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Impacts of Wala Reservoir stored storm waters on Wala-Haidan Well Field

Ali Sawarieh ⁽¹⁾

Julian Xanke ⁽¹⁾

⁽¹⁾ Karlsruhe Institute of Technology

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Corresponding author:

Author Ali Sawarieh / Julian Xanke
Institution: Karlsruhe Institute of Technology (KIT), Germany Institute of Applied Geoscience - Division of Hydrogeology -
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Project Coordination:

Main Coordinator:	Assistant Coordinators	
Prof. Dr. Nico Goldscheider & Dr. Jochen Klinger Institute of Applied Geosciences, Karlsruhe Institute of Technology Adenauerring 20b 76131 Karlsruhe Germany Phone: +49 (0) 721 608 43096 Fax: +49 (0) 721 606 279	Prof. Dr. Martin Sauter Department of Applied Geology Göttingen University Goldschmidtstrasse 3 37077 Göttingen Germany Phone: +49 (0)551 39 79 11 Fax: +49 (0)551 39 93 79	Dr. Roland Mueller & Dr. Stefan Geyer Helmholtz Centre for Environmental Research (UFZ) Permoserstr. 15 04318 Leipzig Germany Phone: +49 (0)341 235 30 00 Fax: +49 (0)341 235 2885

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ABBREVIATIONS:

a.s.l	Above sea level
A7	Wadi As Sir Limestone Formation
b.g.s	Below ground surface
B1	Wadi Umm Ghudran Formation
B2/A7	Upper Aquifer System in Jordan
B2a	Amman Silicified Limestone Formation
B2b	Al Hisa Phosphorite Formation
B3	Muwaqqar Chalk Marl Formation
B4	Umm Rijam Chert Formation
BMBF	The German Ministry of Education & Research
D	Deuterium (^2H) isotope
EC	Electric conductivity
JVA	Jordan Valley Authority
km ²	Square kilometer
m	Meter
m ³	Cubic meter
MCM	Million Cubic Meters
MCM/Y	Million Cubic Meters per Year
MWI	Ministry of Water and Irrigation
O ¹⁸ .	Oxygen-18 isotope
RW	Recharge wells
SWL	Static Water Level
T	Temperature
TDS	Total Dissolved Solids

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1. INTRODUCTION

Jordan is characterized by arid to semi-arid climate with limited water resources and faces a chronic imbalance in the water demand - water resources equation. Groundwater is the main source for domestic water supplies in the country. As a result of increasing water demand, many of the renewable groundwater resources are exploited beyond their safe yield. Therefore, water resources have become one of the main government priorities and several measures were taken to ease the wide-spread shortages; these include the construction of reservoirs, along wadis with relatively high rainfall, to store rainfall water for direct use or for artificial groundwater recharge. Latter will increase the sustainable yield of the downstream aquifers.

Wala-Haidan well field is one of the main groundwater resources in Jordan providing domestic water to Madaba and Amman. During the last three decades, the well field was overexploited, where about 11.5 MCM as yearly average have been continuously pumped for drinking purposes. In addition, about 2.3 MCM in average have been pumped yearly through private wells for irrigation purposes. The natural recharge was not sufficient to replenish the groundwater system and consequently the groundwater level was lowered by about 30m (CD3133). This resulted in a drying of the major part of the base flow in Wadi Wala, lowering the groundwater level and consequently increasing water salinity and deteriorating the groundwater quality. Therefore, managed aquifer recharge (MAR) was an option to boost the natural seasonal recharge process.

Wala Reservoir was constructed on Wadi Wala, 9km upstream of the well field with a maximum storage capacity of 9.3 MCM (actual storage: 8.0 MCM). The function of the reservoir is to facilitate groundwater recharge to the underlying limestone aquifer. The mean annual inflow to the reservoir was estimated at 17.7 MCM and is believed to constitute the annual safe yield from the well field. The reservoir has been designed to supply 5 MCM/Y water to the aquifer of the Wala-Haidan well field by natural infiltration and artificial recharge. The artificial recharge is conducted through 8 injection wells, which are drilled downstream of the reservoir. The construction of the reservoir was completed on 2002 and the first impoundment started in winter 2002/03, when it received about 15.3 MCM of water. Most of the received water seeped naturally from the reservoir into the aquifer and the artificial recharge wells were used as monitoring wells. In 2011 the recharge wells were used for the first time for water injection.

As part of the SMART-II Project, which is supported by the German Ministry of Education & Research (BMBF), this study is aiming to investigate the role of Wala Reservoir stored water on the groundwater system. The long term monitoring of groundwater level and reservoir storage were used to evaluate the quantitative effect of the stored water on Wala-Haidan well field. The main problems associated with Wala Reservoir operation, like sedimentation and turbidity, are also examined.

2. GEOLOGY

Wadi Wala catchment is located to the east of the Jordan Rift, adjacent to the eastern shores of the Dead Sea, and forms the northern third of Wadi Mujib groundwater basin. The Wala reservoir catchment extends from Amman in the north, to Wadi Mujib in the south, with a total area of about 2000 km² (*Figure 1*). It is covered with thick soil especially in the northern and eastern parts.

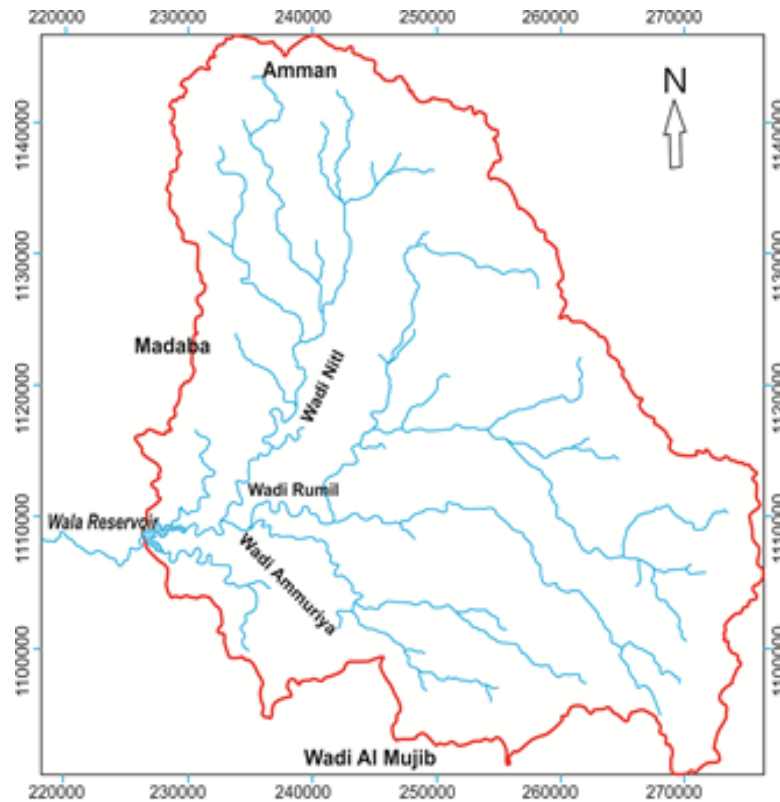


Figure 1: Wadi Wala catchment.

A sequence of more than 400 m thick sedimentary rocks is cropping out in the catchment area and ranging from Turonian to Recent age. This sequence belongs to Ajlun and Belqa groups that have been subdivided into a number of geological formations, as described in the geological maps of Ma'in, Madaba, Khan Ez Zabib, Sahab and Amman. The geological formations, in descending order, include alluvium and soil, Pleistocene gravels, Umm Rijam Chert Formation (B₄), Muwaqqar Chalk Marl Formation (B₃), Al Hisa Phosphorite (B_{2b}) and Amman Silicified Limestone (B_{2a}) formations, Wadi Umm Ghudran (B₁) and Wadi As Sir Limestone (A₇). These geological formations were grouped into three main units to simplify the prepared geological map for this study (*Figure 2*). The first unit includes the superficial deposits that consist of Pleistocene gravels, alluvium and soil. The second includes B₃ and B₄ formations, whereas the third unit comprises the last four formations (A₇, B₁, B_{2a} and B_{2b}) that are grouped into B₂/A₇ aquifer.

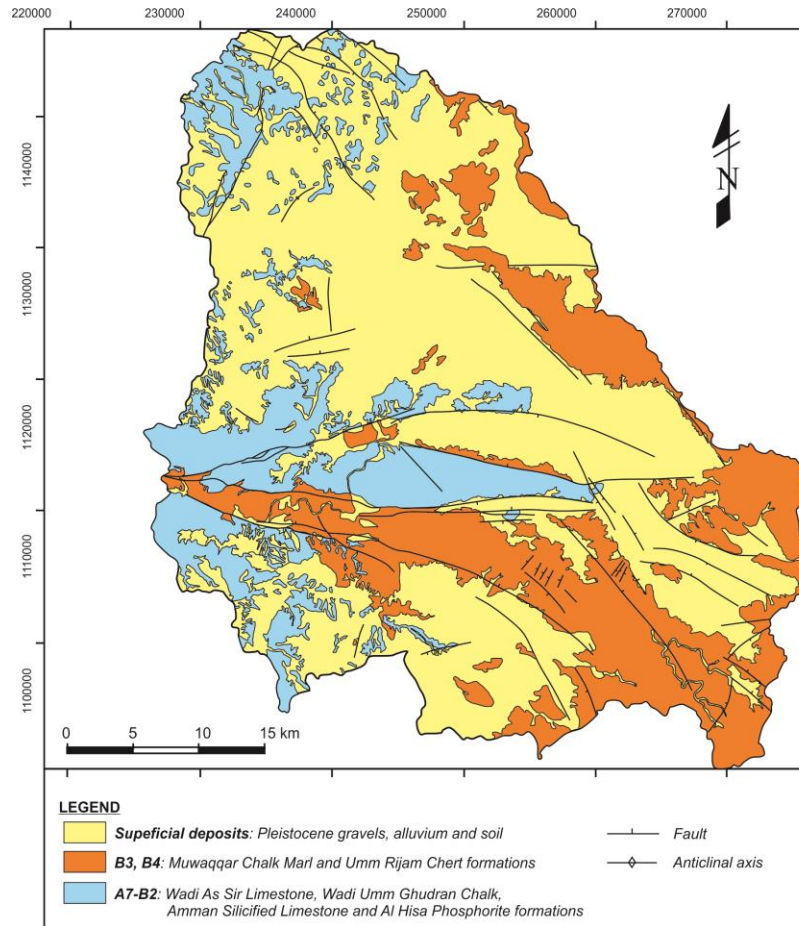


Figure 2: Geological map of Wadi Wala catchment.

3. HYDROGEOLOGY

Wadi Wala catchment drains westwards to the Dead Sea through Wadi Wala and its three major tributaries; Nitl, Rumail and Ammuriya wadis (*Figure 1*). These tributaries are dry except for a short period after rainfall. The mean annual precipitation at the catchment area is about 218 mm, with a mean temperature of 15 °C. The evaporation is around 92% and the groundwater recharge is estimated to be 3 % of the total precipitation.

The B₂/A₇ aquifer is the most important and extensive aquifer system in Jordan and considered as the main source of fresh groundwater. It is composed of limestone, silicified limestone and marl intercalations. The upper part contains phosphatic limestone and cherty phosphate. The middle part (B₁) consists of marl and chalky marl and acts as a minor aquitard within the system. Due to its limited lateral extension, the B₂ and A₇ are hydraulically connected.

The B₂/A₇ formations are the main water bearing layers and forming the main aquifer system in Wala catchment. The upper part of the aquifer (B₂) is mainly unsaturated at the reservoir site. Meanwhile, it forms a major permeable formation and can provide a significant leakage path,

especially when the reservoir reaches its full capacity. The lower part of the aquifer (A_7) forms a major aquifer in the vicinity of Wala and Haidan wadis with a thickness of about 150m. The main natural recharge to B_2/A_7 aquifer takes place along outcrop.

The groundwater flow pattern in the B_2/A_7 aquifer system within Wadi Wala catchment is strongly governed by several features. The most important are; the recharge mounds, the geological structural setting, the presence of Wadi Wala and the Dead Sea. From the recharge mound (Amman-Madaba), where the high hydraulic heads are found, the major part of the groundwater flows southwards to Jiza region, then southwest along the main drainage system of Wadi Wala and passes Wala-Haidan well field towards the Dead Sea, being the final base level for all flows. Other recharge enters the aquifer in the catchment from Karak recharge mound in the south and flows north then to the west towards Wadi Wala. Part of groundwater flows out to the east from both recharge mounds, the groundwater divide (green line) is not correspond with the topographic divide (Figure 3).

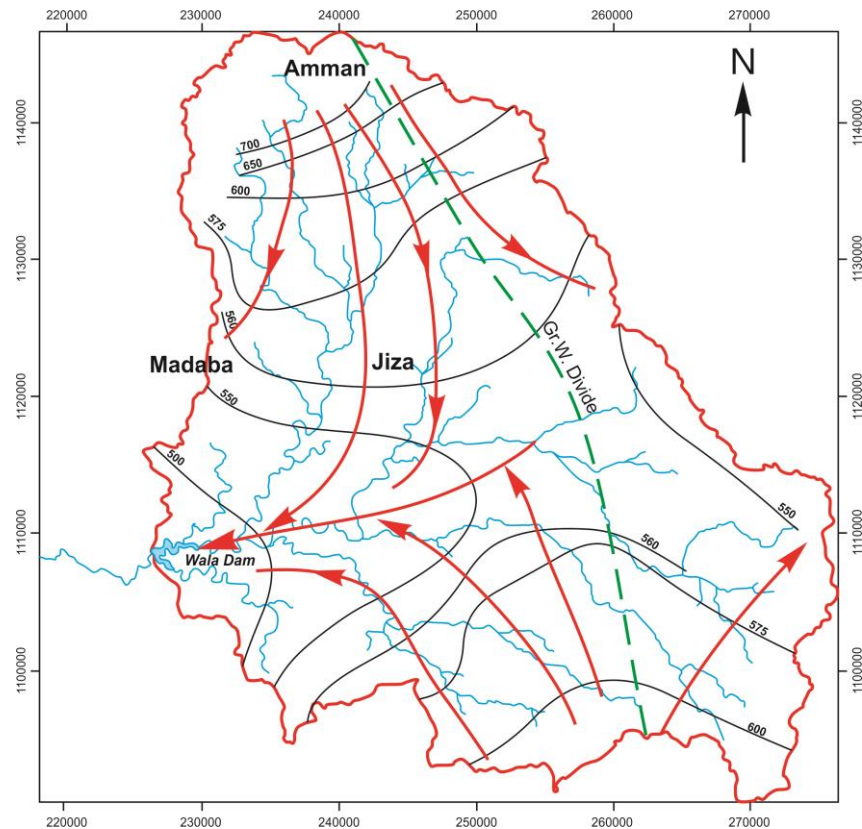


Figure 3: Water level contour map of Wadi Wala catchment.

4. WATER QUALITY

The results of the chemical analyses during the last ten years from the reservoir and some selected wells in the study area (MWI 2012) show that the total dissolved solids (TDS) concentration is ranging from 600 to 900mg/L. This range of salinity is typical for the water of carbonate aquifers, which have a long groundwater residence time. The nitrate concentrations are ranging from 3 to 42 mg/L, where high values resulted from the agriculture activities in vicinity of some wells. The yearly average EC values of the reservoir water ranges from 380 to 700 $\mu\text{S}/\text{cm}$. The highest values were recorded during 2008 and 2009; when the reservoir was dry for five months. A general increasing trend of EC values in the Haidan well field can be observed. Furthermore, a relatively small regional increase in salinity is observed during the period of December 2003 to April 2004, which could be explained as a result of the flushing of the cavities and rock matrix during the period of the first water level increase (Sawarieh et.al 2010).

The reservoir receives water during the rainy winter period and the stable isotope content in the reservoir is depleted, where the $\delta^{18}\text{O}$ ranges from -5.5 to -7.4 ‰, and δD between -25 and -32‰. In summer, the reservoir water became enriched with stable isotopes as it is subjected to evaporation. The relationship between δD and $\delta^{18}\text{O}$ for the water samples collected from the reservoir and four wells downstream shows that all samples are meteoric water and the nearest wells to the reservoir are more depleted than the far wells indicating more recharge from the reservoir.

Intensive agriculture activities and housing along the Wadi Wala and Wadi Haidan causes high contamination potential of the surface waters. Periodical pollution with coliform bacteria and Turbidity was detected in Haidan and Wala wells during the rainy season in the past years, especially at the beginning of the winter season, during major flood events. Several water samples from Wala and Haidan wells were analysed for *E.Coli* (Xanke et.al 2012) and compared with rain events. The conclusion is more *E.Coli* contamination with high rain and Haidan wells more contaminated than Wala wells (Figure 4) and it might be due to the presence of swallow holes.

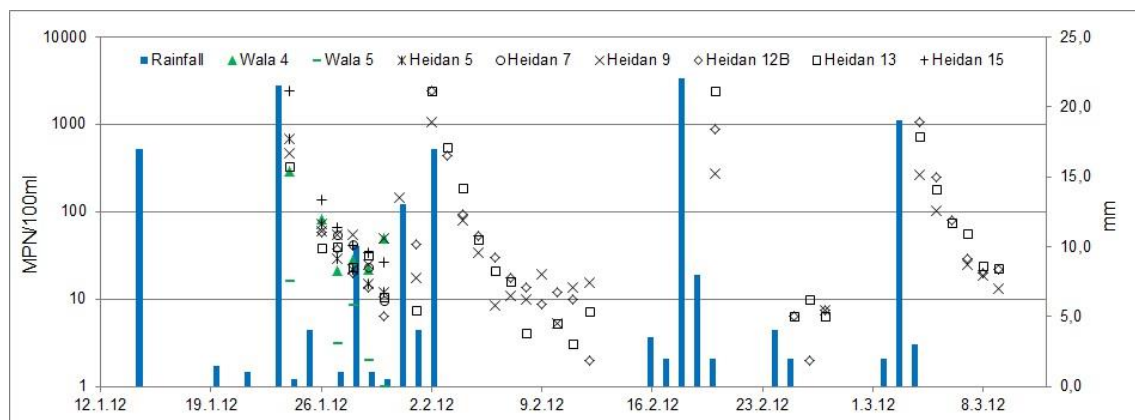


Figure 4: Relation of rainfall and *E.coli* occurrence in Wala and Haidan wells.

5. WALA RESERVOIR

The records of Wala Reservoir storage, the static water level of the artificial recharge wells (RW1-8) and the observation wells (CD1097 and CD3133) downstream of the reservoir during the period from 2002 to 2012 (MWI and JVA data base 2012) were used to assess the quantitative impact of the reservoir stored water on Wala-Haidan well field.

5.1 Reservoir Storage

The storage records of Wala Reservoir (JVA data base) show that the reservoir was almost dry from 6th to 28th November 2003, when the reservoir storage was only 0.369 MCM at an elevation of 490.8 m a.s.l. The records also show that the highest total storage (9.3 MCM) was recorded in the wet years 2004 and 2006, whereas the lowest total storage was in the year 2008. In the latter, only about 2.2 MCM was recorded as maximum storage in the reservoir and it dried out for six months from 11.08.2008 to 11.02.2009 (*Figure 5, Figure 6*). The elevation of the reservoir floor in 2008 was at 498.6m a.s.l, (original: 485m a.s.l.). This means that the reservoir lost about 1.124 MCM from its maximum capacity, due to sediment accumulation and became a new maximum of around 8.176 MCM. Since that time, the reservoir storage is calculated based on the new floor elevation. The storage records show that the reservoir storage reached its new maximum capacity in the years 2009 and 2010 (*Figure 7*).



Figure 5: Wala Reservoir, August 2008.



Figure 6: Sediments in Wala Reservoir, August 2008.

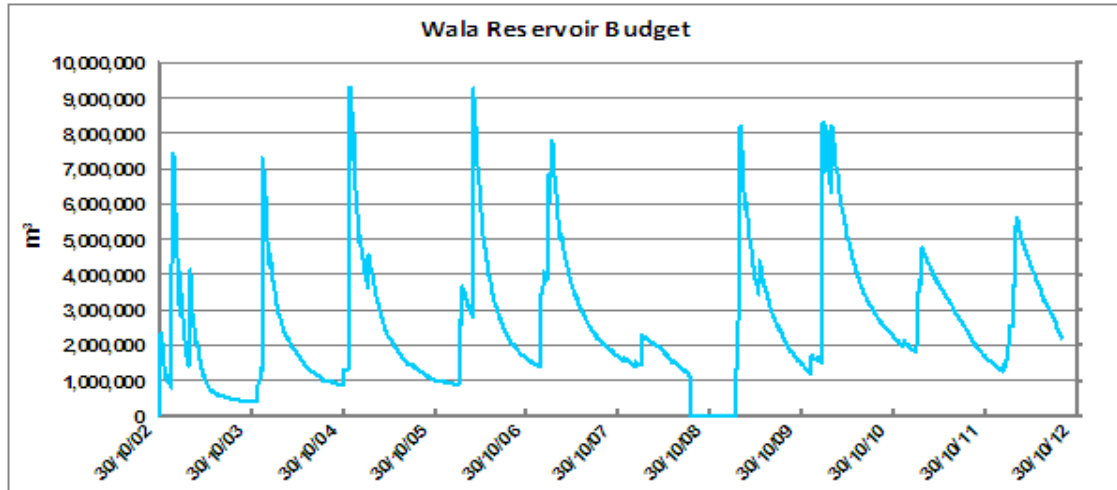


Figure 7: Wala Reservoir storage fluctuations during 2002–2012.

The total inflow to the reservoir during the years 2002–2012 was calculated as 125 MCM. Out of this, about 44 MCM were lost as flood, 8 MCM as evaporation and the rest 73 MCM were recharged to the aquifer. Figure 8 shows the distribution of the total inflow into the reservoir.

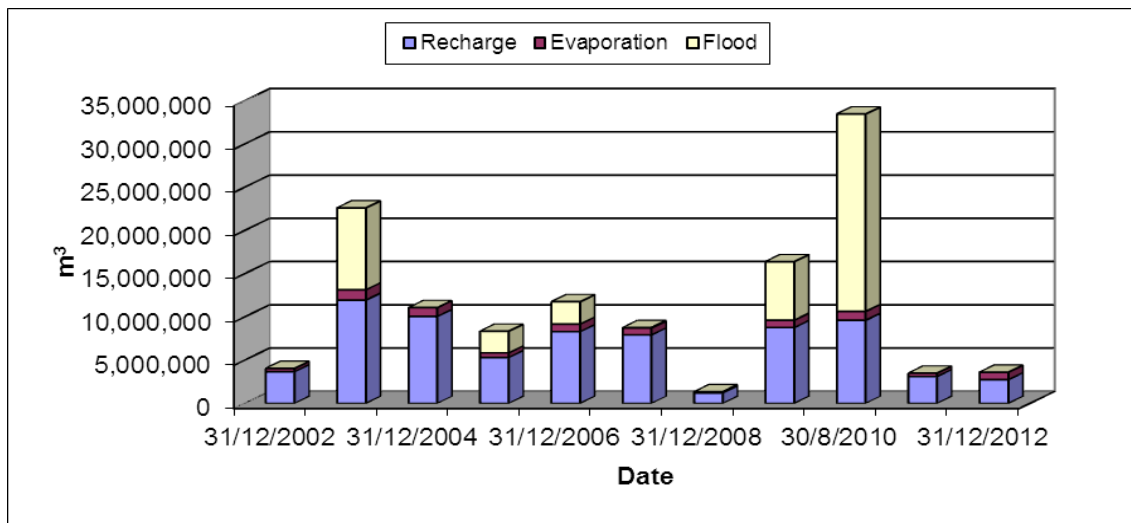


Figure 8: The inflow distribution during the last ten years.

5.2 Recharge Wells (RW1-8)

The reservoir was constructed to recharge about 5 MCM/Y of flood to the aquifer using artificial recharge wells and by natural infiltration. Therefore, 8 wells were drilled downstream of the reservoir and upstream of the Wala-Haidan well field (Figure 9). The reservoir received about 15.3 MCM of water in the first year and most of this water was naturally seeped from the reservoir into the aquifer. The recharge wells were used to monitor the groundwater level downstream of the reservoir and never used for artificial recharge until June 2011.

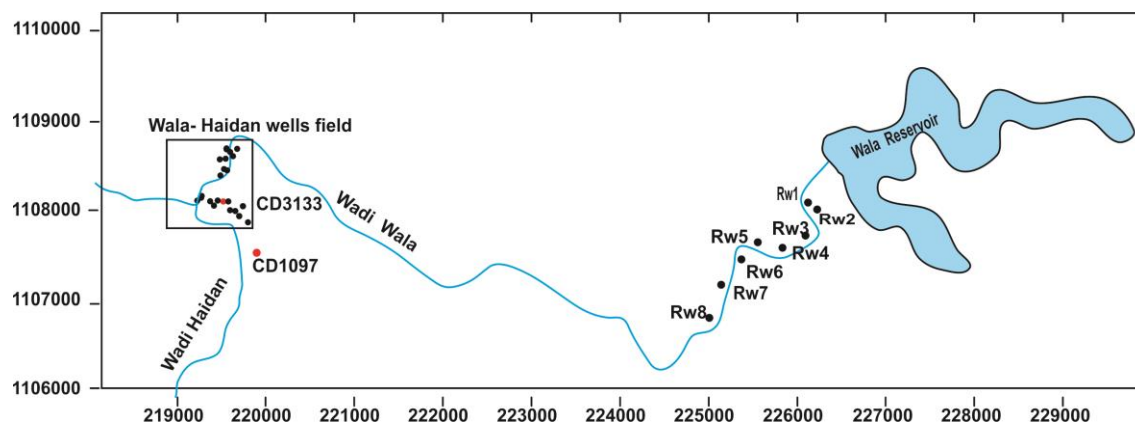


Figure 9: Recharge and observation wells location.

The static water level (SWL) records of the recharge wells before and after reservoir impoundment are shown in Figure 10. It shows that the SWL in the recharge wells was raised by 20 to 32.5 m after the first year of reservoir impoundment. It also shows a sharp decrease of SWL in these wells in the year 2008 when the reservoir was dry. The reservoir received water in the following years and groundwater level raised again.

The first artificial recharge exercise, through the recharge wells, was carried out in June 9th 2011 when 48311 m³ of the reservoir stored water were injected in RW1, RW3 and RW4. The second operation was carried out in July 25th of the same year, when 89177 m³ were injected to all the recharge wells (RW1-8). As a result of these injection operations the water level was increased by 0.1 to 0.4 m in the recharge wells. Since November 30th 2011 an injection campaign was running until the end of the year by injecting 1000 m³ daily in six recharge wells (RW2-7). This resulted in raising the water level in the recharge wells by up to 0.5m. The total amount injected into the aquifer through recharge wells in 2011 was 0.6 MCM. Artificial recharge through recharge wells continued in 2012 and about 0.3 MCM was injected in the aquifer.

Six sensors (WL, T, EC) were installed in the Wala reservoir and in certain wells downstream to ensure a constant record of the reservoir and the groundwater level. The measurements are present in Figure 11, which shows the aquifer response to the natural infiltration from the reservoir as well as to the artificial recharge through the recharge wells (Xanke et.al 2012).

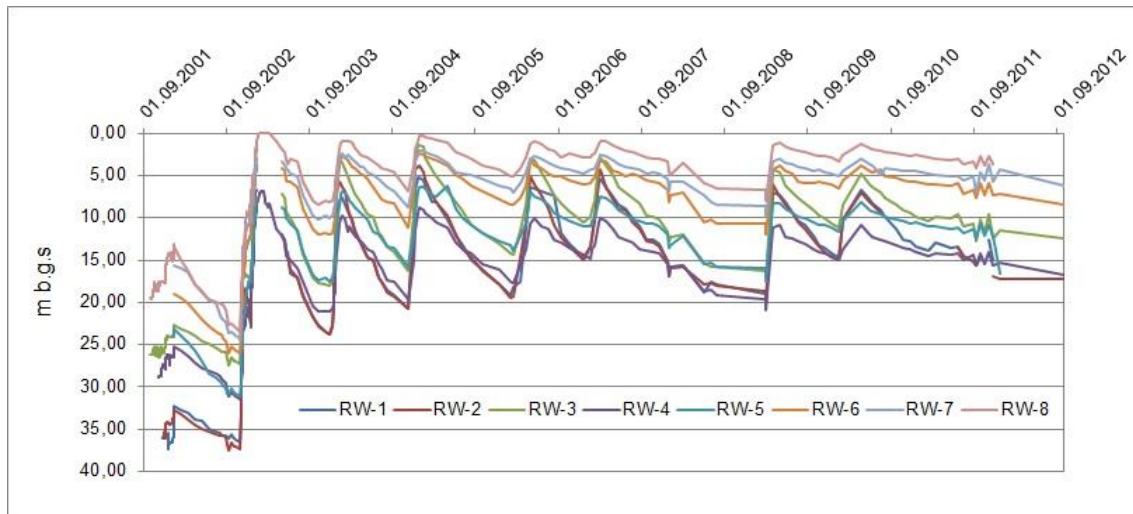


Figure 10: Static water level fluctuation of recharge wells.

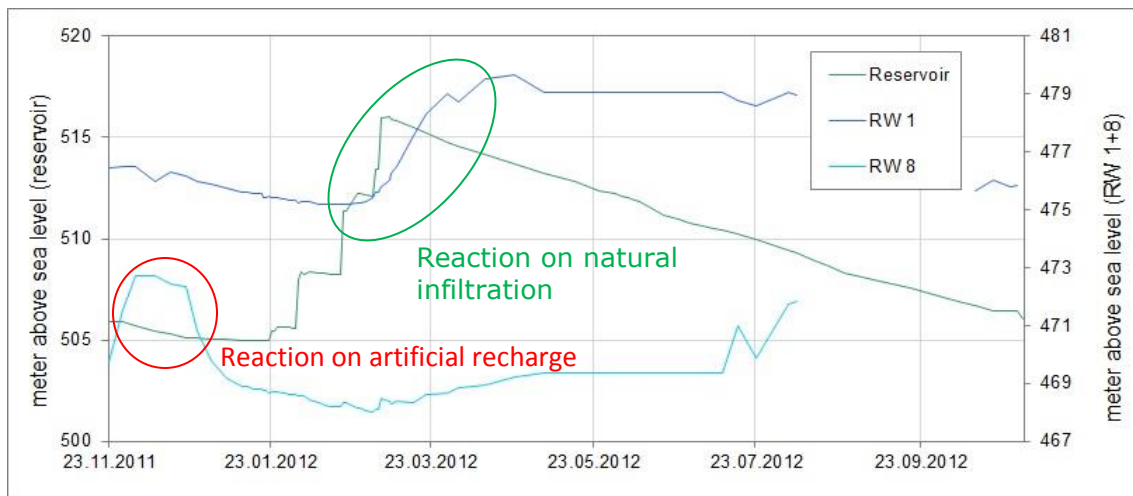


Figure 11: Water level measurements of Wala reservoir and recharge wells.

5.3 Observation Wells (CD 1097 and CD 3133)

The observation wells, CD 1097 and CD 3133, were drilled and equipped with water level recorders to monitor groundwater level fluctuations in Wala-Haidan well field. The recorded SWL data of these wells for the period 1994-2012 (MWI, 2012) were used to evaluate the impact of the stored water in Wala Reservoir on groundwater. The fluctuation of the SWL in wells CD 3133 and CD 1097 is shown in Figure 12. It can be seen from the figure that the water level in both wells was decreasing until winter 2002/2003, when the impoundment in the reservoir was started. The SWL in these wells started rising until the year 2008, when it decreased sharply because the reservoir was dry for about 6 months (August 2008 to February 2009), but it started to rise again in 2009 and 2010 when the reservoir reaches its new maximum storage in 2010 (Sawarieh et.al 2011). This means that the SWL of these wells is directly responding to the reservoir storage.

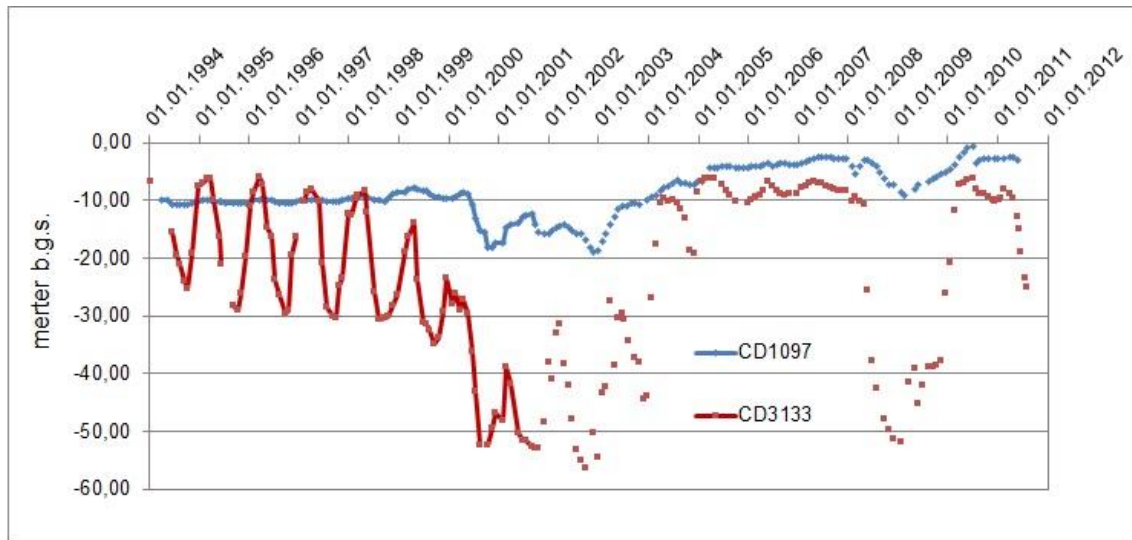


Figure 12: Static water level fluctuation of the observation wells.

6. SEDIMENT ACCUMULATION

Due to sediment accumulation in the reservoir the bottom of the reservoir was raised considerably since the reservoir completion. It can be seen from the reservoir records that the bottom of the reservoir was raised by 5.81 m in the first year (2003) resulting in the loss of about 0.369 MCM of the reservoir capacity. In the year 2008 the reservoir bottom was raised by about 13.62 m and decreased the reservoir capacity by about 1.1 MCM. In February 2010, the gates were opened and about 0.4 MCM of sediments were flushed from the reservoir, this kept the volume of the accumulated sediments as in 2008. The sediment continued to accumulate in the reservoir and the elevation of the sediments in the reservoir reached 501.33 m a.s.l in October 2012. This means that the current maximum storage capacity of the reservoir is 7.7 MCM.

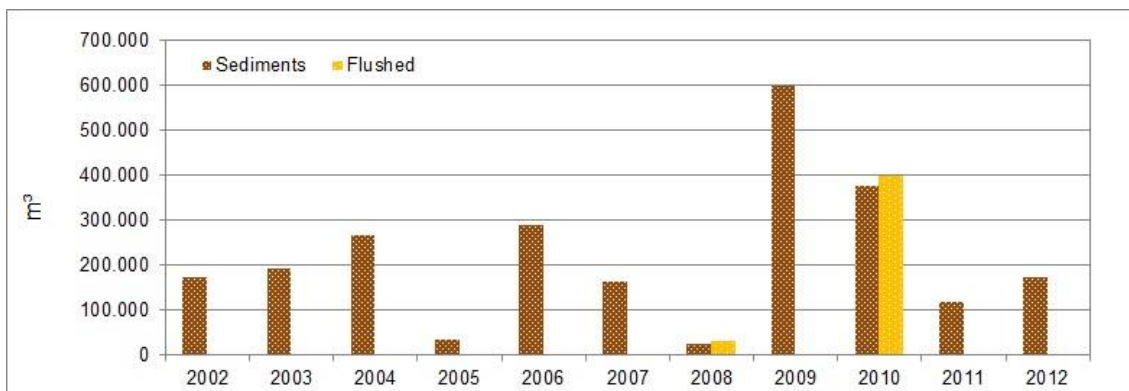


Figure 13: Yearly Sedimentation in Wala Reservoir.

The flushed sediments and the major flood events increased the turbidity in Wala-Haidan well field and production from the well field had been shut down several times for one to two weeks in the last years.

Figure 13 shows the yearly sedimentation in Wala Reservoir.

Based on the known reservoir floor and sediments elevations in the reservoir on four dates 2002, 2003, 2008 and 2012 (JVA 2012) an attempt is made to calculate the sedimentation rate for the three periods. The mean sedimentation rate is calculated by dividing the total volume of sediments on the total volume of stored water in the periods; 2002-2003, 2003-2008 and 2008 - 2012. The average mean sedimentation rate is 29 liter sediments per 1000 liter water inflow.

To characterize the sediments in the reservoir, three soil samples were taken in February 2012. The samples were analyzed for grain size distribution, polycyclic aromatic hydrocarbon (PAH) and carbonate content. The results show that the main components of the reservoir sediments are silt and clay. The carbonate content ranges between 25 and 28 %. The results of 16 polycyclic aromatic hydrocarbons (PAH) show a total content of 208.4 µg/kg in sample 1, 1436.7 µg/kg in sample 2 and 63.7 µg/kg in sample 3 and Naphthalene is the main compound (40-170µg/kg). Smaller amounts (4-38 µg/kg) of Acenaphthene, Fluorine, Phenanthrene, Anthracne, Fluranthracene, Pyrene and Benzo anthracene were detected in samples 2 and 3. All other PAH's lay below the detectable limit (2µg/kg). The higher amounts were found in the sediments at the reservoir inlet.

7. RECHARGE FROM THE RESEVOIR

The reservoir records show the daily recharge quantities from the stored water into the aquifer (*Figure 14*). It can be seen from the figure that there had been a continuous decrease in recharged quantities with the time. This is caused by the accumulated sediment in the reservoir, which not only reduced the reservoir capacity but also decreased the infiltration rate through the reservoir floor and edges.

The total abstraction from Wala-Haidan well field during the operation period of the reservoir 2002-2012 is about 125MCM. In August 2010, 66% of the total production was supported by recharged water, decreased to 60% by December 2011 and to 58% by August 2012. *Figure 15* shows the yearly recharge and abstraction quantities to and from the well field.

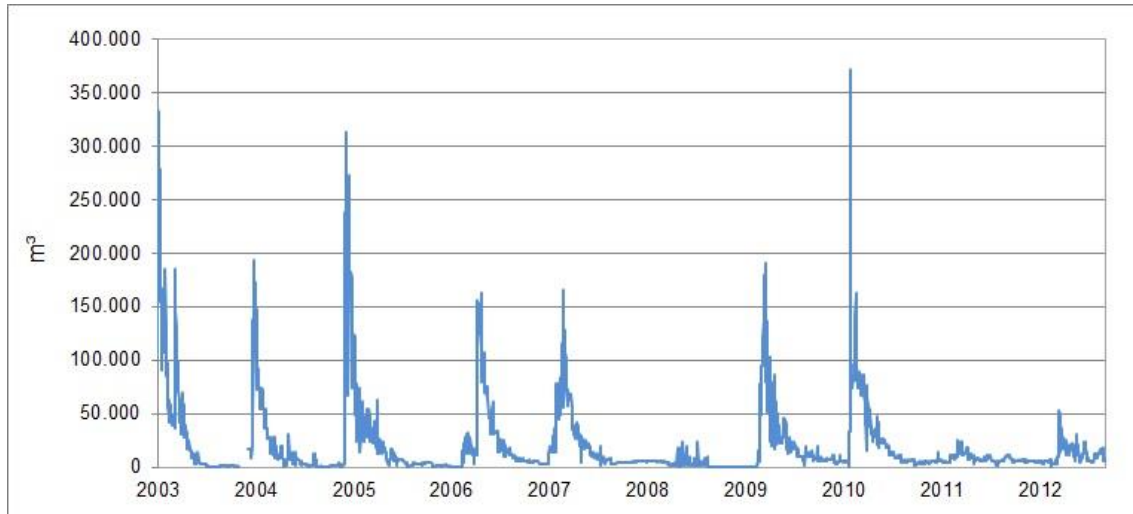


Figure 14: Daily recharge fluctuation from the reservoir into the aquifer.

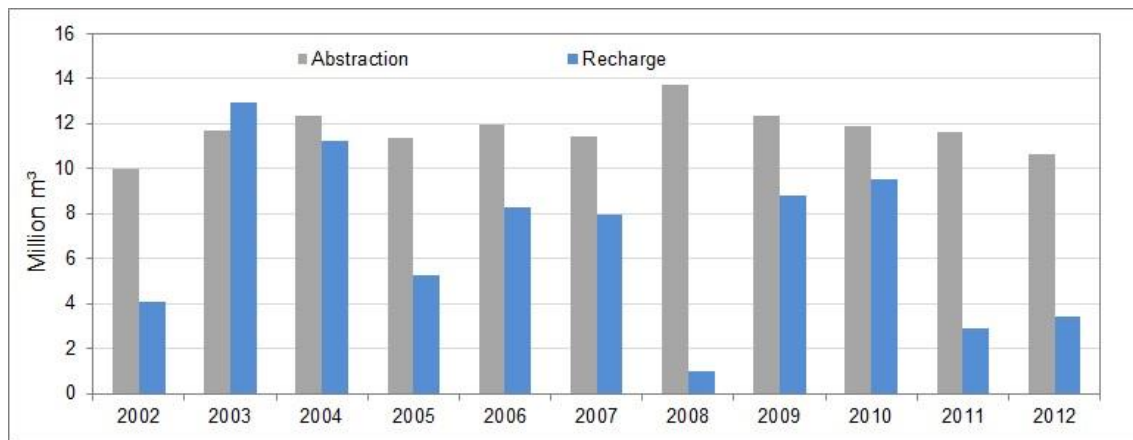


Figure 15: Yearly recharge from the reservoir and abstraction from the well field.

8. SUGGESTED ACTIONS

To overcome the problem of sediments accumulation in the reservoir that affected its storage capacity, JVA is currently proposed to raise the reservoir by 15m, which would result in a live storage of 26.3 MCM. This will not help the continuous decrease in the natural infiltration rate from the reservoir into the aquifer, because the sediment keep accumulate in the reservoir. The permeable remaining parts of the reservoir floor and edges will be covered and the natural infiltration rate will be reduced to about zero. Therefore, to keep the current infiltration rate, check dams, can be constructed upstream; even if the reservoir is raised, on the major tributaries of Wadi Wala (Wadi Rumil and Wadi Ammuriya) to minimize the sediments inflow to the reservoir. Two areas on these wadis were chosen *Figure 16* and the geology of these areas was studied. Finally, two sites were selected for the proposed check dams on elevations more than 535m above sea level to be outside the reservoir lake if it rises in the future.

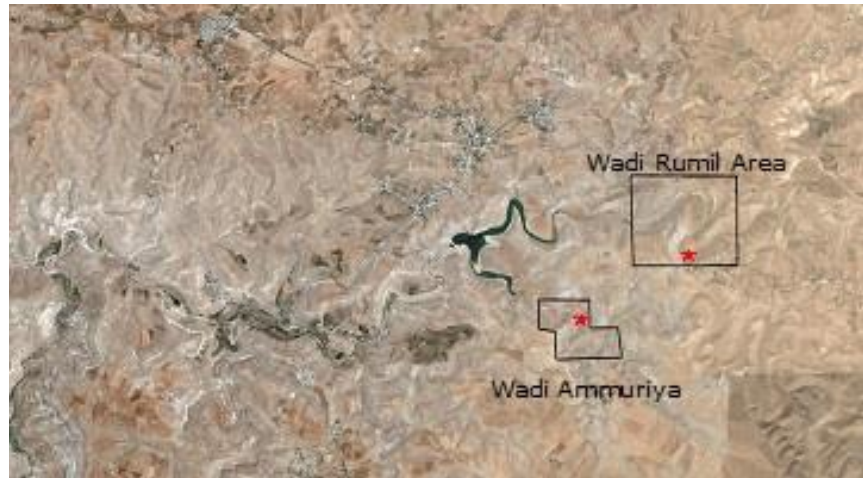


Figure 16: The two studied areas and the proposed check dams (Red stars).

8.1 Detailed Geology

The stratified rock units outcropping in the selected two areas, from bottom to top, (Figs. 13 and 14) are:

8.1.1 Superficial Deposits

The main Pleistocene-Holocene superficial deposits in the study areas are the alluvium sediments that cover the wadi courses, the screes along the wadi shoulders and soil cover of the rock units. These sediments have various facies of unsorted to sorted, matrix-and clast-supported sediments. Clasts and gravels are generally sub-rounded and variable in composition depending on the surrounding rocks.

8.1.2 Wadi Umm Ghudran Formation (WG) (Coniacian-Santonian)

Only the upper part of the formation, Dhiban Chalk member, is exposed in the study area along the flanks of the wadis. The lithology of this member is characterized by its soft and white appearance due to the abundance of chalk. It consists of white to grey, massive to bedded, soft to hard chalk with a conchoidal fracture, intercalated with chert bands and beds, intercalated with marl, and bituminous phosphatic limestone. Secondary gypsum filled the fractures. Bivalves, sponge spicules, fish and shell fragments are present. The exposed thickness is less than 25m in Wadi Ammuriya and it is thicker in Wadi Rumil.

8.1.3 Amman Silicified Limestone Formation (ASL) (Santonian-Campanian)

The formation crops out in the study areas as steep cliffs with a thickness of about 80m and overlying the Wadi Umm Ghudran Formation. It can be subdivided into two units. The base of the formation is marked by a massive dark-weathering chert bed with a distinctive resistant landform above the soft, massive, pale weathering chalks of the underlying formation. The top of the formation can easily be distinguished from the overlying softer-weathering Al Hisa Phosphorite Formation.

The formation consists of hard, resistant and light to dark grey beds of chert, alternating with brown microcrystalline limestone and chalk. Phosphate of low grade type occurs as thin beds, layers and concretions near the top of the formation, and at the top of individual chert and limestone beds. Coquinal limestone occurs in a few localities at the base of the formation.

Chert and carbonates are the two main rock types which were recognized in this formation. The cherts are of many types; homogeneous pinch-swell, spheroidal, concretionary, brecciated and pocellanite. Carbonates are usually interbedded with cherts, and mainly comprise micritic, chalky and oyster coquina limestone, which reaches about 18 m thick and consisting of oyster shells. Limestone is rich in *Thalassinoides* burrows. Other rock types are present such as phosphorites, which increases upwards the sequence, and finely-laminated, yellow, marl, which interbedded with the chert beds especially at the top of the formation and rich in *Thalassinoides*.

8.1.4 Al Hisa Phosphorite Formation (AHP) (Campanian-Maastrichtian)

The formation crops out partly in Wadi Rumil study area of less than 30m thick and completely in Wadi Ammuriya study area of about 60m thick. It forms small rounded hills and sometimes with a cliff of hard coquinal limestone beds. The formation can be divided into three members; Sultani Phosphorite, Bahiyya Coquina and Qatrana Phosphorite.

The formation is lithologically heterogeneous and consists of alternating beds of chalk, chalky limestone common in *Thalassinoides*, phosphatic rock, phosphatic limestone, phosphatic chert, micritic limestone, marl (vary-colored), cross-bedded oyster banks and reworked broken shells. Phosphatic rock is present as soft beds and lenses with fish fragments. Chert beds and concretions are grey to brown with pinch-and-swell structure. Phosphatic chert is abundant especially near the top of the formation.

8.1.5 Muwaqqar Chalk-Marl Formation (Age)

This formation is only exposed in Wadi Rumil study area with thickness less than 15m. It is composed mainly from white, soft-weathering, chalk, chalky limestone and marl. Secondary gypsum is abundant along fractures. The formation is mainly covered by white and soft-weathering soil.

8.2 Structures Settings

8.2.1 Wadi Rumil study area

Compressional structures are the most obvious structural features in this area. A thrust fault extending NE-SW with a downthrown towards the SE has a clear effect on the rock units. Local anticline and syncline folds with axes parallel to the fault and a traverse small normal fault trending NW-SE are present *Figure 17*. Joints and fractures are minor and mainly have NE-SW and NE-SW trends. Dip and dip directions are variable and local.

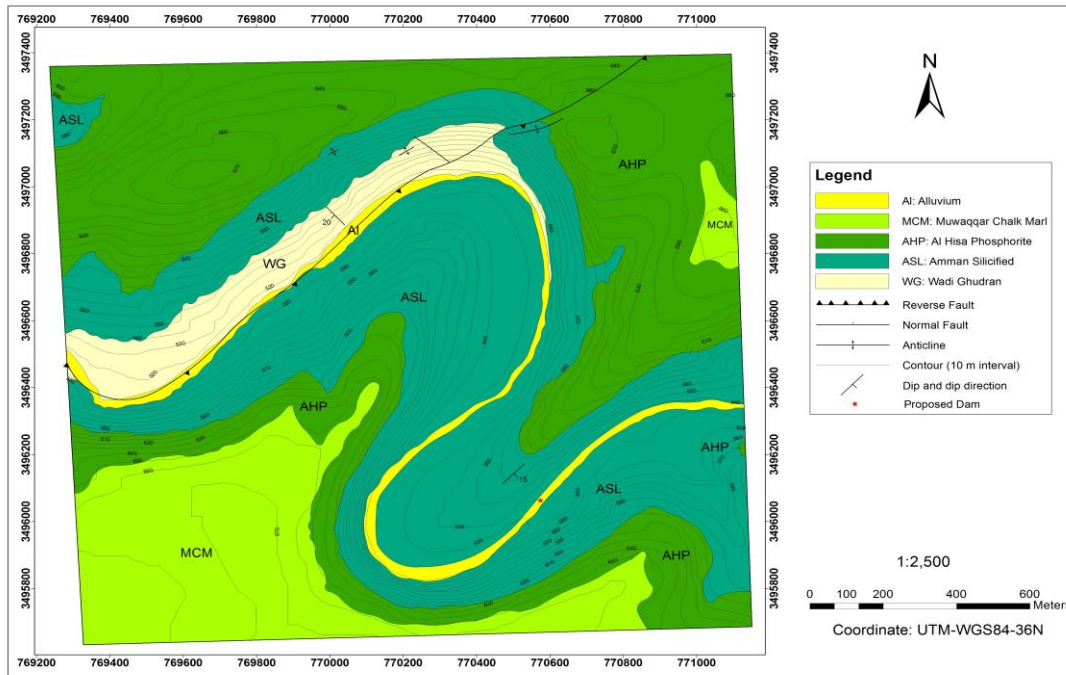


Figure 17 Geology of Wadi Rumil study area.

8.2.2 Wadi Ammuriya study area

Compressional structural features are abundant in this area. Folds, trending NE-SW, without clear effect and a normal fault of NW-SE trend are present *Figure 18*. Joints and fractures are minor and mainly have NE-SW and NE-SW trends. Dip and dip directions are local and hardly can be seen.

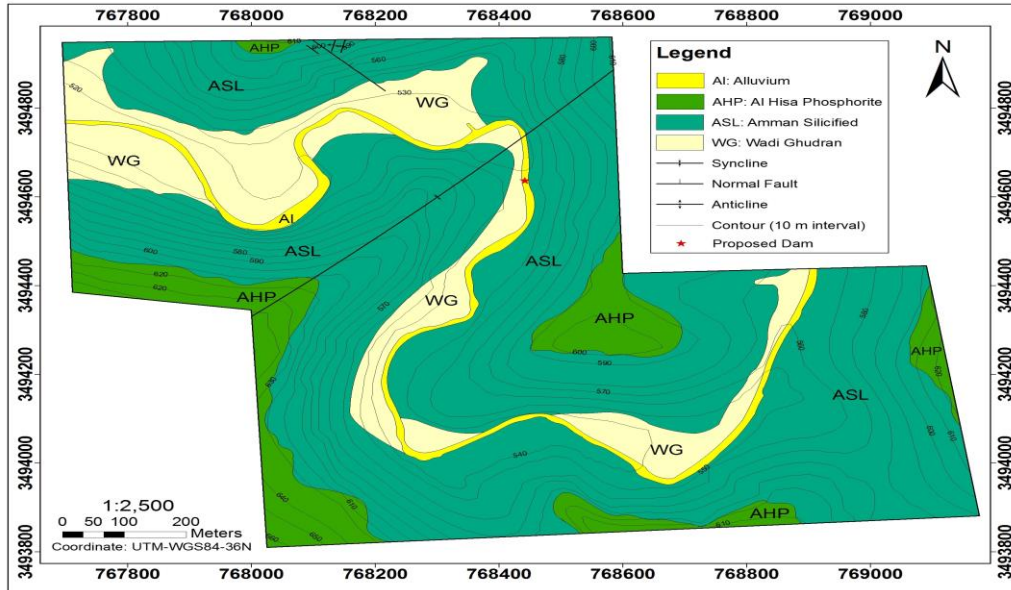


Figure 18: Geology of Wadi Ammuriya study area Cut The empty space.

8.3 Proposed Check Dams

The elevation model of the studied areas and the selected sites for the proposed check dams on Rumil and Ammuriya wadis are shown in Figure 19.

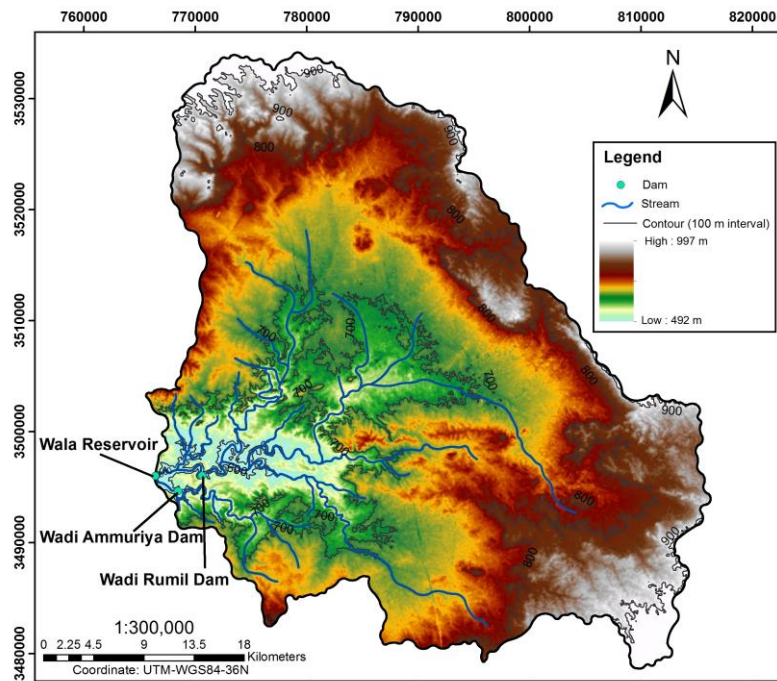


Figure 19: Elevation model and location of the proposed check dams.

8.3.1 Wadi Rumil proposed check dam:

Wadi Rumil drains about 50% of Wadi Wala catchment and its yearly flood is more than 50% of the total flood into Wala reservoir. The sub-catchment of Wadi Rumil is mostly covered by thick soil. This means that most of the sediments accumulated in the Wala reservoir were brought by Wadi Rumil floods; therefore construction of check dam on this wadi will reduce the sediment accumulation in the reservoir and will help in keeping the current natural infiltration rate. A site for proposed check dam on Wadi Rumil is selected at location (1108585 N and 230805 E of Palestine Belt 1923) and at elevation about 538m above sea level. *Figure 20* shows the geological cross section of the proposed dam location. The capacity of the dam is about 2.75 MCM if the dam height is about 15m and it can be built at maximum height of 22m with capacity of about 4.5 MCM to keep the dam lake at elevation of 560m a.s.l., so the dam lake will not reach Rumil Bridge in the east. The estimated cost of the construction ranges from 4 to 7 million Jordanian Dinar (equivalent to 5.6 to 9.8 million US Dollar), depending on the dam capacity.

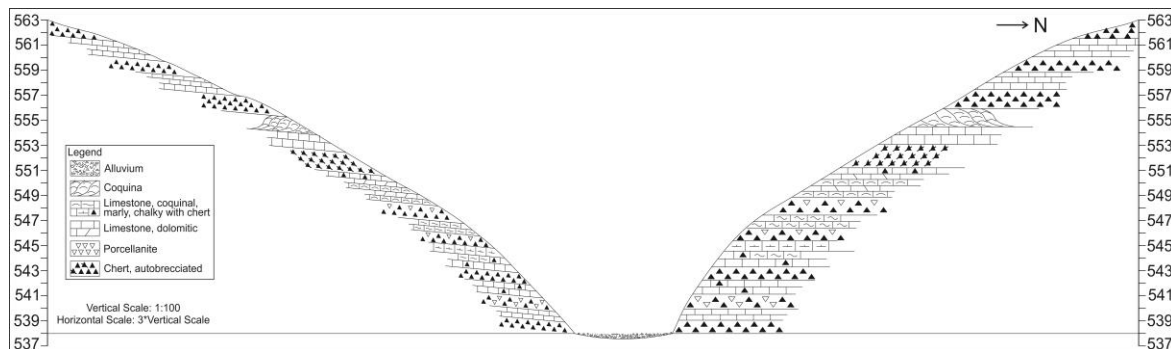


Figure 20: Geological cross section of the proposed dam on Wadi Rumil.

8.3.2 Wadi Ammuriya proposed check dam

Another possible site for check dam can be constructed on Wadi Ammuriya which drains the southern part (about 30%) of Wala catchment. A site for proposed check dam on the wadi is selected at location (1107199 N and 228644 E of Palestine Belt 1923 and at elevation about 538m above sea level. *Figure 21* shows the geological cross section of the proposed dam location. The capacity of the dam is about 3.5MCM with maximum dam height about 20m. The estimated cost of the construction is about 5 million Jordanian Dinar (equivalent to 7 million US Dollar).

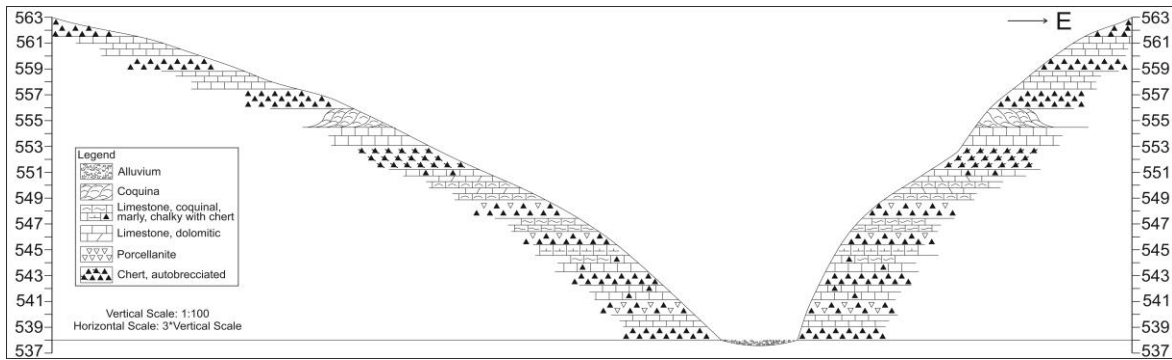


Figure 21: Geological cross section of the proposed dam on Wadi Ammuriya.

The work on these check dams and drilling more injection wells and Installations of large sand filter as well as several management actions have to be followed up in the coming phase of SMART project.

9. DISCUSSION AND CONCLUSIONS

Wala Reservoir is the biggest artificial recharge construction in Jordan. It was built in 2002 to store the flood water of Wadi Wala to recharge the karst limestone aquifer (A₇) of Wala- Haidan well field downstream, by about 5 MCM/year through artificial recharge. The injection is done using 8 wells that were drilled just downstream of the reservoir. Since the construction, most of the stored water was naturally seeped into the aquifer without any artificial recharge through the recharge wells. Therefore, these wells were used as monitoring wells in addition to the two observation wells in Wala-Haidan well field. The SWL records of these wells were responding to the storage volume in the reservoir. In Figure 10, *Figure 11* and *Figure 12* it is obvious that the reservoir lake and the groundwater are hydraulically connected and the aquifer system downstream is receiving recharge from the reservoir lake.

The data of the reservoir during the period, December 2002 to October 2012, show that the reservoir received about 125 MCM as total inflow. Around 44MCM of this amount was lost as flood and 8 MCM as evaporation, while 73 MCM was received by the downstream aquifer as recharge.

Despite the reservoir was acting affectively in recharging the downstream aquifer during the period of operation and supported about 58% of the total production (125MCM) from the well field, it is facing the problem of sediments accumulation that affected the infiltration rate from the reservoir floor to the aquifer and decreased its capacity. The sediments accumulation in the reservoir was increasing year after year, thus decreasing the reservoir capacity. After one year of operation the reservoir capacity was decreased by 0.37 MCM in 2003 and five years later in 2008, when the reservoir was dry, the capacity was decreased by 1.1 MCM. In February 2010, the gates were opened and about 0.4 MCM of sediments were flushed from the reservoir, this

kept the volume of the accumulated sediments as in 2008. According to the sediments elevation in the reservoir in Oct.2012 the capacity of the reservoir is decreased to 7.7 MCM.

Based on the known reservoir floor and sediments elevations in the reservoir an attempt was made to calculate the sedimentation rate and the average mean sedimentation rate. The results showed around 29 liter sediments per 1000 liter water inflow.

The flushed sediments and the major flood events increased the turbidity in Wala-Haidan well field and production from the well field had been shut down twice for one to two weeks in the last two years.

The accumulated sediments in the reservoir not only reduced the reservoir capacity but also decreased the infiltration rate through the reservoir floor and edges. The daily recharge quantities from reservoir stored water into the aquifer show a continuous decrease in recharged quantities with time.

To overcome the sediments accumulation and its effect in decreasing the maximum capacity of Wala Reservoir, JVA is currently proposed to raise the dam by 15 m, which would result in a live storage of 26.3 MCM with total cost of 20 million JD. This will not help the continuous decrease in the natural infiltration rate from the reservoir into the aquifer because as the sediments keep accumulate in the reservoir, the permeable remaining parts of the reservoir floor and edges will be covered and the natural infiltration rate will be reduced to about zero. Therefore, to keep the current infiltration rate, check dams can be constructed upstream, on the major tributaries of Wadi Wala to minimize the sediments inflow to the reservoir. Additional work has been started to examine the possibility of constructing check dams on Wadi Rumil and Wadi Ammuriya. One check dam is proposed on Wadi Rumil with maximum capacity of 4.5 MCM and costs of around 7 million Jordanian Dinar (equivalent to 9.8 million US Dollar). Another check dam is proposed to be constructed on Wadi Ammuriya with a maximum capacity of 3.5 MCM and cost of around 5 million Jordanian Dinar (equivalent to 7 million US Dollar).

The work on these check dams and drilling more injection wells and Installations of large sand filter as well as several management actions have to be followed up in the coming phase of SMART project.

A solid conclusion can be made that Wadi Wala Reservoir was a very successful managed aquifer recharge structure in Jordan and it is highly recommended that this experiment can be copied and applied in several places in Jordan and the region.

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