UNDERSTANDING HYDROLOGIC VARIABILITY FOR BETTER SURFACE WATER ALLOCATIONS IN THE KARKHEH BASIN IRAN[1]

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ABSTRACT

Water-limited environments occupy about half of the global land area and are highly sensitive to change due to scarcity and variable distribution of water and nutrients. The Karkheh basin in Iran is in a water limited region which exhibits increasing competition for scarce water resources between irrigation, domestic, hydropower and environmental needs. Increasing demands for water are making sustainable water management more and more difficult particularly because of lack of understanding of basin hydrology and impacts of water resource development on different users across the basin. An in-depth study was conducted to examine the inter-annual and long-term variability of surface water resource using daily stream flow data from 1961 to 2001 at seven key locations across the Karkheh basin. The water accounting at basin scale was carried out using the available information for the water year 1993-94, which is considered in Iran as the reference year for future development and allocation of water resources in the Karkheh basin. The analysis reveals that water allocation planning on the basis of mean annual surface water availability can only provide a supply security of about 45 %, ranging from 40 to 52 percent. Although, the water allocations to different sectors are lower than the available resources and the competition among different sectors of water use is minimal during the study period, it would be extremely difficult to meet the demands in future i.e. by 2025, as planned allocation will reach close to the annual renewable water resources available in an average climatic year. The competition among irrigation and other sectors will keep increasing in future, particularly during dry years. The analysis conducted in this study is helpful in gaining further insights into the hydrological variability of surface water resources and incorporating it into water development and allocation strategies that will contribute in ensuring the sustained productivity from irrigated agriculture and other uses of water in the coming decades.

Keywords: Surface water, variability, flow duration analysis, water allocation, Karkheh basin, Iran

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INTRODUCTION

Arid, semi-arid and sub-humid regions are called Water-Limited Environments and occupy about half of the global land area (Parsons and Abrahams, 1994). Scarcity and variable distribution of water and nutrients make these environments highly sensitive to change. The pressure on water and other natural resources is increasing in these areas as demands for water for human uses are growing rapidly (Newman et al., 2006). The Karkheh Basin of Western Iran (Figure 1), a semi-arid to arid region, has a fragile balance between environment and human uses of natural resources and there demands for water are increasing and sustainable management of water resources has become an important issue. The main challenges related to land and water resources are land degradation, soil erosion, low water and land productivity, groundwater depletion and growing competition for water among upstream and downstream areas and among different sectors of water use such as irrigation, domestic, hydropower and environment (CPWF, 2003). In this river basin, massive irrigation development is on the way, but the knowledge and understanding of basin hydrology (including the water balance variations in space and time) and impacts of these developments on other users and water uses across the basin are patchy (CPWF 2003&2005; Asfrafi et al., 2004).

Quantitative knowledge of basin hydrology becomes essential as water management needs become complex. Molle et al. (2004) concluded that as water demands increase and more and more water is allocated to different uses, the management of water resources becomes increasingly complex due to range of factors such as upstream-downstream impacts, increasing impacts on environment and changes in *de facto* water rights. They have argued that under such conditions, increasing the knowledge of the basin hydrology is essential for constructing a sound and sustainable water regime. A sound knowledge of basin hydrology is essential for effective water allocation policies so that third party impacts can be avoided, minimized or mitigated (Green and Hamilton 2000). Hydrological analysis provides the basis of detailed accounting of water use and productivity (Molden and Sakthivadivel 1999). It is a basic requirement for water resources development and management evaluations and decision making related to: a) Assessment of surface water and groundwater availability, b) understanding the balance of actual use in comparison with resource availability; c) improving water allocation decisions; d) monitoring the performance of water use; and e) formulating environmental flow requirements and working out ecosystem restoration strategies.

The International Water Management Institute (IWMI) is conducting research through the Karkheh Basin Focal Project in Iran, funded through Challenge Program on Water and Food (CPWF), in order to address some of these issues and challenges. The main aims of the Basin Focal Project for Karkheh (BFP Karkheh) are to provide comprehensive and integrated understanding of the water, food and environment issues in the Karkheh basin. This paper provides an overview of the surface water hydrology of the Karkheh basin and study the nature of its spatial and temporal variability. The basin level water accounts are also provided and the broader issues related to hydrology and water management are highlighted.

METHODOLOGY

Salient features of the Karkheh basin

The Karkheh river basin is located in western part of Iran (Figure 1). The drainage area of the basin is 50,764 km^2, out of which 80 % is part of the Zagros mountain ranges of Iran. About 60 % of the basin area is in the elevation range of 1000-2000 meter above sea level (m asl), and about 20 % is below 1000 m asl. Agriculture and human settlements are mainly found in the valleys of the upper basin and in the arid plains in the lower parts, where the river eventually terminates in the Hoor-Al-Azim Swamp, a large transboundary wetland shared with Iraq. The quality of river water is generally good (electrical conductivity < 500 µS/cm), although it becomes progressively more saline in the South Karkheh sub-basin as it flows downstream of the newly constructed Karkheh dam, with electrical conductivities reaching above 3000 µS/cm.

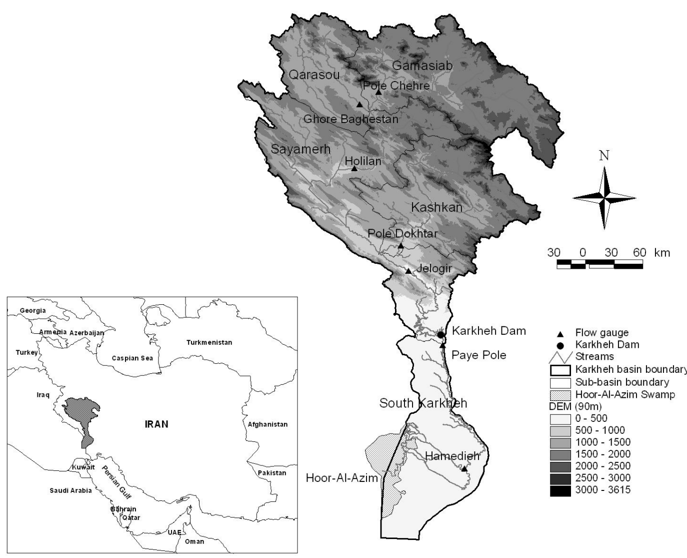

Figure 1. Location of the Karkheh basin in Iran and some of its salient features.

Climate is semi-arid in the uplands (in the north) and arid in the lowland (south). The precipitation (*P*) in the Karkheh basin exhibits large spatial and temporal variability. Generally, the precipitation rates are higher in the upper parts of the basin compared to the lower areas. The mean annual precipitation in the basin is about 450 mm/a, ranging from 150 mm/a in the lower arid plains to 750 mm/a in upper mountainous parts. (JAMAB 1999, Ashrafi et al., 2004). Temporal trends show that about half of the total precipitation falls in winter months (January-March), whereas summer (July-September) rainfall is negligible (less than 2 % of the annual total). The remaining portion is equally distributed over spring (April-June) and autumn (October-December) seasons. Evaporation (*E*) demand is generally higher than precipitation and *E-P* is highest downstream in the south Karkheh sub-basin. Figure 2 shows monthly variations in rainfall, temperature and potential evapotranspiration in upper and lower Karkheh basin.

The basin scale water balance analysis for the year 1993-94 shows that, on average, annual precipitation in the basin totals about 25×10^9 m^3/a (JAMAB 1999). About two-thirds of this water (16.4×10^9 m^3/a) falls on the hilly areas and the plain areas receives about 34 % or 8.5×10^9 m^3/a of this water. About 66 % (16.4×10^9 m^3/a) of total precipitation is returned to atmosphere as evaporation and crop water use (interception, evaporation from bare lands and plant transpiration), without contributing to surface runoff or groundwater recharge. The renewable water of the basin accounts for 34 % of the total precipitation, equivalent to about 8.6×10^9 m^3/a, and represents the sum of surface water and groundwater. Out of 7.4×10^9 m^3/a of the streamflows 2.5×10^9 m^3/a (or 34 %) was diverted to various uses in the year 1993-94. Groundwater contributed about 1.7×10^9 m^3/a for agriculture, domestic and industrial uses in 1993-94. The total irrigation water diverted from the surface and sub- surface resources in the basin was about 3.9×10^9 m^3/a. Surface water and groundwater contributions to total irrigation water diverted at basin scale were 63 % and 37 %, respectively. Based on the JAMAB (1999) study, 1993-94 has been taken as a reference water year for the future water allocation planning in the Karkheh basin. The detailed water allocations for different sectors are provided in Table 1 (JAMAB 2006).

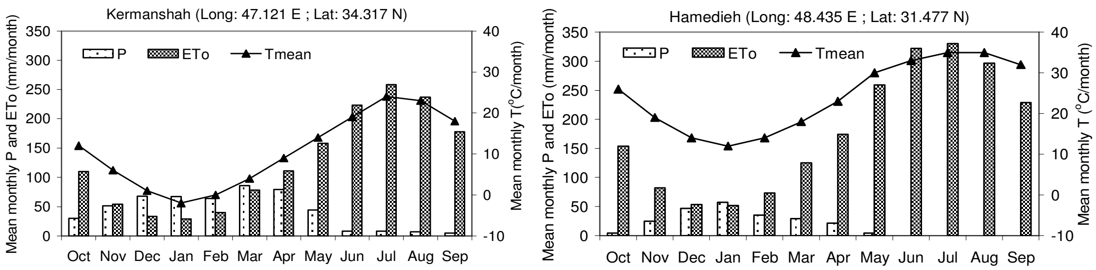

Figure 2. Mean monthly precipitation (P), reference evapotranspiration (ETo) and mean monthly temperature (Tmean) during 1961-1990 for a water year (October to November) in upper and lower Karkheh. (Data accessed through IWMI Integrated Data and Information System (IDIS): http://dw.iwmi.org/IDIS_2007/clickandplot.aspx

Table 1. Current and planned water allocations in the Karkheh Basin, Iran

Sectors	Water allocation in different years (10^6 m^3/a)					
	2001	2006	2011	2016	2021	2025
Rural areas	59	62	66	69	70	67
Urban areas	203	231	242	259	278	295
Mining	0	1	1	1	2	2
Industry	23	30	57	76	93	113
Irrigated agriculture	4149	6879	6814	7135	7476	7416
Fish farming	14	119	249	379	477	510
Environment	500	500	500	500	500	500
Total	**4949**	**7822**	**7929**	**8419**	**8896**	**8903**

Notes: 1) The water sources are surface water, groundwater and reservoirs; 2) Source: JAMAB 2006

Data and Methods

In the Karkheh basin, about 50 streamflow gauging stations were installed after 1950, of which only 24 have been measured continuously. Seven stations on the main rivers (as marked in Figure 1) were selected for the time-series analysis of the hydrologic variability. The rationale for selecting these stations includes their geographical importance, availability of consistent length of records and longer time series. Out of these seven stations, three stations (Pole Chehre at Gamasiab river, covering drainage area of 10860 km^2, Ghore Baghestan at Qarasou river, covering drainage area of 5370 km^2 and Pole Dokhtar at Kashkan river, covering drainage area of 9140 km^2, are located at the outfall of their corresponding sub-basins. Holilan at Saymareh river, covering drainage area of 20860 km^2, represent the combined effect of the hydrologic characteristics of the upstream sub-basins Gamasiab and Qarasou. Jelogir station, covering drainage area of 39380 km^2, is located upstream of Karkheh dam and the Paye Pole station located downstream of the Karkheh dam, covering drainage area of 42620 km^2, is important for downstream flows below the Karkheh dam and also it is an outlet of the four upper sub-basins into South Karkheh sub-basin. Hamedieh station at Karkheh river, covering drainage area of 45977 km^2, is the last gauging station before Karkheh river routes towards Hoor-Al-Azim Swamp. A time series analysis for a period of 1961-2001 was carried out using the daily data of these stations. Mean monthly flows are estimated to understand spatial and inter-annual variations. Longer term mean and median statistics have been calculated for assessing the flow availability at annual scale. Flow Duration Curve (FDC) analysis was carried out to further understand the hydrological variability i.e., high, low and medium surface water availability (Linsley et al., 1982). Some of the important exceedance percentiles of streamflow (e.g. Q_5, Q_{10}, Q_{25}, Q_{50}, Q_{75}, Q_{90}, Q_{95}) were also extracted from the FDC analysis.

The IWMI water accounting framework (Molden and Sakthivadivel 1999) was applied for basin level water accounting. This framework provides a unique way of distinguishing different water use categories such as net inflow, process depletion, non-process depletion, non-beneficial depletion, committed- and uncommitted-outflows. The water accounting framework was applied for the water year 1993-94, as most of the required information was available for this period. The required data for this analysis is extracted from the study of JAMAB (1999).

RESULTS AND DISCUSSION

Spatial and temporal variability of daily streamflow regimes

The mean daily streamflows show large variability within a year and between the years, as exemplified by Figure 3&4. However, the general pattern of streamflows is quite synchronized when different streams or flow behavior at different locations on a single river is compared. The high flow events are mainly concentrated during the months of November to May. The duration of these events vary largely depending upon the precipitation timing and snow melt dynamics. Generally high flow events of small duration (i.e. 1-5 days) occur due to high to rainfall events, but, the high flows prevailing for few weeks to couple of months, mainly observed during February to May, are caused by the snow melt and combined effect of both snow melt and rainfall. The low flow regime is observed during the months of June to October and the lowest streamflows are recorded in September. The high inter-annual variability is observed all across the Karkheh basin (Figure 4), which is mainly governed by the temporal variability of climate. The other factors such as land use, geology, soils and topography cause the differences in flow regime of different rivers across the basin. The flow duration analysis based on daily data is shown by Figure 5 and few important exceeding percentiles used in water resources development and management are provided in Table 2. As indicated by the shape of the flow duration curves (Figure 5), the two upper sub-basins, Gamasiab and Qarasou, show quicker runoff response and less stable base flow regimes compared to Kashkan sub-basin located in the middle part of the basin. This is illustrated by steeper slopes of FDCs observed at Pole Chehre station at Gamasiab river, Ghore Baghestan station at Qarasou river, and by comparatively less steeper FDC slope for Pole Dokhtar station at Kashkan river. The main reason for high baseflow contribution in case of Kashkan sub-basin is the higher proportion of forest area which leads to higher infiltration rates which later slowly discharges to rivers via sub-surface routes. The other reason could be comparatively higher rates of water uses for agricultural purposes in upper sub-basins, particularly in Gamasiab sub-basin. The flow regime of Karkheh river can be stated as the net effect of the major tributary rivers namely Gamasiab, Qarasou, Kashkan and Saymareh. The flow regime of Karkheh at Jelogir, Paye Pole and Hamedien are largely similar to each other, with slightly more stable baseflows in case of Paye Pole. This could be attribute to the presence of Karkheh lake just above the Paye Pole station causing some attenuation in the streamflows. It is anticipated the flow regime of Karkheh river at Paye Pole and Hamedieh may have considerably changed from its natural variability due to Karkheh dam operations after the year 2000, but, this issue is not discussed here as it is beyond the scope of this paper.

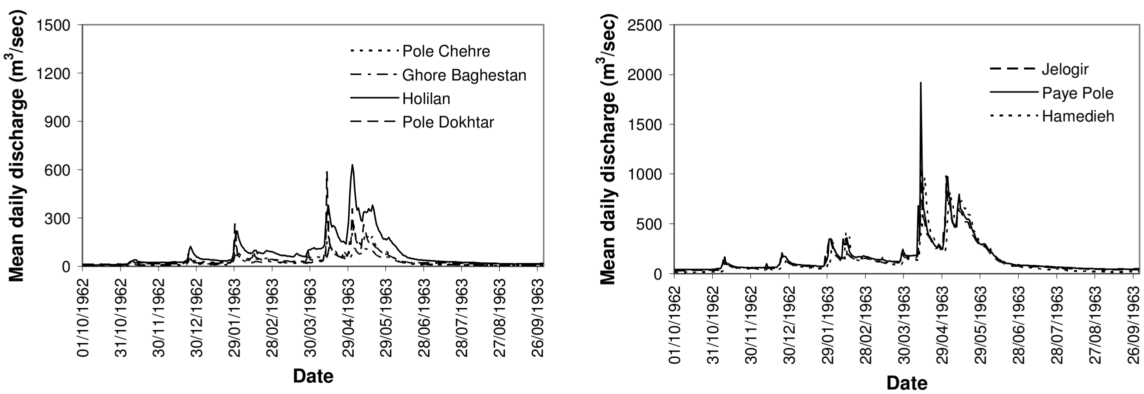

Figure 3. Intra-annual variability of mean daily streamflows, as illustrated by the data of water year 1962-63.

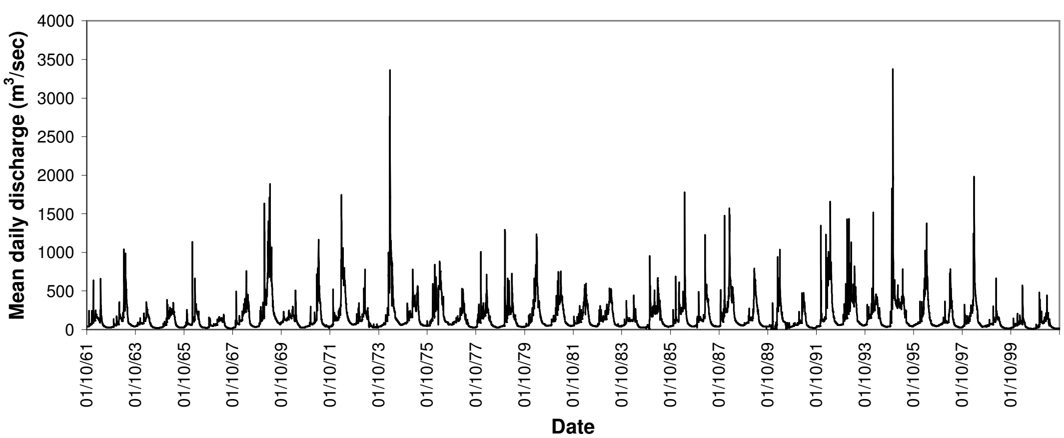

Figure 4. View of the inter-annual variability of mean daily streamflows, as illustrated by streamflows at Jelogir station at the Karkheh river (1961-2001).

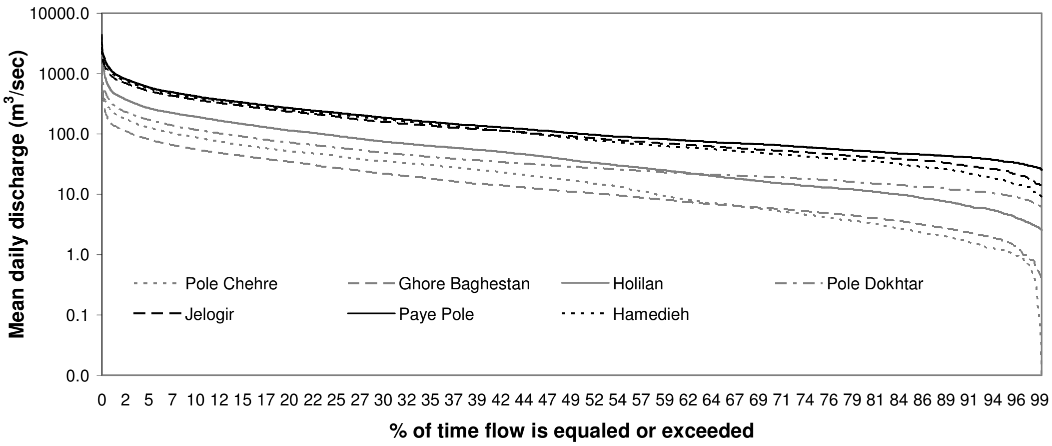

Figure 5. The flow duration curves (FDCs) of the selected locations in the Karkheh basin, Iran. (FDCs plots are based on daily streamflow data of October 1, 1961 to September 30, 2001).

Table 2. Various exceedance percentiles of daily streamflow at the selected locations in the Karkheh basin, Iran

Flow gauging station	Exceedance percentiles of mean daily streamflow (m^3/sec)								
	$Q_{0.1}$	Q_1	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{75}	Q_{90}	Q_{95}
Pole Chehre	538	245	127	87	42	16	4	2	1
Ghore Baghestan	455	149	81	55	27	11	5	3	2
Holilan	1870	518	266	192	91	36	14	7	5
Pole Dokhtar	718	325	171	116	59	29	18	12	10
Jelogir	1723	924	516	365	191	90	48	31	24
Paye Pole	2217	1120	589	418	220	101	59	42	35
Hamedieh	1654	1018	563	393	206	84	41	24	17

Note: These exceedance percentiles are extracted from FDC analysis.

Spatial and temporal variability of monthly streamflows

Monthly discharges at the selected river stations are shown in Figure 6. River flows show a consistent behaviour as depicted by the rainfall patterns in the basin. The hydrograph peaks occur in March and April, roughly one month in lag of peak rainfall. This could be attributed to contributions of snow melt in the winter season, contributions of water into streams after passing through different hydrological pathways (such as groundwater) as well as routing time of rainfall within river reaches of the basin. The peak flows are observed in the month of April at all the plotted stations whereas minimum flows occur in the month of September. Although most of the water flows in winter (about 41 %) and spring (about 39 %) seasons, all the main tributaries of the Karkheh river have some flow all around the year indicating the contribution of base flow to the total annual flow. This could be attributed to the contributions from springs and diffuse groundwater inflows. Visual analysis of the hydrograph (Figure 6) indicates that the contribution of base flow is higher in the spring season and gradually decreases through summer and winter until the precipitation cycle starts again.

The river flows show quite high variability both with respect to space and time, as indicated by high coefficients of variation (CV) in Figure 7. The maximum values of CV are observed for the month of November and it corresponds to river flows at all of the seven selected stations in the basin ranging from 0.96 for Kashkan river at Pole Dokhtar to 1.77 for Gamasiab river at Pole Chehre. Minimum values of CV are observed in February with the spatial variation ranging from 0.44 to 0.53. The annual values of CV fluctuate around 0.47 with the range of 0.41 to 0.54 (Table 3). The comparison of mean and median water availability indicates that the mean values are 0-7 % higher than the median estimates. This exhibits the classic arid and semi-arid hydrology characteristic that the mean is greater than the median, but, in this case, not by a big margin at annual scale (only 4% on average).

This overview analysis shows that the Karkheh river flows throughout the year, although with large monthly variations. The demand for water by agriculture is met through surface water diversion structures (e.g., irrigation canals) but mostly through direct pumping from the rivers in all parts of the basin. The data on the surface water withdrawals was not available, therefore, the analysis of flows, presented above, from upper to lower reaches of the Karkheh basin also accounts for the current levels of abstractions for various uses such as irrigation and domestic. Although the naturalization of streamflows can be made if the withdrawals are known or through indirect ways if the information on daily crop water demand, cropping pattern and cropped area and irrigation efficiencies are available (Masih et al., 2008). A streamflow naturalization approach for agricultural withdrawals in the Karkheh basin has been devised by Masih et al. (2008) for the period of 1987 to 1997. However, it was not possible to carry out naturalization of streamflows over the 40 years of the study period, i.e. 1961-2001, as the required information was not available.

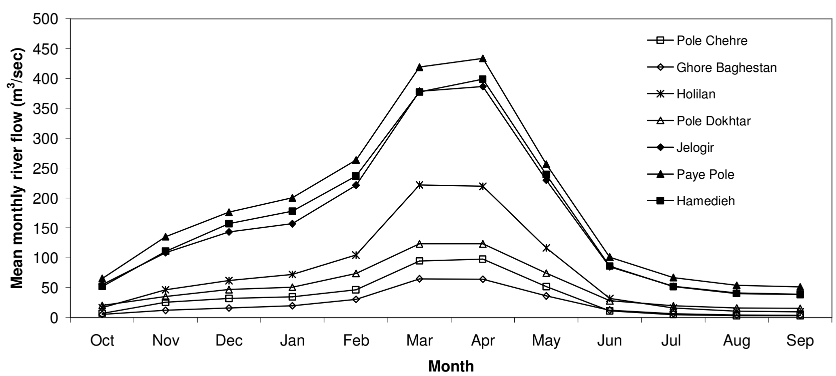

Figure 6. Mean monthly discharge at the selected locations in the Karkheh basin, Iran.

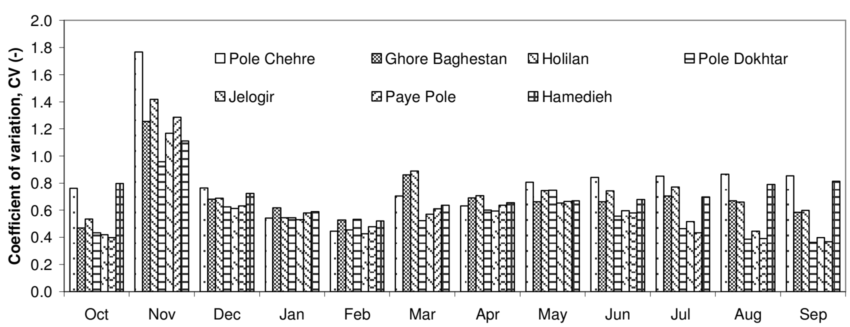

Figure 7. Coefficients of variation (CV) on monthly basis for selected stations.

Table 3. Mean and median annual water availability in the Karkheh basin, Iran.

Flow gauging station	Annual water availability ((10^6 m^3/a)						Difference, % (mean & median)
	Mean	*Standard deviation*	*CV(-)*	*Min*	*Max*	*Median*	
Pole Chehre	1080	540	0.50	198	2851	1003	7
Ghore Baghestan	722	392	0.54	104	1914	712	1
Holilan	2431	1277	0.53	607	6193	2292	6
Pole Dokhtar	1639	667	0.41	645	3206	1637	0
Jelogir	4974	2115	0.43	1790	10773	4692	6
Paye Pole	5827	2512	0.43	1916	12594	5590	4
Hamedieh	5153	2476	0.48	1068	11324	4852	6

Long term variability in annual surface water availability

The long term temporal behaviour in the annual river flows have similar patterns throughout all the sub-basins of the Karkheh basin, whereby high and low flows prevail over all areas simultaneously (Figure 8). The maximum flow of 12.59×10^9 m^3/a occurred in the wet year 1968-69 whereas the minimum flows of 1.92×10^9 m^3/a correspond to the drought year 2000-01, at Paye Pole station. In the time period of this analysis i.e., 1961 to 2001, drought that persisted over more than one year occurred from 1999 to 2001, though the longer term time series do depict both high and low flow years throughout the study period. These large temporal variations indicate high level of supply insecurity for current and further withdrawals for human uses. Flow duration analysis was conducted in order to understand the supply security of mean annual availability of surface water. The analysis of flow duration curves (Figure 9 and Table 4) clearly suggests that planning on the basis of mean annual surface water availability can only provide a supply security of about 45 %, ranging from 40 to 52 % in various parts of the Karkheh Basin. Furthermore, due to the construction of the Karkheh dam and ongoing irrigation schemes in downstream parts, one can anticipate that during the below average/low flow years, the most important conflict would concern retention of water in Karkheh dam for hydropower generation and reduced supplies to the downstream agricultural users whose situation will be exacerbated by soil salinity problems. This would also be accompanied by the diminished flows to riverine ecosystem and floodplains as well as to the Hoor-Al-Azim swamp further downstream.

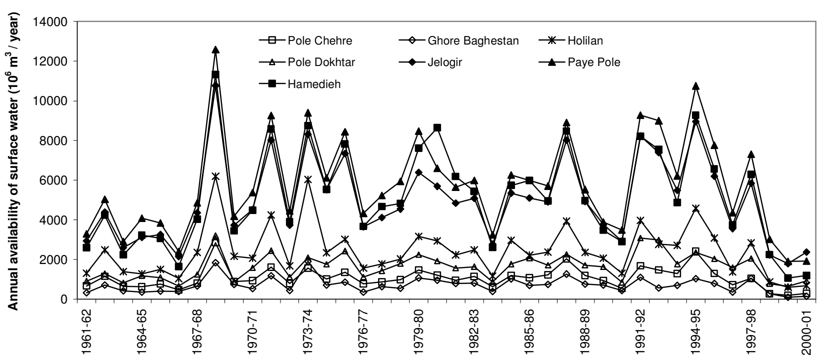

Figure 8. Long term variability in annual surface water availability across the Karkheh basin.

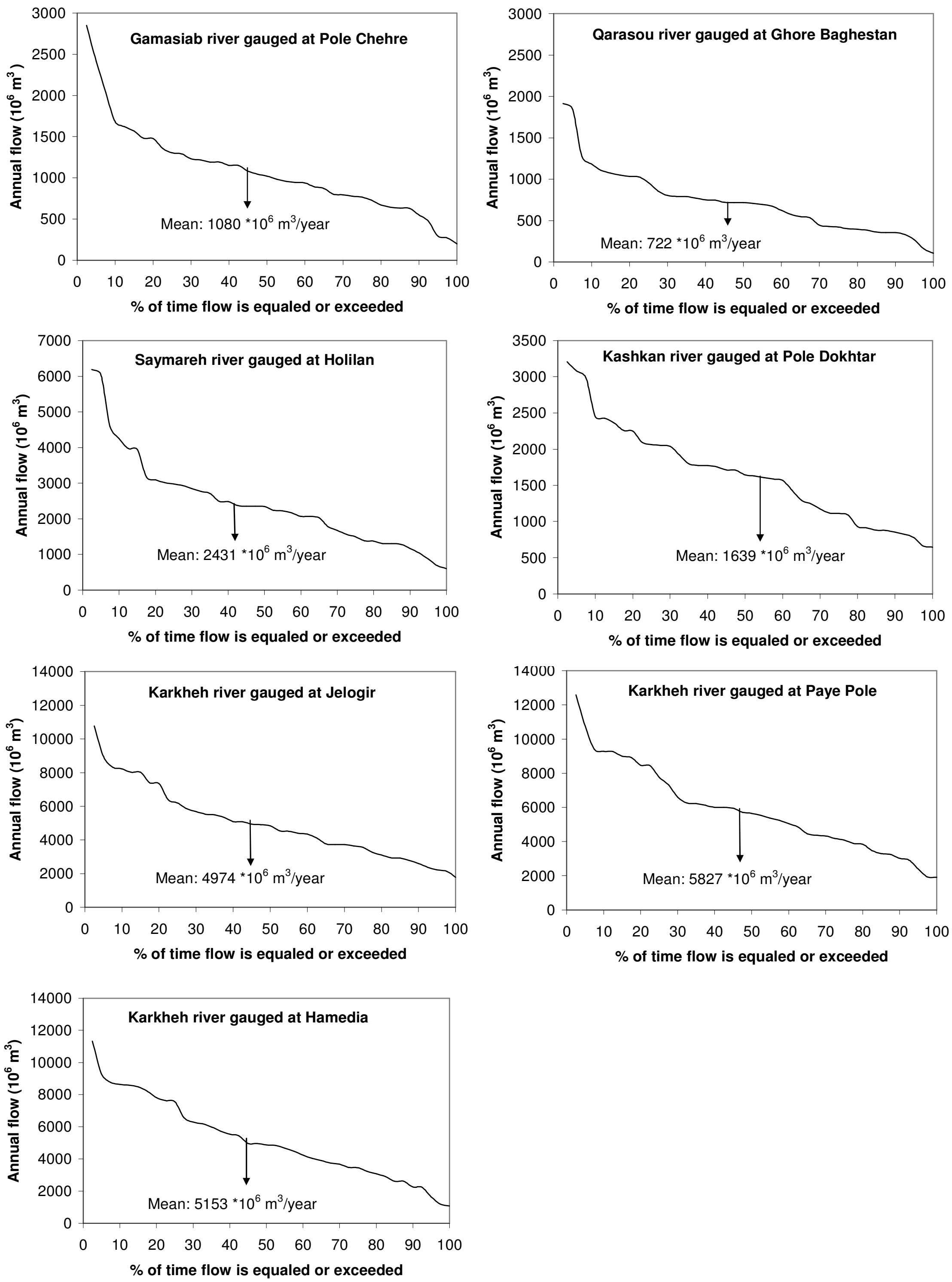

Figure 9. Flow duration curves of the mean annual flow at the selected locations of the Karkheh basin (1961-2001) (note the difference in scales of the y-axis).

Table 4. Various exceedance percentiles of annual volume of river flows at selected flow gauging station across the Karkheh river basin.

Flow gauging station	Exceedance percentiles of annual flow (10^6 m^3/a)						
	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{75}	Q_{90}	Q_{95}
Pole Chehre	2416	1684	1303	1022	766	549	294
Ghore Baghestan	1844	1183	957	716	419	353	268
Holilan	6042	4250	2977	2343	1499	1168	871
Pole Dokhtar	3081	2455	2064	1645	1113	854	778
Jelogir	8958	8227	6193	4836	3562	2601	2230
Paye Pole	10755	9280	7756	5651	4082	3020	2404
Hamedieh	9280	8641	7555	4873	3447	2254	1648

Overview of the basin level water accounting

Using the information from JAMAB (1999), the water accounts of the Karkheh basin for the water year 1993-94 are estimated and provided in Table 5 and Figure 10. The gross inflow, net inflow and total depletion are 24.96×10^9 m^3/a, 25.08×10^9 m^3/a, and 19.94×10^9 m^3/a, respectively. Direct depletion from precipitation constitutes 82% (or 16.39×10^9 m^3/a) of the total depleted water (19.94×10^9 m^3/a) in the Karkheh basin. This water is mainly depleted through cropped areas, pasture, forests and bare lands. Usually this portion is not well accounted for in hydrological studies, planning of basin water resources and accounting for basin water productivity. Rainfed water use has low productivity values when compared to irrigated agriculture (Ahmad et al., 2008). This is mainly due to the fact that stream flow and groundwater can be managed and allocated in most cases, whereas this task is much more complicated if we need to manipulate direct use of precipitation. But there is a need to properly account for this dominant portion of water flows in a basin and look for ways to improve productivity of evapotranspiration in rainfed systems (Rijsberman and Manning, 2006; Ahmad et al., 2008). The portion of irrigation diversions depleted as evapotranspiration from irrigated areas is estimated as 3.21×10^9 m^3/a. This value was derived after subtracting return flows of irrigation water from the total water diverted for the irrigation. The depletion of water in municipal and industrial sectors is very small (only about 0.05×10^9 m^3/a), as most of the water diverted to these sectors generates return flows (about 76 %). The total outflow from rivers is 54 % or 3.99×10^9 m^3/a of the total annual streamflows volume of 7.37×10^9 m^3/a available in 1993-94. The simplest rules of thumb used in determining environmental flow requirements suggest that 50 % of the available fresh water flows are required to maintain excellent conditions in associated riverine ecosystems (Tenant 1976). The minimum environmental flow requirements are usually set to 10 % of the streamflows (Tenant 1976; Tharme 2003), or in many countries, the flow equivalent to Q_{90} (e.g., in Brazil and Canada) or Q_{95} (Australia and United Kingdom) are taken as the minimum environmental flow requirements (Tharme 2003). Based on the values suggested by Tenant (1976), we estimated committed water essentially required to support riverine ecosystem functions in the range of 0.74×10^9 to 3.69×10^9 m^3/a. It should be noted these methods are simple to apply but have the potential for inadvertent misuse because these does not account for specific species/life phase habitat requirements, short-long-term changes in flow rates, seasonal variability or channel geometry.

Table 5. Basin level water accounts of the Karkheh Basin for the year 1993-94.

Water accounting indicators	Value (10^9 m^3/a)	Total (10^9 ^{3}/a)
Inflow		
Gross inflow		24.96
Precipitation	*24.96*	
inflow from outside of the basin	*0*	
Storage Change		-0.12
Surface	*0*	
Sub surface	*-0.12*	
Net Inflow		**25.08**
Depletion		**19.99**
Actual evapotranspiration (*ET*)	19.94	
ET from plains and hills (including all land uses)	*16.39*	
ET from Irrigation diversions to agriculture	*3.21*	
ET from lakes and wetlands	*0.030*	
ET from groundwater evaporation	*0.31*	
Municipal and Industrial	0.05	
Outflow from basin		
Total outflow		**5.09**
Surface outflow from rivers	*3.99*	
Surface outflow from drains	*1.10*	
Subsurface outflow	*0.00*	
Committed water (assumed for environment flows)		0.74 to 3.69*
Uncommitted outflow (Total outflow – Committed water)	5.09-3.69 to 5.09-0.74	1.40 to 4.35

Notes: Data Source: JAMAB (1999). * values are calculated based on 10 % and 50 %, respectively, of the total annual streamflows (7.374×10^9 m^3/year) required for instreamflows, as suggested in Tenant (1976).

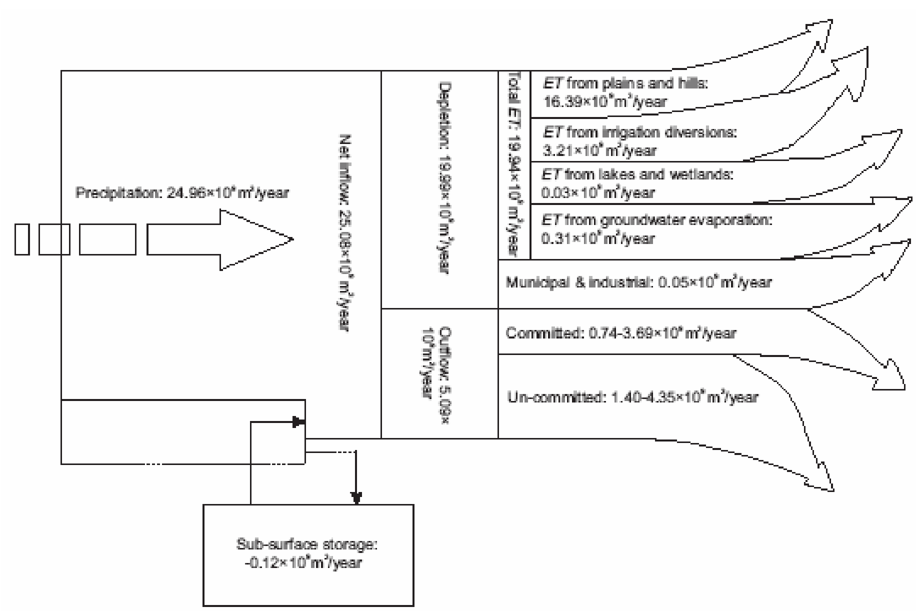

Figure 10. Schematic representation of the basin level water accounting of the Karkheh Basin (1993-94).

It should be understood that most of the environmental flow assessment studies recommend that in order to keep healthy, resilient and productive riverine ecosystems, water management policies should aim to restore the natural flow regime of the rivers, including flow variability, as much as possible (e.g., Poff et al. 1997; Postel and Richter 2003). This requires detailed assessment of the flow characteristics of Karkheh basin streams (e.g magnitude, timing, frequency and duration, rate of change, floods and low flows etc) and to explore further how to make balanced allocations to environment and human demands under varying present and future flow conditions.

However, based on these simple assumptions uncommitted outflow from rivers, in an average year, available for further allocation to various uses, would be in the range 1.070×10^9 to 4.02×10^9 m^3/a. The situation in 1993-94 further highlights the competition between ecosystems and human needs in the view of ongoing/future water resource development in the basin (Table 1). The future planning is to allocate about 8.903×10^9 m^3/a of water to different sectors of water use by the year 2025, among them irrigation share is the biggest (7.416×10^9 m^3/a). The planned allocations are almost equal to the renewable water supplies in an average year (i.e., during the year 1993-94, which is taken as a reference year for detailed assessments and future allocation planning). The flow duration analysis suggests that the planning on the basis of mean annual flows can't provide required streamflows every year. The anticipated situation in low flow years may be more stressful to the ecosystem health, if water allocations to human uses remain at the same levels. This also highlights the increasing stress on groundwater resources that are already overexploited in some areas and greater challenge for managing dam supplies for hydropower generation, irrigation and environment. The water allocated to environmental sector is fixed to around 0.5×10^9 m^3/a (Table 1), which is even below 10 % of the streamflows available in the reference year 1993-94. This indicate that the further studies are required to assess the reasonable allocations for the environment, also looking into the temporal patterns of streamflows whereby streamflows should follow some extent natural patterns of flow variability. The management of releases from Karkheh dam and other reservoirs would be critical to attain that, and will require more detailed scientific studies. Although Karkheh dam is a carry over dam, having designed storage capacity of about 7.5×10^9 m^3/a (and live storage capacity of about 4.7×10^9 m^3/a), and therefore, water stored during high flow years can be used to meet demands during dry years. However, meeting demands of all sectors would be extremely difficult in future, particularly during dry spells. Karamouz et al. (2006) have studied the possibilities of conflicts arising among urban, agricultural and environmental sectors located downstream of Karkheh dam due to water quality deterioration as a result of increased water allocation to agriculture and urban sectors under the current water allocation policies. They have shown that if the current water allocation policies are followed, then by the year 2021 the quality of water flowing to the Hoor-Al-Azim Swamp would be deteriorated to the unacceptable levels during most of the time in a year as the result of decreased quantity of flows and high salinity and agrochemical loads coming from agricultural return flows.

CONCLUDING REMARKS

The study demonstrates that the hydrology of the Karkheh Basin is governed by the natural climatic characteristics of a semi-arid to arid region, which has unique interactions with its diverse drainage areas, mostly located in the Zagros Mountains. The hydrological response of surface runoff from the upper and middle parts of basins is generally mirrored by the variability in precipitation and complex interactions with the diverse hydrological storages (such as groundwater, soil water and snow melt) and land use characteristics. High spatial and temporal variability is a strong feature of the Karkheh basin hydrology and about 80 percent of its surface waters flow in winter (about 41 percent) and spring months (about 39 %).

The flow duration analysis reveals that water allocation planning on the basis of mean annual surface water availability can only provide a supply security of about 45 %, ranging from 40 to 52 % in various parts of the Karkheh Basin. Although, the water allocations to different sectors are lower than the available resources and the competition among different sectors of water use is minimal during the study period, but, it would be extremely difficult to meet the demands in future i.e., by 2025, as planned allocation will reach close to the annual renewable water resources available in an average climatic year. The competition between irrigation and other sectors will increase further in future, particularly during dry years. The analysis conducted in this study will be helpful in gaining further insights into the hydrological variability of surface water resources, and incorporating it into water development and allocation strategies will contribute in ensuring the sustained productivity from irrigated agriculture and other uses of water in the coming decades. Sustainable management of water resources in the Karkheh basin urgently require more detailed studies on the management of the flow regime close to the natural variability as much as possible, estimation of environmental flow requirements both in terms of temporal and spatial dimensions and setting up river/reservoir management targets that can minimize the negative impacts for the environment while ensuring the food security and economic gains from the use of water.

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