



Salinity evolution of the Tigris River

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Abstract

Major modifications regulating the Tigris River, originated in the 1940s and continuing to the present, have resulted in changes in salinity in the system over time and in different portions of the river course. The increase in salinity is due to decreases in stream discharge due to dams, water management structures such as the Lake Tharthar system, irrigation return flow, and soluble minerals in the basin. This research documents the increase and evaluates the causes of the salinity increase of the river from predevelopment to present using published and previously unavailable data. The predevelopment salinity was under 600 ppm, since 1984 has exceeded the 1000 ppm threshold recommended for drinking water downstream of Amara. A minimum instream flow for the river is calculated at Baghdad and Kut at 185 cubic meters per second (cms), approximately 15% of the mean historical flow of the river, but above the lowest minimum flow recorded at 140 cms. Recommended salinity management options discussed include (1) eliminating Lake Tharthar as a water storage facility, (2) managing saline inflows from tributaries, and (3) employing a minimum instream flow for the river.

Keywords Ilisu Dam · Mosul Dam · Lake Tharthar · Environmental flow · Minimum instream flow

Introduction

The modification of stream systems can bring devastating results to the downstream stakeholders (Beaumont 1998). Some processes may divert the whole flow volume to the upstream users and leave the downstream reaches practically dry or involuntarily converted to a wastewater drain (Clark and Magee 2001). In semiarid to arid environments, a common downstream effect is salinization of the river system (FAO 1970; ICARDA 2012a; Ross and Connell 2016). The salinity in the Lower Colorado River at Imperial Dam has doubled in 2011 compared to 1971 (USBR 2013). Salinities as high as 4000 ppm were reported for the lower reaches of the Euphrates River in Iraq (Rahi and Halihan 2010). These effects are also quantified by the total dissolved solids (TDS) or the fluid electrical conductivity (EC) of a stream (Walton

1989). Managing these issues is difficult for developed countries who manage the entire river system such as Australia, but for less developed countries who share international rivers, transboundary management becomes complicated (Uitto and Duda 2002; Kucukmehmetoglu and Guldmann 2010; Voss et al. 2013).

Salinization is fundamentally caused by two processes, evaporation, and mineral dissolution (Peck 1978). Many hydraulic structures added to stream systems, surface water reservoirs in particular, increase evaporation by storing water in surface structures with large surface areas (Rajagopalan et al. 2009; Friedrich et al. 2018). Evaporation is also created through irrigation systems during transport in open channels, water application to fields, or transpiration from crops (Dawes et al. 2004). In areas with soluble minerals such as halite or gypsum, irrigation or modification to flow systems can dissolve these minerals and add to stream salinity (Tanji 2002; Kaushal et al. 2018).

Salinization management is a site-specific issue in most cases, as it must account for the spatial distribution of precipitation, irrigation, municipalities, and topography (Cheng et al. 2014; Wichelns and Qadir 2015). Management approaches include disposal of saline flows prior to returning to streams. This can be accomplished through deep aquifer disposal, evaporation basins, or moving saline water to the ocean. Other options include reusing saline water or mixing with fresh water.

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An additional approach is to ensure that sufficient water remains in a stream to preserve the stream salinity at lower levels. The minimum instream flow (MIF) or environmental flow concept “describes a fresh water flow (typically instream flow) that is maintained (or not allowed to be used for other, typically anthropogenic, purposes) solely for environmental reasons, to maintain the health and biodiversity of a particular water-related entity, such as a river, wetland, groundwater system or estuary. For example, water may be extracted from a particular river for a particular industry. However, an environmental flow may be maintained down the river, not diverted to this industry, to maintain downstream river and/or estuarine ecosystems by allowing natural flows to progress through the system” (Peirson et al. 2002).

In the USA, basin-wide salinity control and management programs have been implemented at the Colorado River (USBR 2013). These programs are conducted by the Natural Resource Conservation Service (of the United States Department of Agriculture), Bureau of Reclamation (Dept. of Interior), the Bureau of Land Management (Dept. of Interior), and state programs of the beneficiary states. These programs are supervised by the state-federal Colorado River Basin salinity control forum and the Environmental Protection Agency (EPA) (Morford 2014). The Colorado River salinity control measures include implementation of best management practices in irrigation practices, erosion control, and reduction in natural saline water spring flows. Salinity control is also achieved on the river by regulating salinity releases at large dams. An important component of the Colorado River salinity control scheme is maintaining the treaty obligations by the USA toward Mexico by keeping an average annual salinity concentration of no greater than 115 ppm (± 30 ppm) greater than the average annual water salinity at the Imperial Dam (USBR 2013; Morford 2014).

In Australia, the managing authorities at the South Australia Murray River have initiated constructive and dynamic salinity control programs. These programs aim to maintain salinity in the Murray River in South Australia at less than 800 $\mu\text{S}/\text{cm}$ (about 512 ppm TDS) at the city of Morgan for 95% of the time (BSM2030 2015). The salinity target was achieved in 2010 through the combination of salt interception schemes, improved irrigation practices, and specific catchment programs.

In the Tigris Basin, incorporating Turkey, Syria, Iraq, and Iran, basin-wide salinity management is not implemented. An understanding of the evolution of the salinity of the Tigris River due to development is essential to improve management of the Tigris river system. The objective of this research is to document the salinity evolution of the Tigris River since 1925 and propose a minimum instream flow (MIF) as a management option to maintain the salinity of the lower parts of the

Tigris, at levels consistent with international standards. Data on discharge and salinity are accumulated from the 1920s to present day to evaluate historic trends and changes. By compiling and comparing data in a historical evaluation, the management of the system can potentially be improved.

Hydrology of the Tigris River

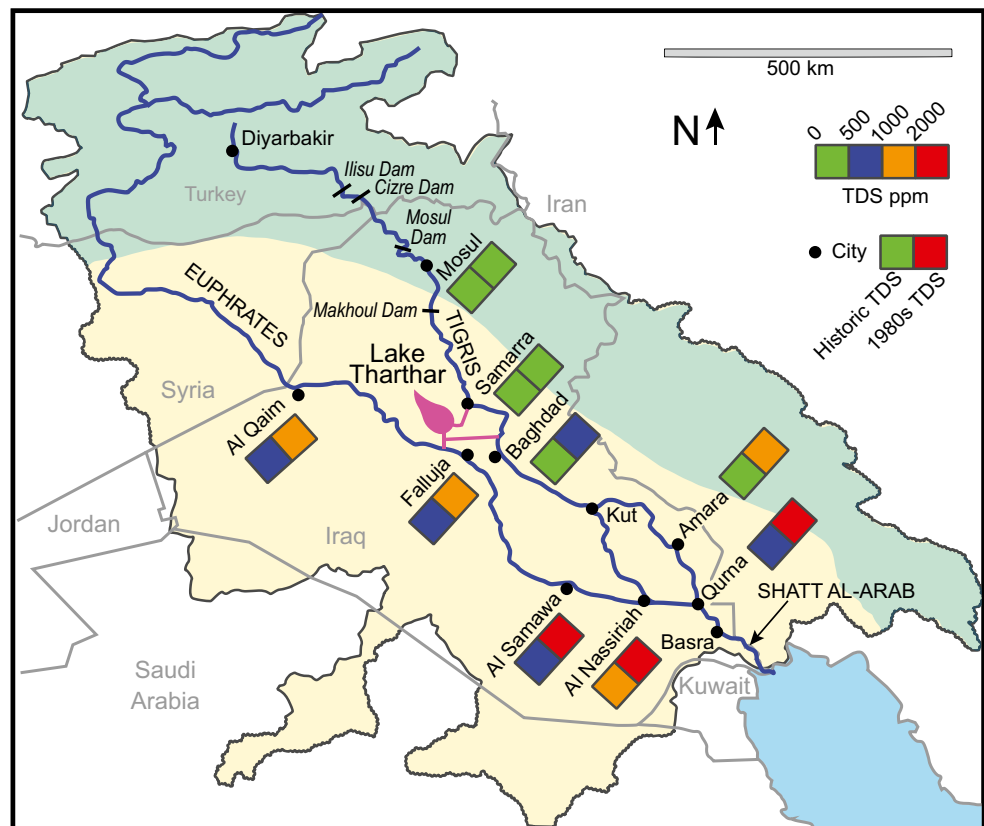
The Tigris River is the second-largest river in western Asia (Fig. 1). It originates in southeastern Turkey on the southern slopes of the eastern Taurus Mountains near Lake Hazar (Altinbilek 2004). The Tigris is approximately 1900 km total length: 400 km in Turkey and 32 km as the Turkey/Syria border, with the remainder in Iraq. The river flows in a southeasterly direction until it joins the Euphrates at al Qurna in southern Iraq. The two rivers together form the Shatt al Arab waterway, which empties into the Persian (Arabian) Gulf.

The Tigris River has a drainage basin of 471,606 km², shared by four countries Turkey, Syria, Iraq, and Iran. About 12% of the basin area is in Turkey, 54% in Iraq, and 34% in Iran (HARC 2015). Syria does not have a significant portion of the basin. Within Iraq, the Tigris is fed from the east by five major tributaries: the Khabur, the Greater Zab, the Lesser Zab, the al Udhaim, and the Diyala. Of these, only the Diyala joins the Tigris downstream of Baghdad (Jalut et al. 2018).

Dams on the Tigris include several large dams (> 1 bcm storage) in Turkey. The Turkish retention capacity, operative and under construction, is about 14 bcm from large dams, sufficient to retain a majority of the Tigris flow generated in Turkey (UN-ESCWA and BGR 2013; Altinbilek 2004). The largest dam is the Ilisu Dam, located in the Tigris River 65 km upstream from the Syrian-Turkish border point (Fig. 1). The dam will impound 10.41 bcm in its reservoir and is intended for power generation and irrigation (UN-ESCWA 2013). The Ilisu Dam will operate in conjunction with the Cizre Dam. The Cizre Dam, a hydraulic diversion structure, is in the planning stage and will be located 45 km downstream the Ilisu Dam (Partow 2001; Declaration et al. 2006). The purpose of the two structures is power generation and irrigation, diverting water to the east of the main river course (Partow 2001).

Iraq has even more large dams than Turkey. The planned and operative retention capacity of large dams in Iraq on the Tigris River, excluding Lake Tharthar, amounts to 24 bcm. The retention structures are capable of storing most of the Tigris waters in the north or central Iraq, and reduce the flow to the southern Iraq substantially (Richardson 2016). The Tharthar Lake (depression) is located between the Euphrates and the Tigris. The depression is a gypsum doline (sinkhole) that was originally used for flood control in 1954 prior to being a water supply reservoir in 1983 (Sissakian 2011). It is fed from the Tigris, diverting flow to the Euphrates and the Tigris downstream. The Tharthar Lake is the largest lake and

Fig. 1 Map of the Tigris River with selected cities, basin and country boundaries, and hydrologic features (after Holmes 2010). Precipitation isohyet of 100 mm/year is delineated by color boundary between sand color and light green with higher precipitation in the northeast portion of the basin. Salinity values are provided for the earliest known TDS values and for the high salinity period in the 1980s



reservoir in Iraq. The lake is a major source of salinity for the Euphrates and Tigris downstream of the lake outlet due to the high evaporation rate of the lake (Rahi and Halihan 2010; Al-Ansari et al. 2014). The salinity of water leaving the lake is close to triple in comparison to the Tigris water at Samarra (ICARDA 2012b). Rahi and Halihan (2010) indicate that the salinity of the lake water flowing to the Euphrates is about 1500 ppm.

Geologically, the Tigris is underlain by thick alluvial deposits along the entire flowpath. Evaporite deposits, primarily gypsum, exist in the karstic Fatha Formation as small beds in a cyclic formation with marl and limestone (Sissakian 2011). These highly soluble deposits are well-known for affecting the Mosul Dam foundation (Kelley et al. 2007). Gypsiferous soils and soil salinity are also mapped in Iraq (Wu et al. 2014).

Iran has several dams in the Tigris Basin, but the only large dam is the Karkheh dam on the Karkheh River which flows into the Tigris just upstream of Qurna (Vaghefi et al. 2013). While Iran does not have many large dams, a significant amount of water is prevented from entering Iraq with smaller structures (Richardson 2016). The altered tributaries join the river downstream of Baghdad, including the Diyala, Galal Badra, al Chabab, Teeb, Dwaireeje, and Karkheh rivers. Most of these tributaries originate and are controlled by Iran (HARC 2015). Iran has dammed most of them, significantly restricting the flow entering Iraq. Reduced flow from the last

three tributaries has adversely affected the restoration process of the Al-Hawizeh Marshes, one of the three major Iraqi Marshes (Richardson 2016).

Apart from the formal storage facilities, the Tigris flow is controlled by two primary hydraulic structures used for regulating hydraulic head in the system, the Samarra Barrage built in 1954 and the Kut Barrage built in 1939. Both structures are located in the cities they are named after (Fig. 1). The Samarra Barrage diverts water to the Tharthar depression along with a separate irrigation canal that bypasses the Tharthar depression. The Kut Barrage diverts water to al Gharraf and al Dujaila distributaries. These systems supply water for several cities and irrigation projects in southern Iraq.

Changes have occurred in the Tigris system due to widespread river development. Large-scale changes to the river systems began with plans originating in the early twentieth century and have continued to the present (Haigh 1951; Harza Engineering Co. 1963). The most recent dam project is the Ilisu Dam in Turkey, as part of the Southeastern Anatolia Project (Turkish acronym is the GAP project). The Ilisu Dam would be the largest dam on the Tigris River in Turkey and is expected to commence operations in 2018. Research indicates that the Tigris flow at the border between Turkey and Iraq would be reduced to lower rates after the opening of the dam (UN-ESCWA 2013; Kolars 1994). An independent assessment of the combined downstream impacts of Ilisu and

Cizre, undertaken in 2006 (Declaration et al. 2006), concludes: “The operation of the Ilisu Dam in combination with diversions from the future downstream Cizre project would probably significantly reduce summer flows in Syria and Iraq below historic levels. It is likely that a significant portion of the recommended minimum flow release from the Ilisu of 60 m³/s during dry years would be diverted. It is even possible that with full implementation of the Ilisu/Cizre projects, during drought periods, all the summer flows could be diverted before it crossed the border.”

Agricultural return flows affect salinity in many arid streams. The sharp increase of salinity in the lower parts of the Euphrates is largely attributed to agriculture return flow (Fattah and Abdul Baki 1980; Rahi and Halihan 2010). In the Tigris Basin, irrigation occurs in many zones with variable salinity in the return flows that are poorly quantified. Return flows in Turkey are not currently adding significantly to salinity, but there are concerns as development continues that a problem may develop (Odemis et al. 2010). In addition, the discharge of agricultural return flows into the river has adversely affected its water quality in the lower, southern parts of the river (ICARDA 2012a; Al-Saady and Abdullah 2014) from irrigation in Iraq and Iran.

Methodology

The approach of this research is to analyze the salinity and the associated discharge of the Tigris River system in Iraq, where spatial and temporal changes in salinity are apparent in the data. Data analyzed includes discharge and total salinity measurements obtained from the literature and from the records of the Iraqi Ministry of Water Resources (IMWR). Although the available data are limited, the analysis attempts to be comprehensive for the basin since the Tigris River development has occurred basin-wide. Previous research dealt with the limited data availability of the Euphrates River system and followed the same approach with only differences in the data sources (Rahi and Halihan 2010). The analysis of the data will include evaluating the causes of historical shifts in salinity. Additionally, a MIF for the Tigris will be calculated using two methods.

Salinity and discharge data sources

Modern discharge measurements for the Tigris extend back to 1925 (Al-Khashab 1958; Haigh 1951). A significant amount of stream discharge data was compiled recently by the United States Geological Survey (USGS) (Saleh 2010). More recent flow data (after 2004) was obtained from additional reports and the Iraq Ministry of Water Resources (UN-ESCWA 2013). These data are similar to other modern data sources (Al-Shujairi et al. 2015).

While the river has significant variability in discharge, the discharge estimates multiyear discharge averages.

Salinity data for the Tigris river is largely available as TDS measurements in parts per million (ppm). Some salinity data were obtained directly from the former Iraqi Ministry of Irrigation in 1997 for research purposes and is compiled for this work. Salinity data for the years 2000 and later was obtained from a number of sources, including UN-ESCWA 2013, the Iraq Ministry of Water Resources and ICARDA 2012a. Salinity analysis of the Tigris River is divided by locations where salinity data were available for the system. This is generally in cities along the Tigris. The measurements can be evaluated to determine if significant discharge or salinity changes occurred between cities and evaluating the cause of the changes. As significant levels or changes in salinity were not noted at Mosul, Iraq, the period of record utilized assumes that significant changes did not occur upstream of Mosul during the period used for this study.

Salinity data were also analyzed for the Lake Tharthar system. Salinity data for the system were available from 1979 to 2009. This includes the period from when Lake Tharthar went from a flood control structure to a water supply structure. Salinity data were available for both the inlet and outlet of the system (Al-Ansari et al. 2014). The data were averaged over similar time periods to evaluate trends.

Salinity and discharge analysis

Discharge data were evaluated both temporally and spatially for the Tigris. At Mosul, Baghdad, and Kut, discharge changes were evaluated for a number of periods to observe changes over time that may influence salinity. Mosul represents upstream conditions, Baghdad central conditions, and Kut downstream conditions. Five time periods were utilized for discharge comparisons, similar to previous work (UN-ESCWA 2013). The period from 1931 to 1952 was considered the historical predevelopment period. The period from 1931 to 1973 was predevelopment but included the presence of Lake Tharthar being used as a flood control structure. The period of 1931–2011 was used as a complete average. From 1953 to 1984, tributary dams were in effect. The final period from 1985 to 2005 was considered a modern developed average.

Salinity data were also compiled on a historic and modern basis. As the highest salinity values for the Tigris system were observed at approximately 1990, modern salinities were tabulated for both the highs of 1990 and the more recent conditions of approximately 2010. These data were compared to hydraulic control structures that have been installed. They were also compared to changes in the geology that occur over the course of the Tigris. Salinity data were averaged for 1950–1970 as predevelopment salinities. Data were also compiled for 1979–1983, 1984–1994, and 1998–2004. Finally, the

modern salinity of the Tigris is evaluated from 2010 to 2016. The salinity for Lake Tharthar dataset was divided at 1991, as there was a shift in the data during this time.

Minimum instream flow analysis

The United Nations Food and Agricultural Organization (FAO 1976) water quality guidelines recommend a 750- $\mu\text{mhos/cm}$ (480 ppm) salinity level for irrigation use and for human consumption. The FAO guidelines classify water with 750–3000 $\mu\text{mhos/cm}$ (480–1920 ppm) as slightly to moderately restricted for irrigation use. The maximum total dissolved solids (TDS) accepted by the World Health Organization (WHO) for drinking water is 1000 ppm. The Iraqi Bureau for Standards sets the salinity level for potable water at 1000 ppm TDS (UNEP 2003). The Iraqi and the WHO salinity level for drinking water (1000 ppm TDS) is employed as a threshold to determine the suggested MIF rates for the River Tigris.

The threshold salinity is targeted for the Amara Measurement Station located on the Tigris at the City of Amara (Fig. 1). The Amara Station is the southernmost major city on the river, and it is highly influenced by increased salinity. Data from two stations, located upstream from the Amara station, are selected to perform the MIF calculations. These stations are Baghdad and Kut. The Kut station is selected because it is the closest upstream station to the Amara station with sufficient hydrological and salinity data to conduct the analysis. The Baghdad station, which is located further upstream from the Kut station, is selected to enhance the finding from the Kut station and to verify the results. Both stations, along with the Amara station, have flow reduction caused by upstream hydraulic control structures.

Different approaches are employed to determine the MIF for a given river system (Peirson et al. 2002). In the Midwestern USA, the MIF is identified as a specified percentage of the mean annual flow: 10% for poor quality habitat (survival), 30% for moderate, and 60% for excellent habitat (Tennant 1976). The hydrological index expressed as Q95 is practiced in the UK as a measure of MIF (Dyson et al. 2003). The index designates that the flow is equaled or exceeded 95% of the time. Since the index flow has a reoccurrence interval of about 1 year; it may be assumed equal to the annual flow of the driest year ever recorded for a given river.

Another MIF calculation scheme is the discharge-salinity correlation approach. This calculation method was applied for the Ganges River in Bangladesh (Mirza 1998) and the Euphrates River in Iraq (Rahi and Halihan 2010). The method is based on determining a maximum acceptable salinity (threshold salinity) as the criteria for the MIF. The adapted TDS threshold is 1000 ppm which the maximum salinity accepted for drinking water (WHO 1997). Mean monthly TDS data are plotted against mean monthly discharge data which

demonstrate a nonlinear relationship. Where the salinity exceeds 1000 ppm on this relationship is the MIF discharge (Mirza 1998).

This correlation method is employed for this paper with two approaches. One approach combines dry and wet year data for the purpose of the MIF calculations as a combined annual dataset. Three years were selected from the Kut Station: a dry year (1999), an average year (1990), and a wet year (1988). These data were evaluated for salinity and discharge, and the MIF was selected as the value where salinity exceeded 1000 ppm. Alternatively, data of the month with the lowest flow of the year—the month of September—from the stations of Baghdad and Kut were combined in one regression analysis, a dry month dataset. The data for al Kut Station was for the years 1979 to 1999, less 1983 to 1987. Baghdad Station data includes the years 1983 through 1994. Once again, the MIF was selected as the flow required to maintain a TDS of 1000 ppm.

Results

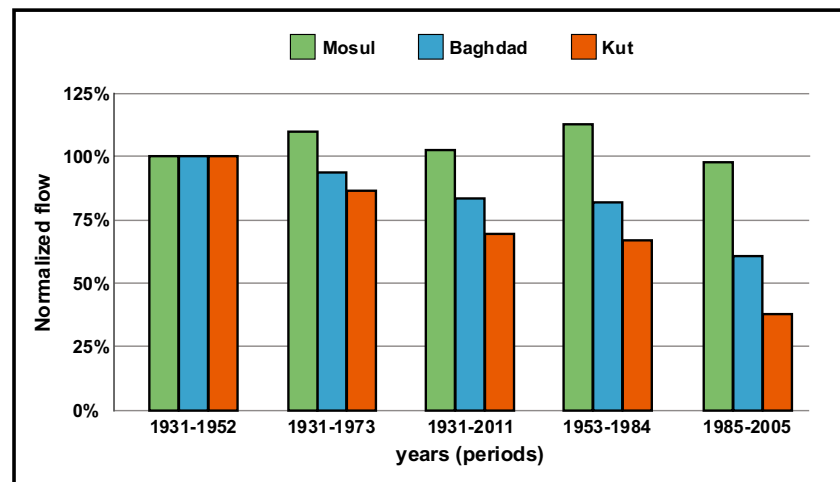
The results evaluate the changes in the discharge salinity of the Tigris River over time from 1931 to present. The results include analysis of features which contribute to changes in salinity. A minimum instream flow estimate is generated using two different datasets, the combined annual data, and the dry month data.

Discharge evolution

The flow of the Tigris River is reduced in the lower reaches (Baghdad and downstream), due to the control structures built upstream (Partow 2001; UN-ESCWA 2013). Currently, two major hydraulic structures control and regulate the discharge; they are the Mosul Dam and the Tharthar Lake, both in Iraq. Discharge of the Tigris measured at three stations (Mosul, Baghdad, and Kut) in Iraq and normalized to the pre-dam period (1931–1952). The discharge values were between 16.2 and 19.4 bcm at Mosul (Bilen 1997; UN-ESCWA 2013), 38.7 bcm at Baghdad (Saleh 2010), and 36.8 bcm at Kut (UN-ESCWA 2013). These are normalized to 100% values to represent historic conditions (Fig. 2). Discharge for the later periods was reduced (Fig. 2) due to the influence of the upstream hydraulic structures. This is most apparent at Kut where flow has been reduced to 13.9 bcm, a reduction of 62% (UN-ESCWA 2013).

The Mosul flow data do not show any significant flow reduction following the pre-development period because it is located upstream of the Mosul Dam and it is affected only by the Turkish structures (Fig. 2). Since no major dam is yet in operation on the Tigris in Turkey, the Mosul data show random variation and are interpreted to represent the natural state

Fig. 2 Tigris River discharge over time, along the length of the river normalized to historic measurements (1931–1952) (Saleh 2010; UN-ESCWA 2013). Variations at Mosul are considered the natural variability of the river upstream of the Mosul Dam



of the river. The Baghdad and Kut stations are both influenced by the Mosul Dam and the Tharthar Lake. The flow to Baghdad and further downstream is reduced compared to the pre-damming period due to diversion and impoundment in these two water storage facilities. The higher flow reduction in Kut compared to Baghdad can be attributed to the reduced flow from the Diyala River, which joins the Tigris downstream of Baghdad and upstream of Kut. In the 1980s, the Diyala flow was diverted to use for irrigation upstream of its confluence with the Tigris (Al-Faraj and Scholz 2014; Jalut et al. 2018). Abd-El-Mooty et al. (2016) evaluated the mean annual flow of the Tigris at Kut over time for the years 1932 to 2002 and found the flow reduced to 27% in 2002 compared to 1932. The flow will be further reduced along the entire length of the Tigris in Iraq when the Turkish Ilisu Dam is put in operation (Declaration et al. 2006).

Other literature provides similar values for discharge. Beaumont (1978) has stated that the annual flow at Mosul is 23.2 bcm, while Kolars (1994) indicated a flow of 20.5 bcm. The average annual discharge of the Tigris at Mosul, Iraq, for the period 1931 to 1970 is 680 cms or an annual volume of 21.4 billion cubic meters (bcm) (Saleh 2010). There does not seem to be any strong disagreements on the discharge quantity among various sources, simply variations in the averaging methods and periods.

The flow of the Tigris River in Baghdad is almost doubled compared to its upstream flow at Mosul. The average annual flow for 52 years (1930–1981) was 1118 cms or about 35.25 bcm (Saleh 2010). The mean annual flow of Diyala River is about 6.1 bcm, which makes the total Tigris flow downstream of Baghdad 41.35 bcm (Saleh 2010). Harza Engineering Co. (1963) quotes an overall annual Tigris discharge value at Baghdad of 43.6 bcm for 27-year period (1929–1956).

Other literature gives discharge averages for the Tigris at Baghdad without being precise on the averaging interval. Beaumont (1978) and Kolars (1994) put the mean annual

Tigris flow at Baghdad at 52.7 and 49.2 bcm, respectively. The Iraqi Ministry of Water Resources (MoWR) published two different numbers. MoWR, 2013 quoted an annual flow of 49.48 bcm.

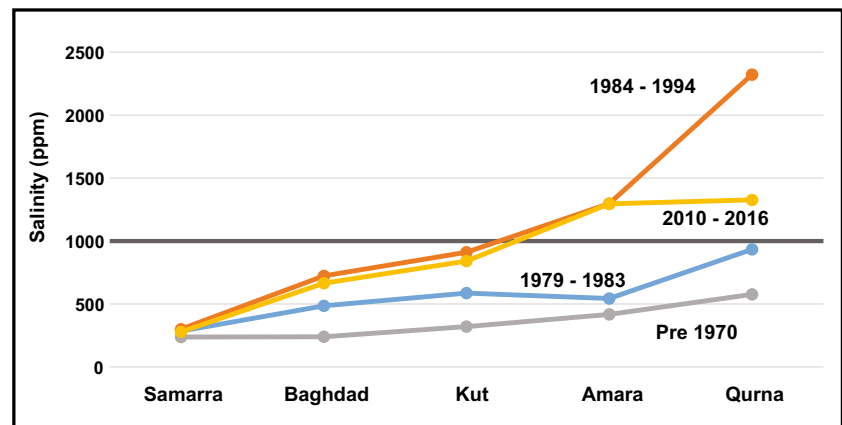
Salinity evolution

Historically, the salinity of the Tigris River was low and the water was suitable for all purposes. Available data indicate salinity (TDS) of 225–255 ppm measured during a survey from 1954 to 1955 (Buringh 1960). FAO (1970) reported a TDS of 250 ppm for the Tigris River in Baghdad. More recently, however, the Tigris salinity in Baghdad and downstream underwent a sharp increase (UN-ESCWA 2013; Al-Sabah 2016). Fanack (2016) reported a sixfold increase in salinity, expressed as TDS, along the Tigris between Mosul Dam and Qurna, based on average monthly water quality data available from the Ministry of Environment for the period 2004 to 2011. Researchers have even reported deterioration in water quality of the river before entering Iraq. Varol et al. (2010) reported salinity as high as 1000 ppm in Diyarbakir, Turkey.

The analysis for this work illustrates a general increase in salinity downstream in the Tigris (Fig. 3). The predevelopment salinity was under 500 ppm for most of the system and was 576 ppm at Qurna. Salinity was not known to have increased substantially prior to 1983 but has increased since that time. The salinity at Amara and downstream exceeded the 1000 ppm threshold recommended for drinking water since 1984 (Fig. 3). The salinity at Samarra and further upstream has remained low and stable for most of the time. The salinity has actually gone down at Qurna since the 1984–1994 time periods when the salinity reached a value of 2320 ppm.

The increase in salinity at Baghdad and further downstream is affected by Lake Tharthar. The use of the lake as water storage adds significant salinity to the river at Baghdad and downstream. The increase in salinity downstream of Kut may

Fig. 3 Salinity along the Tigris River during four time periods. Gray line from pre 1970 datasets (Buringh 1960; FAO 1970; Hanna and Al Talbani 1970). Light blue line and dark orange line illustrate salinity from ranges of approximately 1980 and 1990 (data from the Iraq Ministry of Irrigation 1997). Gold line illustrates more recent salinity (ICARDA 2012b). Heavy line at 1000 ppm indicates WHO salinity limit for drinking water



be attributed to inflows from Hour (marsh) al Shiwiaja and al Chabbab Tributary. The Hour al Shiwiaja has a high salinity due to its low discharge and high evaporation rates. It is confined by a dike but spills to the Tigris during floods and transports the salt load from the river. The Chabbab tributary is an ephemeral stream which occasionally floods into the Tigris. The tributary has high salinity during low flow periods and could contribute to salinity increase of the Tigris River at Amara.

Lake Tharthar

The salinity increase downstream of al-Tharthar Lake indicates the lake acts as a significant salinization source for the river (Al-Ansari et al. 2014). Lake Tharthar inflow salinity mimics upstream conditions with an average salinity of 315 ppm which has been stable for the period of record, 1979–2009 (Fig. 4). The outflow salinity in Lake Tharthar has exceeded freshwater values for the entire period of record (Fig. 4). For the period 1979–1991, the system had average outflow salinities of 1874 ppm, an approximately 600% increase in salinity. Then, the average salinity for the outflow from the lake was 1073 ppm, an increase of 340% from the

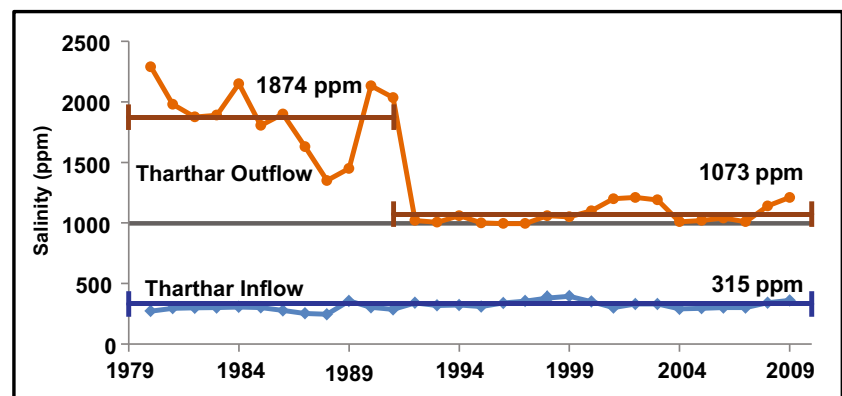
inflow waters. The relative decrease in salinity in the latter period may be attributed to higher rate of recirculation of the lake waters as a result of more extensive use as a water supply reservoir. The lake was also used to impound streamflow that was released to the southern marshes prior to draining them in 1991.

The high salinity of Lake Tharthar is likely due to one or more of the following causes: The evaporation rate of 2.86 bcm/year is 225% higher than the entire water needs of Baghdad (UN-ESCWA 2013). The second cause is likely dissolution of soluble minerals, generally gypsum, and halite that existed or built up in the lake when it was a generally dry wadi (Sissakian 2011). Inflow of saline water into the lake, especially from the northern lake border, may also attribute to the higher salinity. No quantitative study has conducted to clearly partition the various causes of high salinity in Lake Tharthar.

Minimum instream flow

The MIF values calculated from the two methods provided similar results. The MIF calculated for the 3 years from the Kut Station, dry, average, and wet year resulted in a dataset

Fig. 4 Lake Tharthar salinity changes over time, inflow, and outflow. Dark line at 1000 ppm salinity indicates WHO drinking water salinity limit. Average values of Lake Tharthar inflow and outflow indicate for the modern period illustrating a 340% increase in salinity as water moves through the Lake Tharthar system



with 36 values. An exponential fit to the data results in the relationship:

$$TDS = 5539 * Q^{-0.325} \quad (1)$$

where TDS is the total dissolved salts in ppm and Q is the discharge in cms.

The coefficient of determination is 80%, which indicates a reasonable fit between the data points and the regression line. Equation 1 can be used to determine the required discharge for pre-assigned TDS downstream from the station used for analysis (Fig. 5). The MIF for the Tigris to maintain 1000 ppm salinity using this approach is 194 cms.

The low flow analysis for Baghdad and Kut stations resulted in 22 values being included in the dataset. The best fit exponential equation for the data is

$$TDS = 4123 * Q^{-0.274} \quad (2)$$

The coefficient of determination is 68% (Fig. 5). The required MIF to maintain certain level of salinity, at stations downstream of Kut, is determined using Eq. 2 (Fig. 5). The MIF required to maintain 1000 ppm in the Tigris is 176 cms using this approach. As the two methods provide similar values, an average MIF of about 185 cms is required to maintain the TDS of the Tigris water at or below 1000 ppm in the lower reaches (downstream from Kut). This MIF is expected to contribute positively to the remediation processes implemented to improve the water quality of Shat al Arab.

Alternative methods of MIF estimation are also available. If the MIF is estimated as a specified percent of the mean annual flow (approximately 300 cms for the Kut Station), following the Midwestern US practice (Tennant 1976), then the MIF would be around 185 cms for an excellent habitat. For poor to moderate quality habitat, the MIF would range

between 30 and 90 cms. Meanwhile, the hydrologic index method (Dyson et al. 2003) would give an estimated MIF of 140 cms—the lowest flow ever recorded.

Discussion

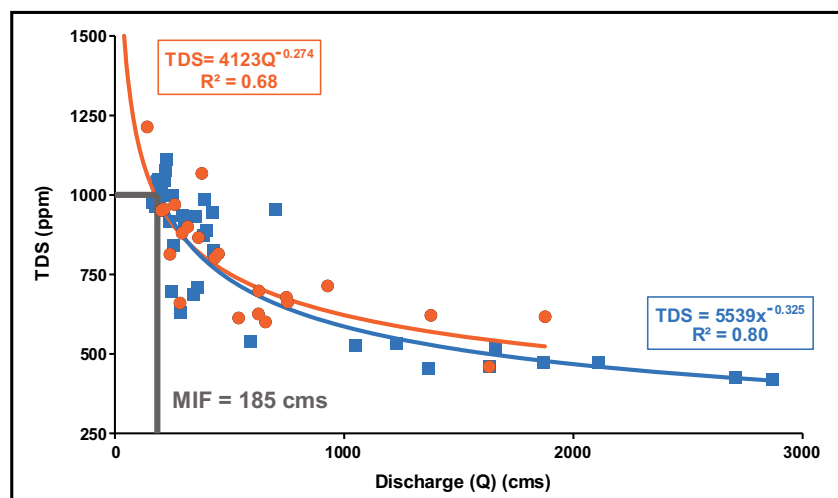
Discharge evolution

Discharge in the upper reaches of the Tigris, above Mosul, has not been significantly affected to date. This should change when the Turkish Ilisu and the Cizre dams are brought online. These upstream changes may significantly affect salinity downstream, as the upstream reaches are the majority of rainfall for the Tigris system. The estimated amount of decrease ranges between 50 and 90% of the current flow at Mosul (Declaration et al. 2006).

Discharge in the Tigris near Baghdad is most affected by the Iraqi Lake Tharthar system. While it may be one of the most important factors for salinity in the downstream portions of the Tigris, data on the amounts and timing of flow diversions are not available for the system. The diversion of the flow of the river at Baghdad, utilizing the resource for adding to the Euphrates, and evaporative losses in Lake Tharthar contribute to the decreased discharge at Kut. This diversion also adds a significant amount of salinity to the downstream portions of the Tigris.

Discharge in the lower reaches of the Tigris is most significantly affected by changes in the Diyala River in Iraq and Iran. The Iranian Karkheh dam primarily affects the marshes in Iraq, not the Tigris itself. The downstream reaches of the Tigris River are experiencing water shortages and an increase in salinity caused by dams constructed at the upper Tigris River Basin (Buringh 1960; FAO 1970; UN-ESCWA 2013; Moyel and Hussain 2015).

Fig. 5 Minimum instream flow at Kut using a 3-year annual analysis as blue data squares and a blue best fit exponential line. Minimum instream flow at Baghdad and Kut using a dry month analysis in orange circle data with an orange best fit line. Heavy gray line indicates WHO limit for drinking water salinity at 1000 ppm and average MIF of 185 cms



Salinity evolution

The Tigris has been utilized as a water resource for human civilization since the beginning of recorded history. Only in recent times, since the 1970s, significant increases in salinity have been observed in the Tigris from Baghdad and downstream. The construction of large upstream dams and the use of Lake Tharthar as a storage system are the direct cause of this increase. These hydraulic controls systems exist in Turkey, Iraq, and Iran, thus limiting the ease of evaluating basin-wide management approaches. The upstream portions of the river have not seen significant salinization to date (Odemis et al. 2010).

Salinity was worse in the downstream reaches of the Tigris during the 1980s. This is interpreted as the results of the release of stored evaporate minerals and evaporation from the Lake Tharthar system. Both accumulated halite from the historic period when the lake was a dry wadi and more recently as evaporative flood control. Additionally, as a gypsum doline, the system had a significant amount of soluble minerals available from the Fatha formation. These contributions are poorly characterized but are evident in the increase in sulfate and chloride in waters south of Baghdad (Al-Shujairi et al. 2015). The amount of evaporation has been evaluated at 2.86 bcm/year. This is more than twice the amount of water needed for the city of Baghdad (1.28 bcm). Future work evaluating the sulfate and chloride along portions of the Lake Tharthar system and the greater Tigris would allow a better understanding of the interactions between soluble minerals stored in the vadose zone along the Tigris and soluble formations that may be accessed through changes in storage and flow along the Tigris.

Salinity management

No basin-wide salinity management scheme exists for the Tigris. Salinity control measures are proposed hereafter to lower the Tigris' salt load downstream from Samarra. These measures are considered the best management practice currently possible. The first proposed measure is to minimize the use of Tharthar Lake as a water supply reservoir and use it for flood control only. In this case, the needed water supply to augment the Euphrates may be delivered via the Tharthar Irrigation Channel instead of the lake. The lake should be replaced by the proposed Makhoul dam, or an alluvial groundwater storage option should be evaluated to minimize evaporative losses. Makhoul is located at about 100 km upstream from Samarra (Fig. 1). These options are considered long-term solutions, whereas eliminating Tharthar Lake as storage can be implemented more quickly.

Second is to prevent any saltwater flow into the Tigris, downstream of Kut, from Hour al Shiwiaja and from the Chabbab Tributary. The existing flow regime impacts the

Amara water supplies. The water of these two sources could be diverted to local evaporative ponds or to the planned East Tigris Drain (ETD) (Oosterbaan 2003). The ETD would provide a major drain and will serve agricultural projects to the east of the Tigris. The other alternative is to divert all saline waters that originates from the east of the Tigris to a system of evaporation ponds. More studies are needed to evaluate alternatives.

The third measure is the environmental flow. It is the most practical option and needs no major hydraulic structures. The environmental flow was recommended by the United Nations Environmental Program on a report published in 2001 (Partow 2001). As it is calculated above for the Tigris River, the environmental flow is approximately 185 cms. This flow should be released from the Kut Barrage toward Amara. The salinity of the discharge to Amara should not exceed 1000 ppm to maintain the UN freshwater standard for the river. The MIF requires a full collaboration and "compliance with international treaties, particularly the United Nations Convention on the Law of the Nonnavigational Uses of International Watercourses (1997)" (Partow 2001) by the riparian countries Turkey, Iraq, and Iran. This may be achieved through a basin-wide transboundary management plan approved and implemented by the riparian countries.

Conclusions

The salinity of the Tigris River has increased due to development along the watercourse, primarily due to changes in Iraq and Iran. The majority of these changes were observed since the 1970s. Future developments in Turkey may further increase salinity in the river. Understanding the historical changes in salinity in the Tigris is required for future water management in the basin.

One significant cause of salinity increase in the Tigris is the decrease in discharge in the lower reaches of the river due to dams upstream. The Tigris is heavily regulated at the upstream reaches, and discharge to the lower reaches is decreased by 62% at Kut Station. The river discharge is expected to decrease further downstream after the completion of the Ilisu and the Cizre Dams in Turkey. The decrease in river discharge is accompanied with a sharp increase in salinity. The Tigris River salinity in Amara and downstream is above the accepted limits for human consumption. The highest salinity was reached in the period from 1984 to 1994 but is still above 1000 ppm TDS.

Lake Tharthar was constructed in a gypsum doline as a flood and water management structure. The system evaporation and mineral dissolution generate a salinization increase of 340% from inflow to outflow of the system. This is an improvement over the period prior to 1992 when the increase was nearly 600%. Separating the lake as a flood control

structure from the use as a water management structure could limit the salinization of the Tigris waters that are passed through the system. Evaluation of the detailed salinity mechanisms in the lake may allow other management solutions to alleviate the situation, but a detailed study would be required. Any changes in inflow of salinity sources would assist with managing salinity, and several alternative hydraulic structures are either available or have been previously proposed.

Another possible management option to deter the high salinity problem in the lower reaches of the Tigris is to institute a MIF of 185 cms. This discharge represents approximately 15% of the mean annual historical flow of the Tigris downstream of Baghdad. This management option requires cooperation across international borders to control salinity. Turkey has the ability to control upstream flow. Iraq can manage salinity by eliminating Lake Tharthar from the flow system and controlling other saline inputs. Iran can manage discharge to the lower reaches of the Tigris. Implementation of a minimum instream flow for the Tigris River will not be a trivial scientific or political exercise. Without salinity management of the system, salinity is expected to rise limiting the habitable areas along the river.

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