



Utilizing non-traditional data sources for estimating channel seepage losses

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Abstract

Accurate streamflow data, which constitute the basic component in estimating seepage losses or gains in streamflow are in short supply in developing countries. The lack of either financial or technical resources, or both, and at times, the lack of understanding of the importance of accurate streamflow measurements in supporting modeling and water resources decision making process hinder the installation and proper maintenance of streamflow gauges. Therefore, the current study adopted the aim of demonstrating the feasibility of utilizing alternative streamflow data sources in hydrologic studies. In the current study, such sources included effluent from a large wastewater treatment plant as an inflow to the river segment under consideration while the outflow from the same river segment was taken to be the flow discharged into a dam reservoir as calculated from daily dam reservoir water balance. A water balance was established for a 48 km segment on the Zarqa River in Jordan with components covering the inputs of discharge from springs, and wastewater treatment plants and outputs such as direct evaporation, and surface withdrawals for irrigation purposes. Channel seepage was estimated as the difference between inputs and outputs of the river segment water balance. Final results demonstrated the feasibility of utilizing non-traditional data sources, whenever available, to conduct analysis that traditionally has not been possible.

Keywords Channel seepage · Groundwater recharge · Streamflow · Differential gauging

Abbreviations

AZB	Amman–Zarqa Basin
CC	Crop consumption
JMD	Jordan Meteorological Department
KSWWTP	Kherbit Elsamra Wastewater Treatment Plant
KTDR	King Talal Dam Reservoir
MCM	Million cubic meters
MWI	Ministry of Water and Irrigation
WAJ	Water Authority of Jordan

Introduction

In arid and semi-arid regions, loss of streamflow to channel bed is an important source of groundwater recharge (Abdulrazzak and Morel-Seytoux 1983; Sorman and Abdulrazzak 1993; Abdulrazzak 1995; Izbicki 2002; Goodrich et al.

2004; Subyani 2004; Niswonger et al. 2008; Dagès et al. 2008; Morin et al. 2009). Variables influencing the interaction between streamflow and aquifers include differences between hydraulic head in streambed and adjacent aquifers, channel geomorphology, lithology variability, and streambed and near-stream formation hydrologic and hydraulic properties (Ruehl et al. 2006). Properly quantifying the portion of groundwater recharge caused by streamflow is critical in managing existing water resources (Lange 2005). This is especially true for arid and semi-arid countries such as Jordan which is one of the poorest counties in the world when it comes to freshwater resources. In the related field of irrigation canals, Gu and Deutschman (2001) stressed the importance of water loss when designing and planning water diversion and delivery systems. Studies by Fipps (2005), Kinzli et al. (2010), Tanji and Kielen (2002) and Yussuff et al. (1994) estimated seepage losses in irrigation canals to be in the range of 20–50% of the canal flow. Even though not all water infiltrating beneath rivers reaches groundwater because a portion of the infiltrating water may evaporate or get transpired by riparian plants (Villeneuve et al. 2015), estimating channel seepage losses is vital since those estimates are used directly in quantifying groundwater recharge.

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While several methods exist for quantifying groundwater recharge from streambeds, most rely on localized measurements that cannot be expanded to a regional scale with great confidence. Techniques to quantify seepage losses from streamflow include empirical formula, analytical or analog studies, point measurements using tracers, seepage meters or infiltrometers, ponding water balance method in channel reaches that are isolated from flow, and the flowing water balance (Alam and Bhutta 2004; Martin and Gates 2014). Vertical temperature profiling has also been used (Vogt et al. 2010) to estimate seepage rates from losing streams. A recent study (Shaikh and Lee 2015) estimated channel seepage as a function of channel and bank soil texture. Point estimates of seepage vary considerably both in space and time. Calver (2001) reviewed prior studies that measured streambed hydraulic conductivity and found that two or three orders of magnitude of variation existed at the same location and the between-site variation was more than eight orders of magnitude.

As part of the flowing water balance method mentioned above, differential gauging offers a method for estimating transmission losses or seepage losses in arid and semi-arid regions. The method has been widely used to assess the exchanges between streamflow and groundwater (Cey et al. 1999; Langhoff et al. 2006; Opsahl et al. 2007; Arnott et al. 2009; Harte and Kiah 2009; Schmadel et al. 2010). The dependence on this method in such regions may be hindered by the lack of available data on streamflow. Even when such data are available, data accuracy may come into question. An approach we name here “modified differential gauging” relies on non-traditional data sources for estimating transmission or seepage losses.

The main goal of this study is to demonstrate the applicability of utilizing non-traditional flow measurement data to quantify seepage losses from riverbed.

Methods

In the current research study, two non-traditional data sources were utilized in place of in-stream flow gauge data to estimate channel seepage losses from flowing water through establishing water balance in a river segment. Namely, effluent from a relatively large wastewater treatment plant was used as the upstream boundary condition for the selected river segment. Flow leaving the downstream end of the segment was obtained as the estimated daily inflow to a reservoir located at the end of the river segment. The two data sources offer more accurate flow measurements than the flow gauge measurements at stations located along the river segment. Existing flow gauging sites may lack the proper maintenance and rating curves may not be updated regularly

to reflect the impact of changes in channel cross sections on the accuracy of flow measurements.

Water balance was estimated for the rain-free summer months of June through September. The rain-free months were chosen to eliminate additional uncertainty that would have been added if the rainfall–runoff processes were simulated to develop the year-long flow input into the river segment. Kalbus et al. (2006) advised that, when incremental streamflow measurements are used to establish the water mass balance, measurements should be taken during low-flow conditions to allow for associated changes in flow to groundwater impact.

Gains in the water balance included effluent from wastewater treatment plants and discharge from springs. Losses on the other hand included discharge to dam reservoir at the downstream end of the river segment, direct evaporation, surface withdrawals for crop consumption, and seepage losses. Very little, if any, baseflow occurs during the summer period in this semi-arid study area where discharge from springs forms the main source of baseflow during the summer months.

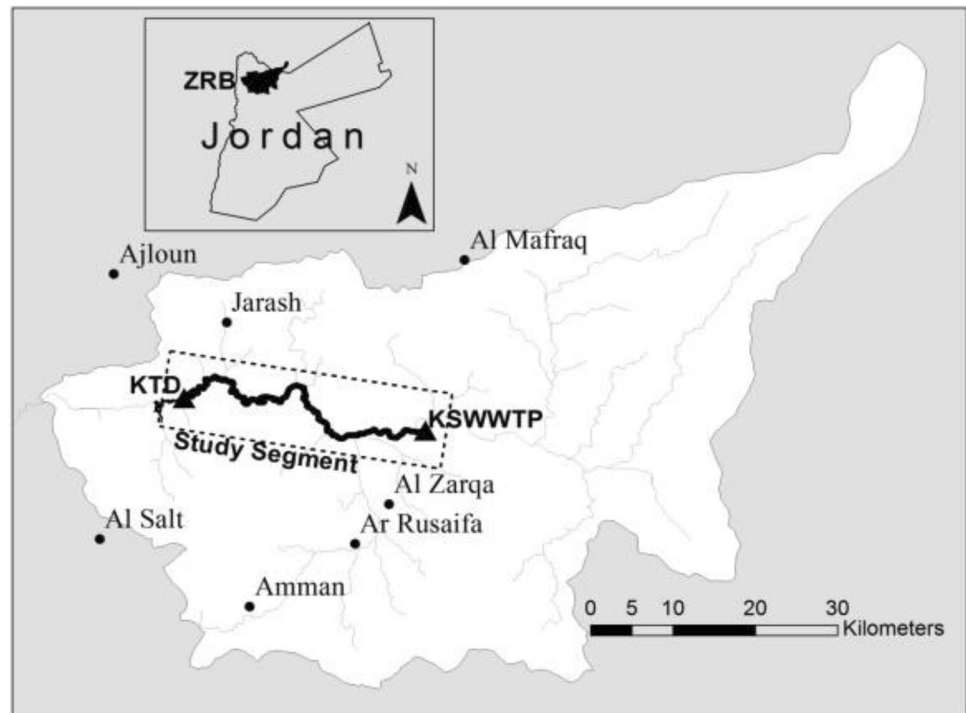
Study area

The Amman–Zarqa Basin (AZB) (Fig. 1) is approximately 3922 km², most of which (3785 km²) drains into the King Talal Dam Reservoir (KTDR). The basin contains densely populated portions of the cities of Amman, Zarqa and Rusaifah. Precipitation in this semi-arid basin takes place during the October to May rainy season. There are three climatic regions within the basin (Shahin 2007). The eastern region of the basin has the least amount of annual precipitation averaging approximately 100 mm per year with hot summers and mild winters. The mid-section of the basin experiences the highest precipitation averages of approximately 500 mm per year with milder summers and cooler winters. Finally, the western portion of the basin nets an average precipitation of 200 mm per year.

The river segment that is the subject of this study is located along the Zarqa River and has its upstream boundary as the Kherbit Elsamra Waste Water Treatment Plant (KSW-WTP) and downstream boundary as KTDR with a length of approximately 48 km. Elevation along the segment drops from 535 m at the KSWWTP outfall to 170 m at the KTDR inlet with an average slope of 0.0076 m/m. The headwater segment of Zarqa River that drains a 665 km² area including a large portion of the city of Amman flows into the river segment under consideration, approximately 10 km downstream of the KSWWTP outfall.

The KSWWTP treats domestic wastewater generated in Amman–Rusaifah–Zarqa region serving over two million people. The plant treats 72% of the entire domestic wastewater in Jordan (Bajjali et al. 2015) and has a daily design flow

Fig. 1 Study area location in relation to Zarqa River Basin



of 365,000 m³. The continuous effluent from the KSWWTP has been shown to cause a rise in the groundwater level at a rate of 20 cm per year (Bajjali et al. 2015). The same study found that groundwater level dropped 43 m since 1968 upstream of KSWWTP. Increased farming activities around the Zarqa River downstream of the KSWWTP utilize the treated wastewater for crop irrigation purposes.

The Zarqa River Basin has three main aquifers. The top two aquifers are hydraulically connected and consist of a basaltic eruption aquifer (B2/A7) at the top, below which falls a limestone aquifer (A4). A 20–35 m thick marl formation separates the top two aquifers from the bottom sandstone (K) aquifer (Al-Zyoud et al. 2015). The upper aquifer is unconfined and forms the most important and productive aquifer in Jordan with varying thicknesses between 40 m in the west to 300 m in the east (Shaqour et al. 2015). Al Farajat et al. (2005) estimated through the use of the gravity method that the alluvium aquifer depth above the bedrock ranged from 8 to 33 m in the vicinity of the study area. The alluvial aquifer beneath the Zarqa River is part of the upper unconfined aquifer.

Approach

The seepage losses within the river segment is given in the following water balance equation (Eq. 1),

$$SL = Q_{us} + S - E - CC - Q_{ds}, \quad (1)$$

where SL is the seepage loss throughout the river segment; Q_{us} is the upstream inflow from the wastewater treatment plants; S is the inflow from springs; E is the direct evaporation from flowing-water; CC is the crop consumption, and Q_{ds} is the downstream outflow from the segment and into the KTDR. Because crop irrigation is supplemented by groundwater pumped from local wells, the crop consumption (CC) is estimated as crop demand minus groundwater pumping. The resulting net amount of crop consumption is assumed to be withdrawn directly from the river.

Temporal resolution of the available data sources was not uniform. Effluent from the KSWWTP and inflow into KTDR were available on daily basis. On the other hand, evaporation and irrigation well pumping were available on monthly basis. Spring flow was measured sporadically and flow rate was reported in m³/h on days of flow sampling. To standardize the temporal resolution of all data sources and to allow for summarizing the results, all input data were transformed into daily time series in m³/s as discussed in the corresponding methodology sections.

The study period was selected to be the overlapping period among all available data sources. Limiting factors were the availability of effluent data from the KSWWTP and suitable satellite imagery for cropland quantification. The final study period was selected to be June 1, 2013 through September 30, 2014. Only rain-free summer months were utilized in the water balance calculations resulting in two summer seasons. Baseflow was limited during this period to flow from springs.

Errors associated with the differential gauging method result from inaccuracies in measuring river flows and errors in estimating other components that go into calculating the water balance. However, such errors in gauging become less important when the distance between the gauges becomes large so that the error is smaller than the transmission loss (Shanafield and Cook 2014; Cook 2015). Therefore, excluding rainy season and using a considerably long segment extending from the upstream boundary to the downstream boundary of approximately 48 km is expected to improve the accuracy of the water balance calculations.

Estimation of outflow from KSWWTP

Daily effluent volume from the KSWWTP was available for the period of January 1, 2010 to July 17, 2015. Effluent volume was measured using a Parshall flume. The accuracy of data is tightly controlled since the government pays the operator for discharged amounts where data consistency is frequently checked. A small wastewater treatment plant serving the town of Jarash also contributes to the inflow to the river segment with an average daily effluent of 4500 m³ based on the Water Authority of Jordan (WAJ) records.

Estimation of spring flow

During summer months, one of the few sources of flow in the region is flow from springs. Spring flow in Jordan responds to the rainy season which starts in October and ends in May, where discharge from springs reaches its peak in the spring season. 27 springs were reported by the Jordan Ministry of Water and Irrigation to be in the study area. Supplied data were in the form of a list of springs each having multiple data points showing the date of sampling and the measured discharge rate. A daily flow rate time series was generated from the data by averaging the measured flow rates for each spring/calendar month combination.

Estimation of evaporation from flowing water

Evaporation losses from flowing stream water were estimated as the product of measured evaporation rate and the surface area of water. The surface area of flowing water in the river segment was estimated by measuring the length and width of flow utilizing aerial photography of the region. Monthly class A pan evaporation estimates were provided by the Jordan Meteorological Department for stations in the region. Averaged evaporation estimates from two stations, one located close to the eastern end of the river segment and the other close to the western end, were used. Evapotranspiration from riparian vegetation was incorporated in the evaporation estimate. Riparian vegetative areas along the river were digitized based on aerial photography. An

approach suggested by McKenzie and Craig (2001) was followed where an evaporation loss was calculated based on the combined water surface area and riparian vegetation area. In the approach, a 50% reduction factor was applied to the riparian area to convert the riparian area into an equivalent surface water area.

Estimation of surface withdrawals for crops

A sizable venue for the loss of flowing water in the segment under study is the surface withdrawals for purposes of irrigating crops. The improvements to water quality achieved in the KSWWTP effluent have encouraged farming communities downstream of the plant to increase the size of land utilized for their crops. Normalized difference vegetation index (NDVI) was used to estimate the area planted with crops for each summer month within the simulation period. Calculation of the NDVI was based on LANDSAT 8 level-2 imagery. Since data from Landsat 8 only became available in the spring of 2013, the period of simulation in the current study was reduced. While Landsat 7 images were available prior to the spring of 2013, the Landsat 7 tiles covering the study area had excessive striping rendering them useless for the purpose of crop area quantification. In addition to the areal extent of crops, a water consumption estimate was needed. The Jordan Ministry of Water and Irrigation estimated that the annual withdrawal for crop consumption in the region is 700 m³ per 1000 m². This estimate was used in the analysis to quantify the crop demand.

Estimation of groundwater pumping for crop irrigation

Irrigation well pumping was estimated based on the location of irrigation wells and their pumping rates as provided by the Jordan Ministry of Water and Irrigation (MWI). Groundwater pumped for irrigation purposes was subtracted from the crop demand that was estimated in earlier steps and the net was assumed to be withdrawn from the streamflow. The net crop demand was estimated on a daily basis and converted into a time series for the length of study period in m³/s.

Estimation of downstream boundary flow

The last component of the water balance is the flow out of the river segment and into the KTDR. One component of the daily water balance of the dam reservoir conducted by the MWI was the inflow into the dam reservoir from the Zarqa River. This component was utilized in the current research as the outflow from the river segment under study. These data were available on a daily basis since 1978. Daily flow volumes from the dam reservoir water balance were converted into daily flow rate in m³/s.

Results and discussion

Seepage losses from streambed were estimated in the Zarqa River in Jordan utilizing a modified differential gauging approach. The adopted methodology utilized effluent from a large wastewater treatment plant (KSWWTP) as upstream boundary. Establishing the downstream boundary of the river segment depended on a second non-traditional data source in the form of a daily water balance of a dam reservoir. Results of estimating all components of the water balance gains and losses are presented in the following subsections. The timeframe for the study was the summer seasons of the years 2013 and 2014. Rainy season was excluded from the calculations to assure that the water balance was not influenced by direct rain, estimated lateral surface runoff, or estimated channel runoff from upstream contributing areas. Daily channel seepage was taken to be the difference between the estimated gains and losses in the water balance.

Upstream and downstream flow boundary

The upstream boundary of the water balance was based on the daily effluent discharge from KSWWTP provided by the Water Authority of Jordan (WAJ). Table 1 provides the annual and summer effluent volume from KSWWTP for the years 2013 to 2014. Summer effluent is the total effluent for the months of June through September of each year. The Jarash WWTP discharges an average of 4500 m³ per day which translates into 0.052 m³/s. Figure 2 illustrates the daily effluent rate from the KSWWTP.

Daily inflow into the KTDR was considered to be the downstream boundary and was estimated utilizing a reservoir mass balance that accounts for variables such as inflow, outflow, evaporation, and seepage losses. During summer months, the bulk of inflow into the dam reservoir comes from the KSWWTP effluent. The obtained historical record of the King Talal Dam starts in the year 1978. Inflow to the reservoir includes the inflow from the Zarqa River and was evaluated by measuring change in volume in the reservoir and the outflow components on a daily basis. The volume change is obtained by measuring the height of water behind the dam and then finding the corresponding volume using a rating curve.

Table 1 Annual and summer effluent from KSWWTP during the period of 2013–2014

Year	Total annual effluent (MCM)	Summer effluent (MCM)	Summer inflow into KTD reservoir (MCM)
2013	90.7	32.4	24.6
2014	101.8	34.9	28.6

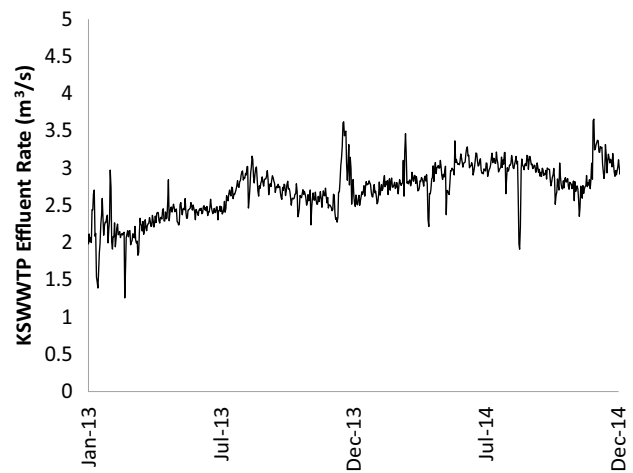


Fig. 2 Daily KSWWTP effluent flow rate for the period of 01/2013 to 12/2014

Outflow from the dam is tightly controlled via two outlets, one through a power generation facility from which the flow out is measured and a second outlet that is used when extra flow is needed for the farmers downstream of the dam in the Jordan valley. Outflow from the dam is supplied through a gate valve at the end of the release pipe and is quantified through a rating curve that takes into consideration the gate opening and the water height in the dam. In addition to these two outlets, the seepage through the dam is measured through an extensive network of monitoring tunnels within the body of the dam and left and right abutments. The flow out through seepage is measured by means of a V-notch weir at the tail end of each of the tunnels. Evaporation is also considered an outflow and is evaluated based on an onsite weather station which has a class A pan evaporation device. Measured daily evaporation rates are used along with reservoir surface area obtained from a depth–surface area rating curve to estimate daily evaporation volume. Releases from the emergency spillway are very rare during summer, but nonetheless are part of the calculation when present.

Total Inflow to the reservoir includes rain in addition to inflow from mainly the Zarqa River. Rain directly falling on the reservoir is quantified via the dam’s weather station. A small tributary contributes approximately 10% of inflow to the reservoir in the summer and merges into the reservoir downstream of the segment under study. A summary of water balance for the available detailed record of dam operations for the period of 1978–2010 (33 years) indicated that during summer months, flow from Zarqa River accounted for 483 MCM (approximately, 90% of inflow). During the same period, outflow to farmers in addition to outflow to power house (which ultimately reaches farmers as well) accounted for 914 MCM (approximately, 89% of outflow). Evaporation losses were in the order of 4%. During this period, outflow

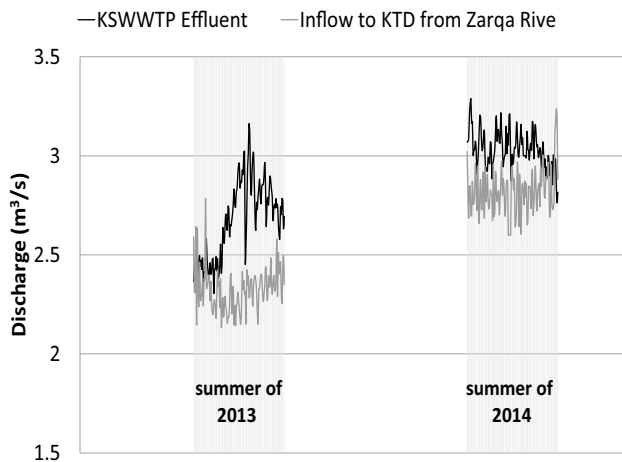


Fig. 3 Daily time series for KSWWTP effluent and KTD reservoir inflow for the summer months of the study period

volume was 490 MCM more than inflows, resulting in a drop in stored water volume of this same amount.

The daily time series of the upper and lower flow boundaries are shown in Fig. 3. Effluent from KSWWTP is higher in both years than the amount of water reaching the reservoir. Moreover, the effluent from the KSWWTP and the influent into the dam reservoir increased from 2013 to 2014, an increase that is in line with the recent trend of year to year increase in plant effluent.

Springs contribution

Spring flow within the study area was estimated based on data provided by the Jordan MWI. A total of 27 springs were identified to be within the study area. A monthly flow rate was calculated for each spring by averaging the flow rate of all measurements within the calendar month over the entire sampling period since 1990. Figure 4 shows the average spring discharge rate for each month from all springs. Spring discharge response to rainy season is evident, where in the month of March spring discharge is more than three times that of the month of September. Spring discharge during the four months of June through September amounts to 25% of the annual spring flow, or 1.8 MCM. The largest spring discharged an average of 257 m³/h and the median spring discharge measured from all springs was approximately 10 m³/h.

Direct evaporation losses

Stream width was measured using aerial photography of the region. An average width of 10 m was identified for the 10.4 km segment between KSWWTP and the entry point of Seil Alzarqa branch of the stream. A 15 m average width

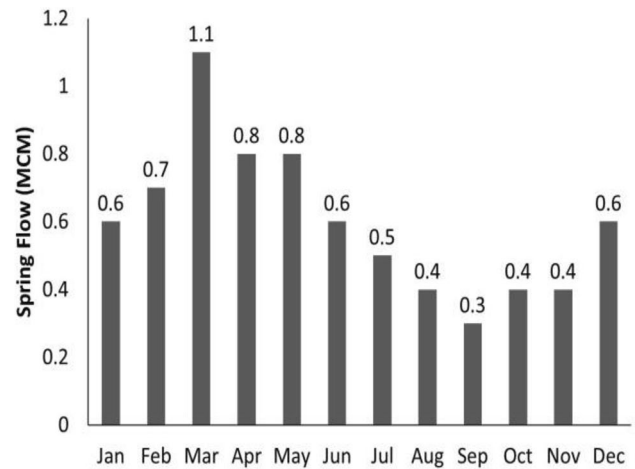


Fig. 4 Monthly spring flow within the study area in MCM

was identified as for the remaining 37.4 km segment to KTDR reservoir. In addition, 0.867 km² of riparian buffers was identified along the river. A 50% reduction factor was applied to the area of riparian buffer and the result was combined with flowing water surface area. The combined water/riparian buffer surface area undergoing direct evaporation was approximately 1.1 km² for the entire segment.

Monthly pan evaporation rates (Class A) were supplied by the Jordan Meteorological Department (JMD). An average evaporation rate from two stations was used including class A pan evaporation rates for the Zarqa Station near the eastern end of the river segment and the Dier Alla Station near the western end of the river segment. Pan evaporation rates are usually reduced by a coefficient to account for the impact of elevated evaporation due to heating of pan sides. However, no reduction to pan evaporation rates were made here to compensate for the fact that flowing water evaporates at a higher rate than standing water due to higher energy of surface water molecules. The average monthly evaporation rate for the simulation period was approximately 189 mm with a standard deviation of 90 mm. Average monthly evaporation for the simulation period for the months of June, July, August, and September were 298 mm, 318 mm, 291 mm, and 230 mm, respectively. Estimated evaporation losses for the two summer seasons ranged from 1.1 to 1.2 MCM.

Crop consumption losses

Considerable agricultural areas were observed around the Zarqa River during field visits and through the use of aerial photography and satellite imagery of the region. Such areas rely on surface withdrawals from the Zarqa River as well as groundwater pumping. Monthly variation in the extent of cropland was quantified by relying on LANDSAT 8 level 2. A total of 16 sets of LANDSAT 8 images were obtained

for the 8 months within the summers of 2013 and 2014. A LANDSAT 8 satellite image was available every 16 days for the study area (Path 174, Row 38). The near infrared and red bands were utilized to calculate the normalized difference vegetation index (NDVI) or the “greenness index” as shown in Eq. 2:

$$NDVI = \frac{NIR - R}{NIR + R}, \tag{2}$$

where NIR is the near infrared band (band 5 in LANDSAT 8) and R is the red band (band 4 in LANDSAT 8).

A raster cell was considered a cropland cell if the NDVI was greater than 0.2. Such values demonstrated good visual agreement when compared to aerial photography of similar date. All 8 months under study had two images each, except June 2013 which had only one image. The land area estimated from multiple images for the same

month was averaged to produce one monthly value. Table 2 shows the crop land area by month. Variability in month to month crop land area was small where the average area was 16.7 km² with a standard deviation of less than 0.5 km². Figure 5 shows the agricultural areas between the treatment plant and the dam reservoir.

An average annual value of irrigation water demand of approximately 700 m³ per 1000 m² was adopted by the MWI and used in this project. Considering that not all agricultural activities in the region rely on surface withdrawals, groundwater utilization through well pumping was quantified and subtracted from the annual irrigation water demand to be withdrawn from the flowing water. It is likely that the wells are hydraulically connected to the flow in the channel and, therefore, subtracting the well pumping from the surface withdrawal has the effect of increasing seepage losses. A total of 29 agricultural production wells were identified to fall within 250 m of the river. Well production amount for the summer months from the 29 wells was approximately 0.85 MCM. When subtracting irrigation well production from crop demand and allowing 25% evaporation losses, the crop consumption for the agricultural fields along the segment ranged between 2.8 and 2.9 MCM for the two summer seasons. It should be noted that the minimum daily effluent during the summer months is approximately four times greater than the maximum daily crop consumption amount and, therefore, no shortage of supply exists for agricultural uses.

Table 2 Size of agricultural area in the stream corridor by month as obtained using the NDVI classification

Month	Crop land area (km ²)
June/2013	16.4
July/2013	17.2
August/2013	17.4
September/2013	16.4
June/2014	16.9
July/2014	16.3
August/2014	16.9
September/2014	16.1

Fig. 5 Agricultural fields (green highlight) along the corridor of the river segment

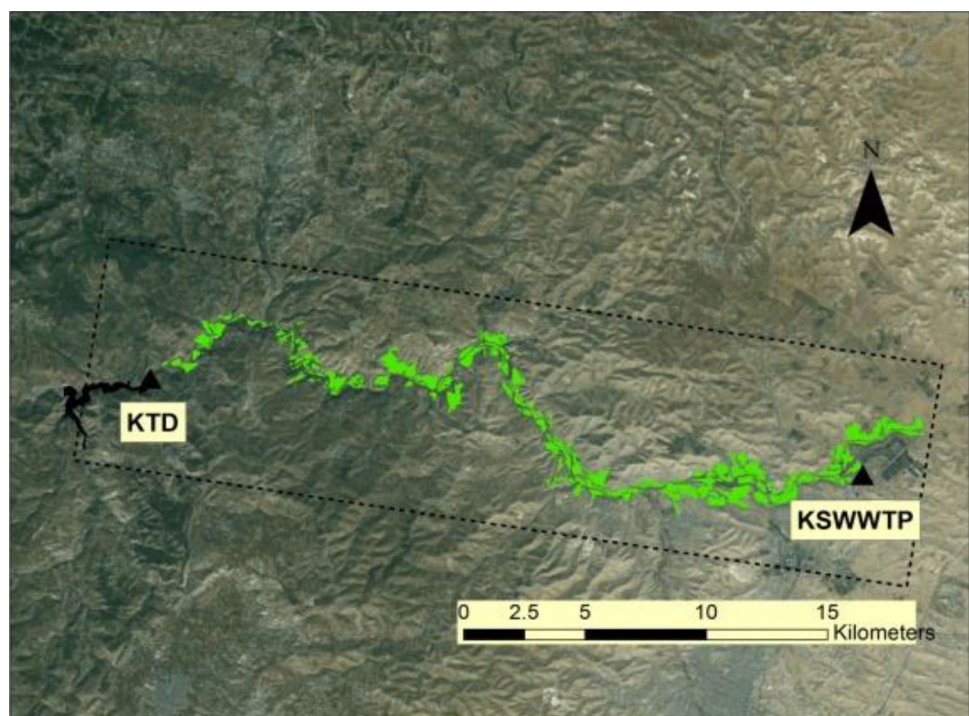
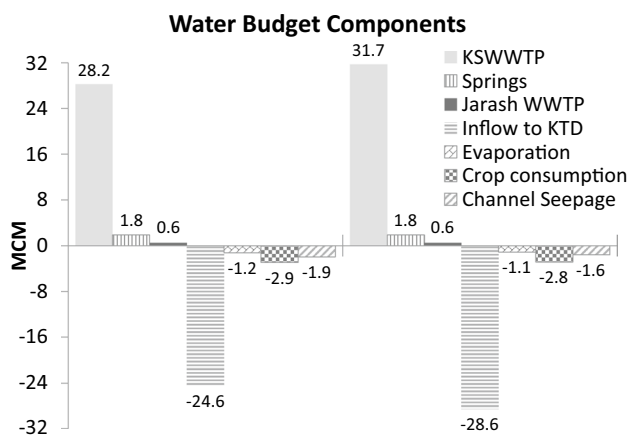


Table 3 Summer season water balance component values

Component	Summer season of the year:	
	2013	2014
Component	Amount: MCM (%)	Amount: MCM (%)
KSWWTP	28.2 (92%)	31.7 (93%)
Springs	1.8 (6%)	1.8 (5%)
Jarash WWTP	0.6 (2%)	0.6 (2%)
Total gains	30.6 (100%)	34.1 (100%)
Inflow to KTD	24.6 (80%)	28.6 (84%)
Evaporation	1.2 (4%)	1.1 (3%)
Crop consumption	2.9 (10%)	2.8 (8%)
Channel seepage	1.9 (6%)	1.6 (5%)
Total losses	30.6 (100%)	34.1 (100%)

The italic values are the percent and the numbers preceding them are in unit of million cubic meter (MCM)

**Fig. 6** Analysis results for the two summer seasons

Channel seepage loss

Water balance was established for the 48-km stream segment for a total of two summer seasons spanning the period from 2013 to 2014. Establishing the water balance was made possible by utilizing non-traditional sources of data: a wastewater treatment plant effluent and a calculated incoming flow into a dam reservoir. As a result of establishing the water balance, channel seepage losses from streambed were derived.

Table 3 summarizes the water balance components within the segment under study and for the two summer seasons. Balance components in Table 3 are grouped into gains and losses. Because the water balance was estimated on a daily basis, monthly or seasonal totals were obtained by summing the daily values for a given month or season. Figure 6 shows, for the two summer seasons, the water balance components. Gains are positive and plotted above

the x axis, while losses are negative and plotted below the x axis.

The vast majority of gains in the water balance come from the KSWWTP where the plant effluent exceeds 90% of all inflows into the river segment during the summer season. Summer effluent from the treatment plant is steadily increasing over the past several years, a trend that is maintained in the 2 years shown here. Plant effluent during the summer of 2013 was 28.2 MCM compared to 31.7 MCM during the summer of 2014. Other positive contributions to the water balance during the summer season come from springs and the small WWTP at the town of Jarash. Spring flow during summer months is approximately 5–6% of the total gains (1.8 MCM). Jarash WWTP accounts for approximately 2% of incoming flow with 0.6 MCM for the summer season.

For the period of 2013 to 2014, outflow from the stream segment and into KTD accounts for 80–84% of the segment losses. Crop consumption losses between the 2 years varied only slightly and ranged between 2.8 and 2.9 MCM. The combined direct evaporation from water surface and transpiration from riparian vegetation were between 1.1 and 1.2 MCM (3–4%).

Channel seepage losses from the streambed were 1.9 and 1.6 MCM for the summers of 2013 and 2014, respectively. These totals make up 5–6% of all losses.

The estimated channel seepage takes place during a 4-month period and along the entire stream segment. An average channel seepage per unit length per day is estimated by dividing the total recharge amount by the stream segment length and by the number of days within the simulation period resulting in approximately $0.3 \text{ m}^3/(\text{m day})$.

Monthly values of channel seepage were examined. The 8 months under consideration demonstrated a wide range of variability in channel seepage ranging from 0.03 to 1.2 MCM per month.

To verify the impact of groundwater recharge resulting from channel seepage losses on observed groundwater levels in nearby monitoring wells, groundwater levels were compared between wells upstream versus downstream of KSWWTP outfall. To demonstrate this observation, groundwater level in well AL1043, which is located upstream of the KSWWTP (not impacted by the treatment plant effluent), is plotted on the same graph as groundwater level from well AL2700, which is located downstream from the KSWWTP. The resulting groundwater level plots for the period of 1988–2016 are shown in Fig. 7. Even though groundwater extraction from the unconfined aquifer was taking place both upstream and downstream of the KSWWTP, groundwater levels downstream of the KSWWTP remained around the same level over the years, while levels of groundwater upstream of the plant dropped by approximately 44 m within the same period. It is evident that channel seepage from flowing effluent of the KSWWTP causes enough recharge

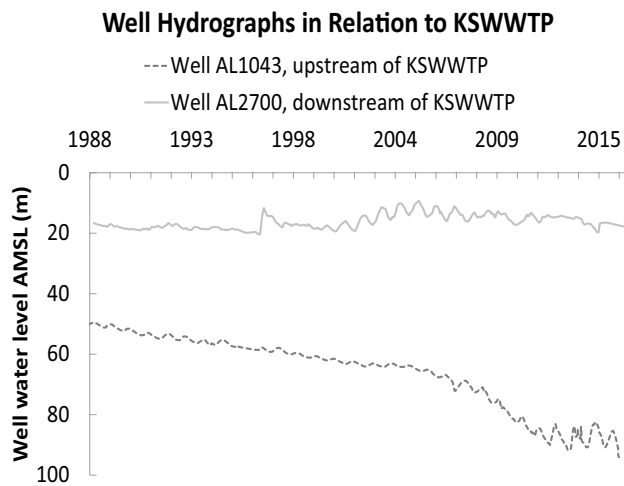


Fig. 7 Well hydrographs upstream and downstream of KSWWTP showing the impact of channel seepage on groundwater levels

in the area downstream of the plant to compensate for the groundwater extraction. Quantitatively, from the MWI records, we have approximately 0.9 MCM of well withdrawals in the vicinity of the river segment during the summer months. We estimate an average of 1.75 MCM of seepage loss per summer season over the 2-year period. Knowing that some of the seepage loss does not contribute to groundwater recharge, we can see that there is likely just enough recharge to keep the water level in well AL2700 around a relatively steady baseline, which matches with the predicted recharge estimates.

Conclusions

An innovative procedure to estimate channel seepage from the streambed was developed. The current project demonstrated that it is possible to utilize non-traditional data sources for the purpose of estimating channel seepage from streambed during flow through a modified differential gauging approach. The alternative flow data sources were in the form of daily records of wastewater treatment plant effluent and reservoir daily water balance records. These sources were combined with traditional data sources to quantify other parameters included in the water balance such as crop consumption, discharge from springs, groundwater well pumping, and direct evaporation.

The implications of the current research project are helpful in encouraging the use of non-traditional data sources in hydrologic studies to overcome data limitations, especially in the form of accurate streamflow measurements. Finding the right combination of alternative sources may not always be a viable option. Therefore, the results of this work should not be understood by governmental and other agencies

involved in the field of water resources as an invitation to ignore the quest of developing accurate and reliable flow gauging systems. The availability of such non-traditional data sources is not limited to Jordan and, therefore, the findings of this research are applicable anywhere in the world where such data exist.

Gains and losses along the river segment are estimated in the same way in both the traditional differential gauging approach and the new approach, except for the sources of stream flow data. Therefore, the accuracy of estimating such components is not adversely impacted by implementing the new approach. Similar to the accuracy of the traditional differential gauging approach being dependent on the accuracy of flow gauge measurements, the accuracy of the new approach is dependent on the accuracy of the non-traditional data sources. Therefore, this new approach should only be used in cases where flow gauge data are not available or where their accuracy is questionable with non-traditional flow data offering better accuracy.

Similar to the traditional differential gauging method for estimating channel seepage (or gain), the modified method is well suited for regional scale and extended river segments. When a river has mixed flow regime where both losing and gaining segments exist, neither the traditional nor the modified method has the ability to identify the extents or location of the losing and gaining portions of the river. In both approaches, the more detailed spatial identification of losing versus gaining segments may be made possible with the inclusion of additional flow gauge data and non-traditional flow data sources. Moreover, when longer river segments are considered, it is more likely to have side tributaries that contribute to the flow in the river. Flow from such tributaries should be quantified and used in the water budget calculations.

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