousand cubic meters, has been constructed at the entrance of the river into Wadi Araba, very close to the Dead Sea, to regulate flood and base flow water for its local use, mainly in irrigation.

The catchment area is sparsely populated, with the main town of El-Hasa, where a sewage system and a wastewater treatment plant exist, but whose effluents are locally used for irrigation in the close vicinity of the town (Table 14). Phosphate, gypsum, and calcareous rock mining for the cement industry are main activities in the catchment area, with impacts on flood and base flow water qualities.

The quality of the dam's water is given in Table 15. Due to its geologic set-up, the dam reservoir leaks water from its bottom, which emerges in the downstream area loaded with salts (Table 14), causing major quality changes in the water flowing in the dam's downstream area. However, further downstream, within a distance of a few kilometers, the river is joined by large quantities of thermal freshwater. When no water is artificially released from the dam, the dam's immediate downstream area (until the confluence with the fresh thermal water) discharges brackish water, with all the implications for the wadi aquatic life and environment.

Phosphate extraction in open mining processes and the accumulation of by-products enhance their physical and chemical weathering and transportation with the floodwater into the dam. In addition, the by-products of phosphate beneficiation produce washing wastewater with high EC values, as well as phosphate and trace element concentrations.

Table 15. Composition of Afra and Burbeita thermal spring feeding wadi El-Hasa, phosphate washing and treated wastewater effluents, Tannur Dam, and dam seepage water (EC $\mu\text{S}/\text{cm}$, all others in mg/l).

Source/Parameter	EC	pH	T	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	NO ₃	PO ₄
Afra sp.	463	7.03	46.6	47	17.6	36.3	2.4	68.6	66.2	135.2	0.0	na
Burbeita sp.	618	6.8	46.0	96	29.6	85.6	5.6	71	60	256.1	6.1	na
Phosphate washing	3670	7.77	20.1	193	53.9	428	4.8	651	471	101.7	0.36	6.3
Treated wastewater Hasa WWTP	1044	7.40	26.3	61.6	29.6	101	14.4	187	57.6	202	1.83	7.85
Tannur Dam 2023	680	8.05	26.5	50.7	22.7	48.5	11.3	51.5	130.2	142	5.2	0.02
Dam deep seepages	7330	7.82	20.6	314	247	817	24.8	1740	816	246	0.6	na

Present status and required actions

The river water is used for irrigation purposes along its course and in the southern Ghors. Extreme floodwater exceeding the storage capacities of Tannour Dam and El-Hasa Weir flows and reaches the Dead Sea. The many thermal springs issuing along the tributaries of the El-Hasa River downstream of the dam are partly used in spas for curative and rehabilitation purposes. That use is expected to in-

crease with time due to the curative properties of the water. In order to protect the river water quality, it is recommended that spa facilities should not be licensed unless they treat their wastewater in an adequate way. Even in the dam upstream areas, household wastewater should be treated before reaching the dam's water, which is already loaded with a high concentration of phosphates that may lead to eutrophication processes in the dam's water if nitrates reach the dam water as a result of human activities within the dam's catchment area.

Mining and beneficiation of phosphate, gypsum, and other minerals result in the addition of dissolved and suspended minerals to the dam's water, which, with the passage of time, may cause major degradation in the dam's water quality, and which may, in turn, cause deterioration in the agricultural products grown with that water. Therefore, better governance of mining and urban development to serve the environment is strongly required.

4. Conclusions and Recommendations

Like elsewhere worldwide, urbanization, industrialization, and agricultural activities have brought about major changes in the environmental situations in their areas of effect and even beyond. That can be proven by the effects observed along water courses across countries and regions. Just like the effects of fossil fuel burning, not only in their areas of burning but worldwide, expressed in global climate change. In Jordan, the impacts of socio-economic development on the environment, especially on the water resources, have been dramatic during the last few decades. That is due to the natural multiplication of its native population and due to the huge refugee waves coming into the country during the last seven decades (The population increased from around 240,000 inhabitants in the 1940s to more than 11 million at present).

The water and related quantitative and qualitative issues in Jordan are exacerbated by being shared with neighboring countries, especially Syria and Israel, which are upstream countries to the Yarmouk and Jordan Rivers, respectively. These two countries have developed within their territories more of the shared water than the agreed upon quantities with Jordan, depriving Jordan of its fair shares of these waters. In addition, both countries used the river courses for the disposal of polluted and saline water, thereby contaminating the water of the downstream recipient, Jordan.

The socio-economic development in Jordan has produced all types of liquid and solid wastes, which have had negative quantitative and qualitative impacts on the scarce water resources of the country. These impacts have manifested themselves in decreasing water availability and in water quality deterioration.

To counteract these negative impacts, Jordan has resorted to building dams, weirs, water harvesting facilities, canals, wastewater treatment plants (with their effluent reuse in irrigation), industrial water recycling, drinking water purification plants, and brackish water desalination, in addition to introducing the necessary regulation and legislative measures. The balance between the impacts of socio-

economic developmental stresses on the water sources and the undertaken protection and mitigation measures (especially dam building (and other water harvesting projects), wastewater treatment and reuse, and the safe disposal of solid wastes) have all been very positive projects and have resulted in improving water quality and quantity. This is exemplified by the rehabilitated downstream areas of dams, with the outstanding example of the Zarqa River and the many wastewater treatment plants covering all parts of the country.

It is recommended to continue and intensify the application of mitigation measures, especially the construction of wastewater treatment facilities and related reuse projects, the construction of check dams to lessen siltation rates of water harvesting projects, and to separate the storage of good quality flood and base flow water from that of treated wastewater. Nonetheless, all the undertaken measures will not solve Jordan's water problem. The country needs more water, which is only obtainable by seawater desalination. Such a project is very expensive due to pumping heads of more than 1000 m, and distances of 300 - 400 km.

The water environmental problems in Jordan and the undertaken mitigation measures with the assistance of donor agencies can serve as an example for other countries, especially in the semiarid and arid climatic zones. In that concern, the lesson is: vigorous Environmental Impact Assessment (EIA) for all projects is the way forward to avoid environmental degradation. In addition, we strongly urge the international organization to apply the principle of "Polluter Pays" to countries sharing water resources.

Acknowledgements

Sincere thanks are extended to the Bundesministerium für Bildung und Forschung (BMBF, recently renamed BMFTR) und das Transfers-Projekt for supporting the study through: Grant-number: 02WME1608. Thanks are also due to the National Agricultural Research Center (NARC) for hosting the project and facilitating its smooth implementation. The authors are especially thankful in that regard to Dr. Sireen Naoum.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] MWI: Ministry of Water and Irrigation, Jordan Open files.
- [2] NWMP: National Water Master Plan (1977) and Updates, Bundesanstalt für Geowissenschaften und Rohstoffe BGR, Natural Authority Jordan NRA, and Ministry of Water and Irrigation
- [3] Salameh, E., Shteiwi, M., and Al-Raggad, M. (2018a) Water Resources of Jordan: Political, Social, and Economic Implications of Scarce Water Resources. *World Water Resources*
- [4] Salameh, E., Bandel, K., Alhejoj, I. and Abdallat, G. (2018) Evolution and Termination of Lakes in Jordan and Their Relevance to Human Migration from Africa to Asia

- and Europe. *Open Journal of Geology*, **8**, 1113-1132. <https://doi.org/10.4236/ojg.2018.812068>
- [5] Alhejoj, I., Salameh, E., Alzughoul, K. and Alamaireh, M. (2022) Geology and Palaeoenvironments of Quaternary Tawil Deposits in Ma'an Desert, Jordan. *Neues Jahrbuch für Geologie und Paläontologie-Abhandlungen*, **303**, 243-256. <https://doi.org/10.1127/njgpa/2022/1045>
- [6] Ionides, M.G. (1939) The Water Resources of Transjordan and Their Development. Government of Transjordan. London Crown Agents Colon. 4 Millbank, London S.W. 1, 372
- [7] Baker and Harza Eng. Co. (1955) Yarmouk-Jordan Valley Project. Master Plan Report. Vol. 1-13. Report for the Government of Jordan.
- [8] NRA: Natural Resources Authority, Jordan. Open files.
- [9] Irwin, W. (1925) The Origin of the Salts in the Jordan. *The Geographical Journal*, **66**, 527. <https://doi.org/10.2307/1783008>
- [10] Wilson, G.R. and Wozab, D.H. (1954) Chemical Quality of Water Occurring in the Jordan Valley Area. X-Congr. *Union Géodésique et Géophysique Internationale*, Rome, 1954, 170-178.
- [11] Dead Sea Works (1946) In: Neev, D. and Emery, K. (1967) The Dead Sea. Ministry of Development. Geol. Survey of Israel. Bulletin no. 41, 147
- [12] Farber, E., Vengosh, A., Gavrieli, I., Marie, A., Bullen, T.D., Mayer, B., et al. (2005) Management Scenarios for the Jordan River Salinity Crisis. *Applied Geochemistry*, **20**, 2138-2153. <https://doi.org/10.1016/j.apgeochem.2005.07.007>
- [13] Salameh, E. (1991-2022). Own Measurements (Private Files).
- [14] Salameh, E. and Bannayan, H. (1991) The Inadequacy of Stabilization Ponds Treatment as Manifested by the Effects of Khirbet As-Samra effluents on the Groundwater Quality of the Surrounding Area. *Hydrogeologie und Umwelt*, **2**, 33-58.
- [15] Salameh, E. (2012) Water situation in Jordan—Challenges, Achievements, and Future Prospects. In Application of Satellite Technology in Water Resources Management. Inter-Islamic Network on Space Science and Technology (ISNET).
- [16] MWI/JVA and RSS: Ministry of Water and Irrigation/Jordan Valley Authority and Royal Scientific Society (2023) Water Resources Quality Control in the Jordan Valley area. MWI/JVA and RSS Open Files
- [17] Alkhoury, W., Ziegmann, M., Frimmel, F.H., Abbt-Braun, G. and Salameh, E. (2010) Water Quality of the King Abdullah Canal/Jordan—Impact on Eutrophication and Water Disinfection. *Toxicological & Environmental Chemistry*, **92**, 855-877. <https://doi.org/10.1080/02772240903143828>
- [18] Macdonald, M., Partners and Hunting Technical Services Ltd. (1965) East Bank Jordan Water Resources. Report for the Jordan Government, Archive Natural Resources Authority.
- [19] VBB: Vattenbyggnadsbyran (Stockholm) and Fawzi & Associates (Amman) (1977) Water Resources Study for Amman Water Supply.
- [20] Salameh, E. (1978) The Dangers of Eutrophication in the King Talal Dam Reservoir. *Dirasat*, **5**.
- [21] Salameh, E. (1980) Hydrogeology and Hydrochemistry in the Catchment Area of the King Talal Reservoir, Jordan. *Zeitschrift der Deutschen Geologischen Gesellschaft*, **131**, 319-338. <https://doi.org/10.1127/zdgg/131/1980/319>
- [22] Khoury, H. and Salameh, E. (1985) Leaching of Ruseifa Phosphate and Maqarin Bi-

- tuminous Limestone and Its Effects on the Quality of Groundwater. *Dirasat*, **12**, 81-98.
- [23] Salameh, E. and Bandel, K. (1981) Hydrochemical and Hydrobiological Research of the Pollution of the Amman Zarqa Area. GTZ, 94.
- [24] Salameh, E. and Al-Ansari, N. (2000) Water Pollution Issues in the Zarqa Area. Publications of the Strategic and Environmental Water Research Unit. Research Paper No. 2. Al al-Bayt University.
- [25] Salameh, E., Saliba, E., Hashwa, F., Rimawi, O. and Jreisat, R. (1987) The Effects of Khirbet es Smara Effluents on the Water Quality of Wadi Dhuleil and Zarqa River. Water Research and Study Center (WRSC) Bulletin no. 10. University of Jordan.
- [26] Salameh, E. and Bannayan, H. (1996) Water Resources of Jordan—Present Status and Future Potentials; Friedrich Ebert Stiftung (FES) and Royal Society for the Conservation of Nature (RSCN). 178 p.
- [27] Salameh, E. (1996) Water Quality Degradation in Jordan—Impacts on Environment, Economy, and Future Generation's Base-Friedrich Ebert Stiftung and Royal Society for the Conservation of Nature.