Water Resour Manage
DOI 10.1007/s11269-012-0144-8

Hydrology of the Jordan River Basin: Watershed Delineation, Precipitation and Evapotranspiration

G. F. Comair · D. C. McKinney · D. Siegel

Received: 30 January 2012 / Accepted: 4 September 2012
© Springer Science+Business Media B.V. 2012

Abstract The Jordan River Basin is shared between Lebanon, Syria, Israel, Jordan and Palestine; the waters of the River are a critical resource for the future water security of the co-riparians. Because of the political situation in the region, field data such as rainfall and evapotranspiration are very difficult to obtain making the use of remote sensing and Geographic Information System (GIS) very useful to study water availability in the basin. The approach used in this paper integrates recently compiled data derived from satellite imagery (evapotranspiration, rainfall, and digital elevation model) into a GIS geodatabase to measure the contribution of each riparian country to the total available water in the basin.

Keywords Jordan River · Transboundary basins · Precipitation · Evapotranspiration · GIS

1 Introduction

Today, 40 % of the world's populations live in transboundary river basins (Phillips et al. 2006; The World Bank 1992). The water-scarce Middle East region in particular is known for the fact that a considerable amount of its freshwater resources cross national boundaries. Thus increasing pressures on water resources in the area requires adequate planning and management in order to promote cooperation between all riparian countries and achieve an equitable distribution of water. This planning process also involves conflict resolution (Barrow 1998), the former being essential in international basins such as the Jordan River Basin. Major hydro-political and geo-political events have impacted this basin since the Ottoman Empire in 1299, and water allocation has been an element of tension between riparian countries for the last 40 years. Many water allocation plans were proposed such as

---

G. F. Comair (✉) · D. C. McKinney · D. Siegel
Center for Research in Water Resources, University of Texas at Austin, Austin, TX 78712, USA
e-mail: doctorg@utexas.edu

D. C. McKinney
e-mail: daene@aol.com

D. Siegel
e-mail: dsiegel@mail.utexas.edu

Published online: 12 September 2012

the Johnston Water Allocation Plan of 1955, but all failed to be ratified. Moreover, the historical and political instability in the region has hindered the possibility for any basin-wide agreement on water.

In this context, more efforts are needed in order to foster collaborative and sustainable management of the Jordan River Basin. In order to achieve this purpose, obtaining accurate and up to date data on the river basin is crucial. International water laws such as the Helsinki Rules on the Uses of the Waters of International Rivers of 1966 (ILA 1966) and the 1997 United Nations Convention on the Law of the Non-navigational Uses of International Watercourses (United Nations 1997), mention main components to be considered for water allocations in international river basins. These include the basin's geography including the drainage area in each basin state, the basin's hydrology, and in particular the contribution of each basin state to global flow, as well as climatic factors. In the past, drainage areas and stream length were obtained through maps and field surveys. However, since these techniques are subject to considerable operator modification (Patiño-Gomez et al. 2007), the area of the Jordan River Basin mentioned in the literature has differed significantly.

Values of watershed areas and precipitation over the Jordan River Basin are only found in two comprehensive report known to the authors, which are the Middle East Regional Study on Water Supply and Demand Development (GTZ 1995) and the Water Data Banks (WDB) project through the cooperation of Jordanian, Palestinian and Israeli water authorities in the Executive Action Team (EXACT) (EXACT 1998). Other more recent available literature such as Mimi and Sawalhi (2003); Courcier et al. (2005); Al-Abed and Al-Sharif (2008); Black (2009); Simpson and Carmi (1983) and Rimmer and Salingar (2006) analyzed specific countries or basins such as the Lower Jordan River Basin or the Zarqa Basin but not the entire Jordan River Basin. Although discharges of streams have been recorded and analyzed by the WDB project for the Lower Jordan River Basin, no precipitation analysis of the entire Jordan River Basin was performed and little explanatory work has been done. The latest study by GLOWA-EXACT (Gunkel and Jens 2011) modeled seasonal water availability in the Lower Jordan River Basin excluding the Yarmouk and Zarqa Rivers. In addition, Gunkel and Jens did not calibrate or validate the model, as their work was not intended to represent the current state of the water available in the Lower Jordan River Basin (Gunkel and Jens 2011).

In this study, we complement the work done by GTZ, and to comply with international laws on water allocation, two main factors are taken into consideration, that is riparian watershed area and precipitation contribution to the Jordan River Basin.

Using a newly available 30 m Digital Elevation Model (DEM), released in June 2009 under the Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) program (ASTER GDEM Validation Team 2009), catchment areas can be determined more precisely than Gunkel and Jens (2011) who used data captured by the Space Shuttle (SRTM DEM) with a resolution of 1 arc second (about 90 m). In addition, in February 2011, NASA released a global evapotranspiration (ET) product based on imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) (NASA 2011).

This paper is thus the first to apply this valuable new datasets towards understanding evaporative losses in the Jordan River Basin, and aims at reporting and sharing (1) riparians area contributions to the basin; and (2) providing complete estimates of precipitation and evapotranspiration in the basin, at the country and sub-basin level. This study is part of an ongoing research that ultimately aims at creating a common database to provide unified access to water information for the globe (Bermudez and Arctur 2011). The results of this study (catchment areas, precipitation and ET) will thus be incorporated into a geographically referenced database (geodatabase) using the recently updated hydrologic information system (CUAHSI-HIS) similar to the Arc Hydro framework (Maidment 2002; Horsburgh et al.

2008; Tarboton and Maidment 2010) called World Water Online (WWO) (Espinoza et al. 2012). Later publications will document how World Water Online enables web-based analysis to understand global water issues. To date, three riparians of the Jordan River Basin have adhered to the WWO project, representing a major achievement for this politically stressed region. Presently, each riparian has their own understanding of how the Jordan River Basin works, based on their own, privately collected data. This research will thus contribute to improve the understanding of the basin with up to date information and promote collaborative efforts among riparians for the management of this vital resource.

2 Study Area

The Jordan River is a 250-km long transboundary river shared between five riparians: Israel, Jordan, Lebanon, Palestine (West bank) and Syria (Fig. 1). The Banias, Hasbani and Dan tributaries are part of the Upper Jordan River. After their confluence, the river flows into Lake Tiberias, passes through the Lower Jordan to eventually discharge into the Dead Sea at the end of its course.

The Upper Jordan River derives its base flow primarily from a group of karstic springs on the western and southern slopes of Mount Hermon that flow into the three upper tributaries (Simpson and Carmi 1983). The largest of the springs is the Dan Spring, which supplies a steady flow and accounts for about one-half of the base flow of the Upper Jordan River, which represents around 270 million cubic meters per year, (MCM/year) (IWA 2010). The average annual water inflow into Lake Tiberias is estimated at 610 MCM/year with 240 MCM/year being lost to evaporation (IWA 2010). The bulk of the Lake's water, estimated at about 440 MCM/year is diverted by Israel through its National Water Carrier (NWC) (Klein 1998).

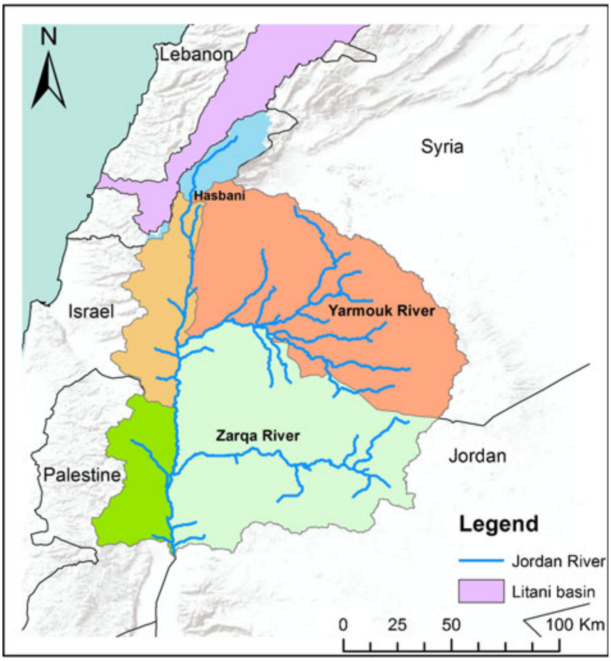

Fig. 1 The Jordan River Basin

The next largest tributaries to the river are the Yarmouk and Zarqa Rivers that are part of the Lower Jordan River Basin. The latter river mostly carries wastewater from Amman, the basin's largest city. The Yarmouk River is fed by springs and wadis located in Syria and has an annual flow of about 470 MCM/year (Salameh and Bannayan 1993).

It is important to emphasize the distinction between the Jordan River Basin, which is the focus of our study, and the Dead Sea Basin. The Dead Sea is a natural sink for the Jordan River Basin, which receives discharge from the Jordan River. Since several other streams also discharge their waters into the Dead Sea, the Dead Sea Basin comprises the Jordan River Basin and the drainage basins of these other streams as well (including Egypt). The Dead Sea Basin area is close to 40,000 km^2, which represents more than the double of the Jordan River Basin area (Niemi et al. 1997).

3 Methodology

3.1 Watershed Delineation

GIS tools Arc Map and Arc Hydro (Maidment 2002) were used to delineate the Jordan River watershed as well as subwatersheds from a 30 m resolution ASTER DEM provided through Japan-U.S. collaboration (ASTER GDEM Validation Team 2009). The DEM is in GeoTIFF format with geographic latitude/longitude coordinates and a 1 arc-second (30 m) grid of elevation postings. It is referenced to the WGS84/EGM96 geoid. The region of the Jordan River Basin was selected to be in the 30N-35E region. The DEM obtained from ASTER contained sinks that could vary between 0.1 m and 4.7 m in a 30 m DEM (Tarboton et al. 1991). In order to perform a proper hydrological analysis, sinks were identified and eliminated using the Spatial Analyst extension. The ArcGIS Geoprocessing toolbox and Arc Hydro techniques were used to isolate the watershed. As mentioned earlier, this study isolates exclusively the Jordan River Basin, including drainage areas from the headwaters of the Hasbani down to the outlet point of the Jordan River at the Dead Sea, located at 31°45′36N and 35°33′28E.

The Arc Hydro tools were used to derive several data sets that collectively describe the drainage patterns of the catchment. Geoprocessing analysis was performed to recondition the digital elevation model and generate data on flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation. These data are then be used to develop a vector representation of catchments and drainage lines from selected points that can then be used in network analysis. The full process of the methodology is described by Tarboton and Maidment (2010).

Using the Arc Hydro data model (Maidment 2002), a geographically referenced database containing geographic and hydrographic data was created for the Jordan River Basin. This database included political boundaries, basin, sub-basin and stream networks. The database will be improved in the future to include water bodies and dam locations, monitoring points and climatologic and hydrometric information (time series). Once the Basin was delineated and the streams defined, a shapefile for world countries was downloaded from the Natural Earth data and North American Cartographic Information Society (Natural Earth 2011) and used to overlay the basin and identify each country within the basin. Every polygon was projected from the WGS84 coordinate system to the Jordan JTM projection to allow area calculations. Using ArcGIS's intersect tool, each country's portion of the basin was extracted (Fig. 1), and their contributing area recorded (Table 1).

Additionally, even though this is not the main purpose of this study, the Litani River Basin was also delineated in order to assess whether any hydrological connection with the Jordan River Basin exists.

Table 1 Results obtained for basin areas, precipitation, evapotranspiration and available water (AW) in the Jordan River Basin

Riparian country	Total Area[a] in km^2	Basin area		Average P			Average ET			Average AW (P-ET)	
		In km^2	As % of total basin area	In mm/yr	In MCM/yr	As % of total P in basin	In mm/yr	In MCM/yr	As % of total ET in basin	In MCM/yr	As % of total AW in basin
Israel	21,640	3,033	17	438 Range: 312–580	1,328	25	283	858	19	470	48
Jordan	88,780	7,183	40	266 Range: 87–432	1,911	36	236	1,695	37	216	22
Lebanon	10,452	606	3	490 Range: 432–580	297	6	238	144	3	153	16
Palestine (West Bank)	6,020	1,542	8	301 Range: 222–466	464	9	205	316	7	148	15
Syria	183,630	5,740	32	225 Range: 87–470	1,292	24	274	1,573	34	−281 (0)	0
Total in basin		18,103		1,720	5,292		1,236	4,586		987	

[a] The World Bank 2011

3.2 Precipitation

Precipitation (P) data was obtained from the Water Systems Analysis Group (WSAG), University of New Hampshire (Fekete et al. 2004). The WSAG data was derived by Mitchell et al. (2004) using a dataset developed by the Climate Research Unit (CRU) at the University of East Anglia and the Department of Geography at the University of Delaware (Willmott and Matsuura 2001; Legates and Willmott 1990). The data was downloaded from an online GIS database in raster format. The raster represents long term (1950–2000) average annual precipitation (mm/year) for the globe on a 0.5×0.5 ° global grid. The raster was projected to the Jordan JTM projection and since the grid cell resolution was larger than some catchment sizes, the raster was re-sampled to reduce the cell size from 0.5 ° (38 km) to 30 m using the nearest neighbor sampling method. The zonal statistics tool in ArcGIS was used to calculate the average annual precipitation in each catchment over the period 1950–2000. Since the Jordan River region is modulated by complex topography, for this large scale study of the precipitation in the basin, the modeled rainfall data is known to have values lower than those obtained from rain gages (Black 2009).

3.3 Evapotranspiration and Available Water

Evapotranspiration (ET) in the basin was calculated using the MOD16 data product, a global map of ET derived from MODIS (MODerate-resolution Imaging Spectroradiometer) imagery (NASA 2011). It provides 8-day estimates of global evapotranspiration from January 2000 when MODIS was first launched aboard the NASA satellite Terra. Evaporation and transpiration are treated separately, both according to the Penman-Monteith equation below (Maidment 1993).

$$ET = \frac{(Rn - G) + \rho C_p (e_{sa} - e_a)/r_a}{+\gamma\left(1\,\frac{r_s}{r_a}\right)} \tag{1}$$

The two variables that drive this equation are available energy ($R_n - G$) and vapor pressure deficit ($e_{sa} - e_a$). The latter is a function of air temperature and humidity, which are taken from NASA's Global Modeling and Assimilation Office (GMAO 2011), while the former is derived from other MODIS data products. Net radiation (R_n) is calculated using the methodology described by Cleugh et al. (2007), which is mostly driven by the MOD42 product: surface albedo. The soil heat flux (G) is assumed to be inversely proportional to the fraction of absorbed photosynthetically active radiation (MOD15). The resistance of the surface (r_s) and air (r_a) to energy transfer are calculated differently for transpiration and evaporation. For a more complete explanation of the MOD16 algorithm, refer to the work of Mu et al. (2011). In this study, the average annual ET over the Jordan River Basin is calculated using the MODIS toolbox, which was developed at the Center for Research in Water Resources (Siegel 2011). This toolbox is a collection of python scripts freely available online that automate the process of downloading MOD16 data and converting it into ArcGIS layers. Using these tools, the authors imported all 10 years of MOD16 data into Arc Map and used the raster calculator tool to average them together, creating a single map of annual evapotranspiration (Fig. 2).

Annual average Available Water (AW) was estimated by subtracting evapotranspiration data from precipitation estimates (P-ET).

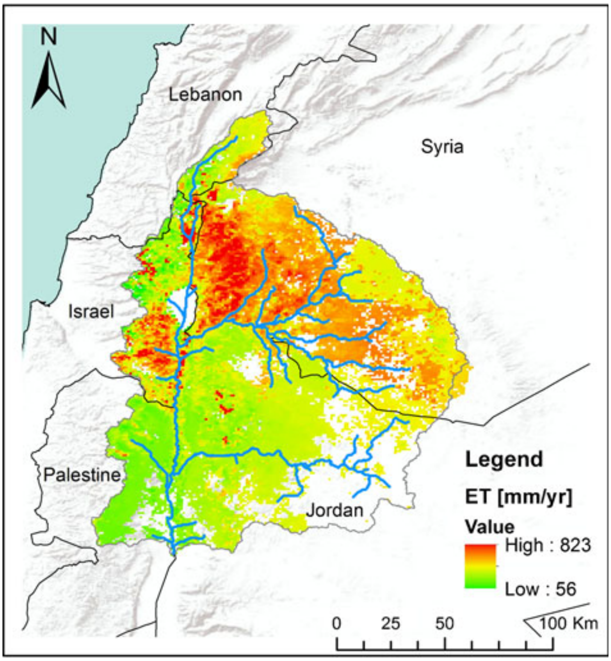

Fig. 2 Mean annual evapotranspiration map of the Jordan River Basin

4 Results and Discussion

4.1 Watershed Areas

As shown in Table 1, 40 % of the Jordan River Basin is located in Jordan which represents the highest share of the Jordan River Basin in terms of watershed area, the lowest share being in Lebanon, contributing 3 % of the total basin area. The total area of the Jordan River Basin obtained using a 30 m resolution DEM was found to be 18,103 km^2, significantly lower than values previously reported in the literature. For instance, the GTZ lists the total surface area of the basin to be 18,850 km^2 (GTZ 1995), while Elmusa (1997) mentions a value as high as 19,839 km^2. Amery and Wolf (2000) reported 18,300 km^2. Suleiman (2004); Courcier et al. (2005); and the Jordan Natural Resources Authority (1977) reported an area of 18,194 km^2, which is the closest value to our analysis.

At the sub-basin level, catchment area of the Upper Jordan was found to be 1,547 km^2. The Hasbani basin area, which is part of the Upper Jordan, was found to be 611 km^2, which is close to the value of 612 km^2 reported by Rimmer and Salingar (2006). Areas of the Yarmouk and Zarqa basins were estimated at 6,975 km^2 and 3,984 km^2 respectively. The Yarmouk's basin area is similar to the area of 6,974 km^2 obtained by Suleiman (2004) but lower than the GTZ value of 7,250 km^2 (GTZ 1995).

By comparing the different area values reported in the literature with ours, we see that the former area estimates result from difference in the DEM cell sizes used, which were lower in our study and thus more accurate than in the references mentioned. Furthermore, the GTZ (1995) and Elmusa (1997) values seem to have included the area of the Dead Sea subwatersheds in the Jordan River Basin, which have a surface of about 800 km^2. This could explain the higher area estimations for the Jordan River Basin mentioned previously. Although Mimi and Sawalhi (2003) objective was to divide proportionally by area, flow, etc. the Jordan River waters between the five countries, they actually used combined data for the Dead Sea Basin (GTZ 1995). Their study on optimization shows that the data provided by GTZ consider Lebanon and Syria to be in the same basin. After carefully reviewing the original GTZ data we found that the authors mention the Jordan River Basin as part of the Dead Sea Basin, which makes it confusing for the reader not familiar with the region's geography.

On the other hand, it is worthy to note that while analyzing the Lebanese part of the Jordan River Basin, no connection between the Litani River Basin and the Jordan River Basin was found in terms of surface flow, even though both basins lie close to each other (Fig. 1). The former basin was found to lie entirely in Lebanon. This result removes any ambiguity pertaining to the inclusion of the waters of the Litani River in any future water allocation scheme for the Jordan River Basin. As it was mentioned in the Johnston Plan and the Israeli "Cotton Plan", some Israeli negotiators wished to include the Litani River in the Jordan River Basin plan (Amery 1998). Today, the inclusion of the Litani River is still present in the opinion of some politicians but these arguments are not credible since hydrological connections between the Litani and Jordan River Basin have not been proven (Medzini and Wolf 2004; Zeitoun et al. 2012).

4.2 Precipitation

Globally, we notice that precipitation contribution of Jordan, Lebanon and Palestine are somewhat consistent with their area contribution to the Jordan River basin. However, even though Syria contributes almost twice as more area than Israel to the watershed, both countries are similar in terms of precipitation contribution to the whole watershed (Table 1).

Minimum and maximum (range) values are averages over the period 1950–2000. When comparing our study with the GTZ study, we can see that two distinct values of precipitation were obtained for Lebanon and Syria in our approach, which is more accurate than the GTZ studies that considered Lebanon and Syria to have the same contribution of 508 mm/year of precipitation (GTZ 1995).

On the other hand, the Lebanese part of the basin is characterized by a complex topography similar to the coastal mountains of Israel. This factor is often disregarded and therefore, all precipitation models underestimated the mean precipitation over these mountainous terrains (Mithen and Black 2011). This is also the case with the values obtained by our precipitation model, that are lower than the actual observed rain gage data recently obtained by the Ministry of Energy and Water in Lebanon indicating a mean rainfall of 700 mm/year in Lebanon (MEW 2011). Some simple linear regressions were made between one precipitation gage in the Lebanese part of the basin (Kfar Qouq) and the satellite data which indicated that values were correlated with a correlation coefficient R^2 of 0.65. Our precipitation value obtained for Syria could not be verified with local authorities. Previous studies using Regional Climate Models (RCMs) of the same resolution and lower (0.4 °) were also unable to resolve the issue of the complex and changing topography with regard to the precipitation pattern of southern Lebanon (which includes the Western part of Mount Hermon at 2,814 m above sea level) as well as mountainous areas and coastal mountains in Israel and Jordan (Goldreich 1994; Lionello and Giorgi 2007; Krichak et al. 2007; Kitoh et al. 2008; Evans et al. 2004; Mithen and Black 2011). However, it is interesting to mention that although the underestimation of precipitation reported in this study is consistent with other RCMs used in the region, overall, the values of precipitation presented here can be considered acceptable for the purpose of this study that looks at the global annual rainfall and ET over the entire Jordan River Basin, without focusing on monthly or seasonal precipitation variations.

The average precipitation over the Jordanian part, which contributes for most of the precipitation in the basin, has been mentioned in two reports (Suleiman 2004 and Courcier et al. 2005) that both obtained the precipitation from the EXACT team and estimated the average volume of rainfall in this area to be about 2,200 MCM/year. In contrast, this study computed 1,911 MCM/year. The mean annual precipitation estimated in these reports ranged between 100 and 490 mm, which are very close to the range of 87–432 mm obtained in this study. At the sub-basin level, Al-Abed and Al-Sharif (2008) studied the Zarqa River Basin using hydrological modeling and GIS analysis and reported a long-term (1937–1998) mean annual rainfall of 248 mm. In this study spanning a wider timeframe, mean annual rainfall over this sub-basin was calculated to be 229 mm.

Concerning Israel and the West Bank, the rainfall distribution could not be compared with other studies, because past analyses that dealt with isotope studies (Simpson and Carmi 1983) or modeling of the precipitation-streamflow processes (Rimmer and Salingar 2006; Gilad and Bonne 1990) and hydrochemistry (Gur et al. 2003) mentioned that precipitation data was obtained from the Israel Hydrological Survey and cannot be retrieved publicly.

4.3 Evapotranspiration and Available Water

There is substantial spatial variation in ET over the basin, depending mostly on climate and land use. As shown in Fig. 2, highest levels of evapotranspiration are found in the northern part of the basin, where there is more precipitation, but small areas of intense transpiration, most likely irrigated agriculture, can be seen in Jordan and Israel. Our study shows that 88 % of all precipitation within the basin is lost to ET. This matches up well with estimates in the literature, which range from 85 to 90 % (Fisher et al. 2002; El-Naser 1998; Courcier et al. 2005). The basin-wide ET average is 247 mm/year. The authors could not find any previous papers that studied ET over the whole Jordan River Basin, but a study of the Lower Jordan River Basin used the Shuttleworth-Wallace equation to come up with an estimate of 269 mm/year for this area (Gunkel and Jens 2011). Our study calculates 254 mm/year over the same region – well within the 25 % Root Mean Square Error (RMSE) typically found when comparing the MOD16 data to local measurements (Mu et al. 2011).

Observations of each country's area, precipitation and evapotranspiration contribution with regard to available water show that even though the Lebanese headwaters receive the highest precipitation rates in the basin, the West Bank, which receives 40 % less precipitation per square meter, provides a similar amount of water to the basin because it has lower ET than Lebanon and greater surface area contributing to the basin (Table 1). Once baseflow from springs is added to the geodatabase, the contribution recorded as coming from Lebanon will most likely increase.

As for Syria, we observe that it does not provide any water to the basin at all. In fact, this part of the basin averages 274 mm/year of evapotranspiration despite only receiving 225 mm/year in precipitation. As shown in the table, this translates to an annual water deficit of 281 MCM, which is most likely attributable to intensely irrigated agriculture fed by groundwater pumping. In fact, several studies have shown that the Syrian water budget is dominated by groundwater, and that the country's agricultural sector is extremely inefficient (Bakir 2001; Daoudy 2005; Phillips et al. 2009).

Israel does not possess as much territory in the Jordan River Basin as Jordan does, nor does it receive as much precipitation as the Lebanese part of the basin. However, the 17 % of the basin's it does control receives 438 mm/year of precipitation, the highest rate of any riparian other than Lebanon. Because of this, 48 % of the available water in the basin comes from Israeli territory. Jordan, which possesses 40 % of the basin's land, only receives 266 mm/year of precipitation. Despite a lower rate of ET than Israel, there is only 216 MCM of available water left over each year – about 22 % of the basin's total supply.

Based on our results, the total quantity of available water for anthropogenic withdrawal is estimated at 987 MCM/year. If we compare this value with estimates from the literature The literature reports that water use in the basin is estimated at around 800 MCM/year (Mithen and Black 2011) with Israel diverting around 500–600 MCM (FoEME 2011; Zeitoun et al. 2012); Syria withdrawing approximately 200 MCM from the Yarmouk River, and another 100 MCM diverted by Jordan to supply the King Abdullah Canal (Courcier et al. 2005). Due to all these abstractions, the Jordan River discharge to the Dead Sea is currently estimated at 150–200 MCM/year (Gavrieli et al. 2005; Courcier et al. 2005). In addition to what is left from the river and tributaries flow, this discharge to the Dead Sea originates from drainage of fishponds, wastewater, fresh and saline springs, and agricultural return flows (FoEME 2010). Thus if we estimate the initial amount of available water based on the literature (adding up the abstractions and the discharge to the Dead Sea; i.e. 950–1,000 MCM), we find that is it close to the value obtained in our study.

5 Conclusion

Managing water resources in the Jordan River Basin is difficult, due to the transboundary nature of the basin and the absence of an agreement between the riparian countries. The difficulty of studying the Jordan River Basin lies in interpreting the diverse references and sources of data available. Regional studies besides that of the GTZ (1995) typically only mention one country; it is up to the reader to extract the sub-basins of the Jordan River. The political context does not help, and for the most part data are exclusively obtained from each government.

This study is the first to provide additional information using GIS and remote sensing about the natural water available for runoff in the Jordan River Basin from precipitation without considering anthropogenic effects. It was found that the total precipitation falling over the Jordan River Basin was about 5292 MCM/year. 88 % of this precipitation is lost to ET which makes the total available water inside the basin about 987 MCM/year, with nearly half the flow contributed by Israel. Even though 32 % of the drainage basin lies within Syrian territory, this land contributes no water to the river, because evapotranspiration in the region is high. The Jordan River's natural flow is estimated to be about 1000 MCM/year, yet this study estimates the total available water to be 987 MCM/year. This underestimation is not surprising, as discharge from springs is not accounted for, and a negative bias in precipitation was identified as well. Opportunities to check statistically the results were limited due to data scarcity; linear regression was performed for precipitation gages in Lebanon showed that observed and satellite values were correlated with an R^2 of 0.65.

As better data becomes available, the geodatabase will be improved and expanded, acting as a central repository for authoritative data. An emphasis will be placed on acquiring better precipitation data, and on accounting for stream-aquifer interactions. The effects of climate change and anthropogenic influence are also crucial. Global climate projections, land use change, dams, withdrawal points, and water quality measurements all fit into the data model and the authors are working to acquire these data.

Future research will follow the methodology outlined in this paper for other transboundary river basins. Because the geodatabases they create have the same data model, the same set of tools for data sharing and analyses will work on all of them. The authors hope that by providing a standardized, web-based architecture for sharing and analyzing hydrological data, World Water Online will encourage cooperation between nations in the Jordan River Basin.

Acknowledgments This research project was partially funded by the Global Water Partnership Mediterranean and the University of Texas at Austin. The writers would like to express appreciation to Dr. David Maidment, Dr. Jacques Ganoulis, Jean-Francois Donzier, Dr. Shaddad Attili, Dr. Ralf Klingbeil, Dr. Andrew Davis Assaf, Prabhas Gupta and Harish Sangireddy for their insightful comments and suggestions. ESRI is acknowledged for making available necessary GIS software for this project.

References

Al-Abed N, Al-Sharif M (2008) Hydrological modeling of Zarqa River basin – Jordan using the hydrological simulation program – FORTRAN (HSPF) model. Water Resour Manag 22(9):1203–1220

Amery H (1998) The role of water resources in the evolution of the Israeli–Lebanese border. GeoJournal 44 (1):19–33

Amery H, Wolf A (2000) Water in the Middle East. University of Texas Press, Austin

Bakir H (2001) Water demand management and pollution control: key to securing and safeguarding the water supplies of MENA in the 21st century. In: First Regional Conference on Water Demand Management, Conservation and Pollution Control, Amman, Jordan 7–10 October, 2001. WHO Regional Centre for Environmental Health Activities, Amman

Barrow C (1998) River basin development planning and management: a critical review. World Dev 26 (1):171–186

Bermudez L, Arctur D (2011) OGC® engineering report: Water information services concept development study. Open Geospatial Consortium. http://portal.opengeospatial.org/files/?artifact_id=44834 Accessed September 15 2011

Black E (2009) The impact of climate change on daily precipitation statistics in Jordan and Israel. Atmos Sci Lett 10(3):192–200

Cleugh A, Leuning R, Mu Q, Running S (2007) Regional evaporation estimates from flux tower and MODIS satellite data. Remote Sens Environ 106:285–304

Courcier R, Venot JP, Molle F (2005) Historical transformations of the lower Jordan River basin (in Jordan): Changes in water use and projections (1950–2025). Comprehensive Assessment Research Report 9. Comprehensive Assessment Secretariat, Colombo, Sri Lanka

Daoudy M (2005) Le partage de l'eau Entre la Syrie, l'Irak et la Turquie– Négociation, sécurité et assymétrie des pouvoirs. coll.'Moyen-Orient'. CNRS Éditions, Paris

Elmusa S (1997) Water conflict: economics, politics, law and Palestinian-Israeli water resources. Institute for Palestine Studies, Washington DC

El-Naser H (1998) The partition of water resources in the Jordan river basin: History and current development. Paper presented at the Conference on Water in the Mediterranean Countries: Management Problems of a Scarce Resource, Naples, 4–5 December, 1998

Espinoza G, Whiteaker T, Maidment DR (2012) A test case using Mexican data for a world water online. Paper presented at the Geographic and Information Systems (GIS) and Water Resources VII Conference, New Orleans, Louisiana, 26–28 March, 2012

Evans JP, Smith R, Oglesby R (2004) Middle East climate simulation and dominant precipitation processes. Int J Climatol 24:1671–1694

EXACT (1998) Overview of Middle East water resources-water resources of Palestinian, Jordanian, and Israeli interest. Executive Action Team. http://exact-me.org/overview/index_pdf.htm. Accessed September 15 2011

Fekete BM, Vörösmarty CJ, Roads JO, Willmott CJ (2004) Uncertainties in precipitation and their impacts on runoff estimates. J Climate 17(2):294–304

Fisher FM, Arlosoroff S, Eckstein Z, Haddadin M, Hamati SG, Huber-Lee A, Jarrar A, Jayyousi A, Shamir U, Wesseling H (2002) Optimal water management and conflict resolution: The Middle East water project. Water Resour Res 38(11):1–16

FoEME (2010) Towards a living Jordan River: an environmental flows report on the rehabilitation of the lower Jordan River. Friends of the Earth Middle East, Amman, Bethlehem, Tel Aviv

FoEME (2011) Roadmap for the rehabilitation of the lower Jordan River. Friends of the Earth Middle East, Amman, Bethlehem, Tel Aviv

Gavrieli I, Bein A, Oren A (2005) The expected impact of the peace conduit project (The Red Sea-Dead Sea Pipeline) on the Dead Sea. Mitig Adapt Strateg Glob Chang 10:3–22

Gilad D, Bonne J (1990) Snowmelt of Mt. Hermon and its contribution to the sources of the Jordan River. J Hydrol 114(1/2):1–15

GMAO (2011) Overview. Global Modeling and Assimilation Office. https://gmao.gsfc.nasa.gov/. Accessed October 22 2011

Goldreich Y (1994) The spatial-distribution of annual rainfall in Israel—a review. Theor Appl Climatol 50:45–49

GTZ (1995) Middle East Regional Study on Water Supply and Demand Development. Gesellschaft für Technische Zusammenarbeit. Al-Najah University Press, Nablus

Gunkel A, Jens L (2011) New insights into the natural variability of water resources in the lower Jordan River basin. Water Resour Manag 25:1–18

Gur D, Bar-Matthews M, Sass E (2003) Hydrochemistry of the main Jordan River sources: Dan, Banias and Kezinim springs, north Hula Valley, Israel. Isr J Earth Sci 52:155–178

Horsburgh JS, Tarboton DG, Maidment DR, Zaslavsky I (2008) A relational model for environmental and water resources data. Water Resour Res 44(W05406)

ILA (1966) The Helsinki Rules on the uses of the waters of international rivers. International Law Association. http://webworld.unesco.org/water/wwap/pccp/cd/pdf/educational_tools/course_modules/reference_documents/internationalregionconventions/helsinkirules.pdf. Accessed September 5 2010

IWA (2010) The Kinneret watershed. Israel Water Authority. http://www.water.gov.il/Hebrew/ProfessionalInfoAndData/2012/09-Israel-Water-Sector-Lake-Kinneret-watershed.pdf. Accessed May 8 2012

Jordan Natural Resources Authority (1977) National water master plan of Jordan. Hashemite Kingdom of Jordan and GTZ, Amman

Kitoh A, Yatagai A, Alpert P (2008) First super-high-resolution model projection that the ancient “Fertile Crescent” will disappear in this century. Hydrological Research Letters 2:1–4

Klein M (1998) Water balance of the upper Jordan River basin. Water Int 23(4):244–248

Krichak SO, Alpert P, Bassat K, Kunin P (2007) The surface climatology of the eastern mediterranean region obtained in a three-member ensemble climate change simulation experiment. Adv Geosci 12:67–80

Legates DR, Willmott CJ (1990) Mean seasonal and spatial variability in gauge-corrected, global precipitation. Int J Climatol 10:111–127

Lionello P, Giorgi F (2007) Winter precipitation and cyclones in the mediterranean region: Future climate scenarios in a regional simulation. Adv Geosci 12:153–158

Maidment DR (1993) Handbook of hydrology. McGraw-Hill

Maidment DR (2002) Arc Hydro: GIS for water resources. ESRI Press, Redlands CA

Medzini A, Wolf AT (2004) Towards a middle east at peace: Hidden issues in arab-Israeli hydropolitics. Water Resour Devel 20(2):193–204

MEW (2011) Precipitation in southern Lebanon. Ministry of Energy and Water in Lebanon, Beirut

Mimi ZA, Sawalhi BI (2003) A decision tool for allocating the waters of the Jordan River basin between all riparian parties. Water Resour Manag 17(6):447–461

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Working Paper 55. Tyndall Centre for Climate Change Research, Norwich, UK

Mithen SJ, Black E (2011) Water, life and civilisation: climate, environment and society in the Jordan Valley. Cambridge UP, UK, Cambridge

Mu Q, Zhao M, Running S (2011) Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens Environ 115(8):1781–1800

NASA (2011) ASTER L1B. Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center. https://lpdaac.usgs.gov/lpdaac/products/modis_products_table. Accessed April 5 2012

Natural Earth (2011). http://www.naturalearthdata.com. Accessed October 23 2011

Niemi TM, Ben-Avraham Z, Gat J (1997) The dead sea: the lake and its settings. Oxford University Press, New York

Patiño-Gomez C, McKinney DC, Maidment DR (2007) Sharing water resources data in the binational Rio Grande/Bravo basin. J Water Res Pl 133(416)

Phillips D, Daoudy M, Öjendal J, Turton A, McCaffrey S (2006) Trans-boundary water cooperation as a tool for conflict prevention and broader benefit-sharing. Global Development Studies No. 4. Stockholm. Ministry of Foreign Affairs, Sweden

Phillips DJH, Jägerskog A, Turton A (2009) The Jordan River basin: 3. Options for satisfying the current and future water demand of the five riparians. Water Int 34(2):170–188

Rimmer A, Salingar Y (2006) Modelling precipitation-streamflow processes in karst basin: the case of the Jordan River sources, Israel. J Hydrol 331(3–4):524–542

Salameh E, Bannayan H (1993) Water resources of Jordan: present status and future potentials. Royal Society for the Conservation of Nature/Friedrich Ebert Stiftung, Amman

Siegel D (2011) Accessing historical evapotranspiration data in ArcGIS. University of Texas at Austin. http://data.crwr.utexas.edu/blog/news/historical-evapotranspiration-data/. Accessed March 20 2011

Simpson B, Carmi I (1983) The hydrology of the Jordan tributaries (Israel): hydrographic and isotopic investigation. J Hydrol 62(1–4):225–242

Suleiman R (2004) Water resources development in the lower Jordan River basin. International Water Management Institue (IWMI) and Ambassade de France en Jordanie (MREA), Stockholm

Tarboton D, Maidment DR (2010) Watershed and stream network delineation. University of Texas, Austin

Tarboton DG, Bras RL, Rodriguez-Iturbe I (1991) On the extraction of channel networks from digital elevation data. Hydrol Process 5:81–100

The World Bank (1992) World development report 1992 : development and the environment. http://econ.worldbank.org/external/default/main?pagePK=64165259&theSitePK=469072&piPK=64165421&menuPK=64166322&entityID=000178830_9810191106175. Accessed May 13 2011

The World Bank (2011) Land area (sq. km). http://data.worldbank.org/indicator/AG.LND.TOTL.K2. Accessed May 18 2012

United Nations (1997) Convention on the law of the non-navigational uses of international watercourses. http://untreaty.un.org/ilc/texts/instruments/english/conventions/8_3_1997.pdf. Accessed January 16 2010

ASTER GDEM Validation Team (2009) ASTER Global DEM validation summary report. NASA/LPDAAC, METI/ERSDAC and USGS/EROS. http://www.jspacesystems.or.jp/ersdac/GDEM/E/image/ASTERGDEM_ValidationSummaryReport_Ver1.pdf. Accessed October 22 2011

Willmott C, Matsuura K (2001) Terrestrial air temperature and precipitation: Monthly and annual time series (1950–1999) Version 1.02. http://climate.geog.udel.edu/ climate. Accessed November 5 2011

Zeitoun M, Eid-Sabbagh K, Dajani M, Talhami M (2012) Hydro-political baseline of the upper Jordan River. Association of the Friends of Ibrahim Abd el Al, Beirut