Journal of Hydrology 454–455 (2012) 56–63

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A potential approach for low flow selection in water resource supply and management

Ying Ouyang *

USDA Forest Service, 100 Stone Blvd., Thompson Hall, Room 309, Mississippi State, MS 39762, United States

ARTICLE INFO

Article history:
Received 28 November 2011
Received in revised form 20 April 2012
Accepted 25 May 2012
Available online 9 June 2012
This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Muhammad Ejaz Qureshi, Associate Editor

Keywords:
7Q10
Frequent-low approach
Low flow selection
Water resource management

SUMMARY

Low flow selections are essential to water resource management, water supply planning, and watershed ecosystem restoration. In this study, a new approach, namely the frequent-low (FL) approach (or frequent-low index), was developed based on the minimum frequent-low flow or level used in minimum flows and/or levels program in northeast Florida, USA. This FL approach was then compared to the conventional 7Q10 approach for low flow selections prior to its applications, using the USGS flow data from the freshwater environment (Big Sunflower River, Mississippi) as well as from the estuarine environment (St. Johns River, Florida). Unlike the FL approach that is associated with the biological and ecological impacts, the 7Q10 approach could lead to the selections of extremely low flows (e.g., near-zero flows) that may hinder its use for establishing criteria to prevent streams from significant harm to biological and ecological communities. Additionally, the 7Q10 approach could not be used when the period of data records is less than 10 years by definition while this may not the case for the FL approach. Results from both approaches showed that the low flows from the Big Sunflower River and the St. Johns River decreased as time elapsed, demonstrating that these two rivers have become drier during the last several decades with a potential of salted water intrusion to the St. Johns River. Results from the FL approach further revealed that the recurrence probability of low flow increased while the recurrence interval of low flow decreased as time elapsed in both rivers, indicating that low flows occurred more frequent in these rivers as time elapsed. This report suggests that the FL approach, developed in this study, is a useful alternative for low flow selections in addition to the 7Q10 approach.

Published by Elsevier B.V.

1. Introduction

Water use, supply, conservation, and sustainability have emerged as critical issues in USA and around the world. In recent decades, extensive usages of surface and groundwater leading to overdrafts and declines in water resources have resulted in water shortages and water quality degradation, which are increasingly common and are more likely to become severe in the future. As an example, back in frontier days (or around 1950s), the southern USA has historically been considered as a water-rich region that supported a high standard of living and biodiversity. The region is, however, experiencing an increasing water stress due to climate change, land use conversion, and population increase (Sun et al., 2008). Prior to 1950s, there was little or no concern over limits to the seemingly endless water resources in Florida. From 1950 to 1990, the Florida's fresh water withdrawals had increased 158% to 7.5 billion gallons per day serving a population of about 13 million (http://www.ise.ufl.edu/cao/water/in.htm). In the past three decades, withdrawals of groundwater aquifer for agricultural industry have resulted in drawdown of water table by about 7 m and in decline of baseflow for many rivers or streams in the Mississippi Delta region (Pennington, 2011). Therefore, there is a greater need to establish minimum water flows and/or levels required to prevent significant harm to water resources and ecosystems resulting from water withdrawals (373.042 Florida Statutes, http://www.flsenate.gov/Laws/Statutes/2011/373.042).

Low flow selections are essential for water resources management, water supply planning, and ecological restoration. In water management, low flow is used for issuing discharge permits and developing treatment plants. In water supply planning, low flow is used for determining allowable water transfers and withdrawals (Tallaksen and van Lanen, 2004). In ecological protection, low flow is used for assessing stream flow habitats. In general, low flow is a flow of water in a stream during prolonged dry weather (WMO, 1974), a seasonal phenomenon, and an integral component of a flow regime of any river (Smakhtin, 2001). Low flows are normally derived from groundwater discharge or surface water discharge and usually occurs in the same season each year. The magnitude

* Tel.: +1 662 325 8654.
E-mail address: youyang@fs.fed.us

0022-1694/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jhydrol.2012.05.062

of annual low flows, the rate and variability of flows in the absence of precipitation, the duration of continuous low-flow events, and the relative contribution of low flows to the total stream flow hydrograph are the widely used characteristics in hydrology analysis. Low flow also is affected by climate, topography, geology, soils, and human activities (Smakhtin, 2001). With an increased understanding of the importance of water quantity and quality to human consumption, aquatic and terrestrial life, and their adverse ecological and environmental impacts, there is a greater need to assess low flow characteristics.

Several methods have been developed for low-flow analysis, including flow duration curve (FDC) analysis, low flow frequency curve (LFFC) analysis, analysis of flow recessions, and storage-yield analysis (Riggs et al., 1980; McMahon and Mein, 1986; Vogel and Fennessey, 1995; Smakhtin, 2001; Laaha and Bloschl, 2007). Currently, the most commonly used methods for low flow estimation are the FDC and LFFC analysis. The FDC is a relationship between any given discharge value and the percentage of time that this flow is equaled or exceeded. A FDC can be constructed by assembling the flow time series values in a decreasing order, assigning flow values to class intervals, and counting the number of occurrences (time steps) within each class interval. Cumulated class frequencies are then calculated and expressed as a percentage of the total number of time steps in the record period. Finally, the lower limit of every discharge class interval is plotted against the percentage points (Smakhtin, 2001).

In contrast, a LFFC shows the proportion of years when a flow is exceeded. The proportion of years is equivalent to the average interval in years, which also are referred to recurrence interval that the river falls below a given discharge (Smakhtin, 2001). The LFFC is normally constructed based on a series of annual flow minima (daily or monthly minimum discharges or flow volumes), which are extracted from the available original continuous flow series (one value from every year of record) (Harris and Middleton, 1993; Midgley et al., 1994). A major difference between the FDC and the LFFC is that the FDC shows the proportion of time during which a flow is exceeded, whereas the LFFC displays the proportion of years when a flow is exceeded. Neither the FDC nor the LFFC provides information about the length of continuous periods below a particular flow value of interest (Smakhtin, 2001). It should be pointed out that most of low-flow estimation methods require adequate observed stream flow records which are provided from gauged catchments. For ungauged watersheds, the low flow estimation is a challenge and is beyond the scope of this study. An elaborate review of low flow estimation for ungauged watersheds can be found elsewhere (Gustard et al., 2004; Engeland et al., 2006; Laaha and Bloschl, 2007).

Traditionally, the 7Q10 approach has been used to obtain a particular low flow value (Riggs et al., 1980; Telis, 1992; Reilly and Kroll, 2003). The 7Q10 is defined as the lowest average flows that occur for a consecutive 7-day period at the recurrence interval of 10 years, which can also be viewed as a LFFC-based index. Although this approach has provided useful insights in low flow analysis, it is designed for most extreme low flow conditions that exceed 95–99.5% of the time on the flow duration curve (Smakhtin, 2001). These extremes may not occur very often in many watersheds, which would hinder its use for an elaborate analysis of low flows. To this end, a need exists to develop a simple approach to undertake this issue.

The objectives of this study were to: (1) develop a new approach (i.e., the Frequent-Low or FL approach) for low flow selections; (2) compare the 7Q10 approach with the FL approach in low flow selections; and (3) apply the FL approach to analyze low flow characteristics such as recurrence probability and interval of low flows in selected watersheds.

2. Methodology

2.1. Low flow selection

Fig. 1 shows the flowchart for low flow selections with two different approaches, one is the 7Q10 approach (Riggs et al., 1980; Telis, 1992; Laaha and Bloschl, 2007) and the other is the FL (frequent-low) approach. Originally, the FL is one of the five categories (defined in Category 4 below) used in minimum flows and/or levels (MFLs) programs by St. Johns River Water Management District (SJRWMD), Florida, USA. The MFLs are the minimum water flows and/or levels required to prevent significant harm to water resources resulting from water withdrawals (Neubauer et al., 2008; SJRWMD, 2010). MFLs describe how often and for how long the high, average, and low water levels and/or flows should occur to prevent significant harms. When uses of water resources alter the water flows and/or levels below the defined MFLs, significant ecological harms can occur. MFLs have been divided into the following five categories (SJRWMD, 2010; Fig. 2): (1) Minimum infrequent-high (5%): A chronically high surface water level or flow with an associated frequency and duration that allows for inundation of the floodplain at a depth and duration sufficient to maintain wetland functions; (2) Minimum frequent-high (20%): An acutely high surface water level or flow with an associated frequency and duration that is expected to be reached or exceeded during or immediately after periods of high rainfall so as to allow for inundation of a floodplain at a depth and duration sufficient to maintain biota and the exchange of nutrients and detrital material; (3) Minimum average (50%): The surface water level or flow is necessary over a long period to maintain the integrity of hydric soils and wetland plant communities; (4) Minimum frequent-low (80%): A chronically low surface water level or flow that generally occurs only during periods of reduced rainfall and results in dewatered wetlands. This level is intended to prevent deleterious effects to the composition and structure of floodplain soils, the species composition and structure of floodplain and in-stream biotic communities, and the linkage of aquatic and floodplain food webs; and (5)

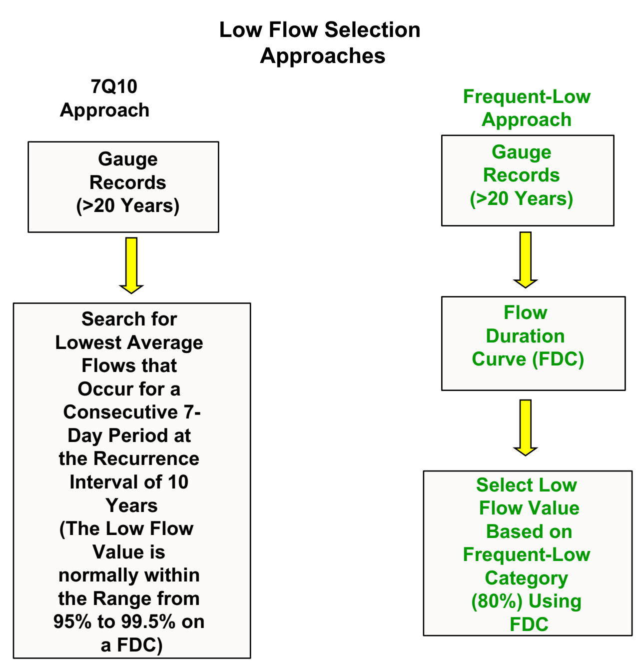

Fig. 1. A flowchart showing the low flow selection with the 7Q10 and FL (frequent-low) approaches.

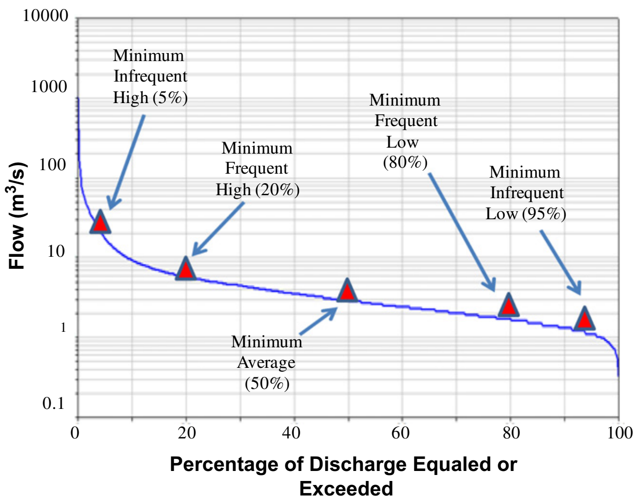

Fig. 2. Flow duration curve related to the five categories of the minimum flows and/or levels (MFLs) program.

Minimum infrequent-low (95%): An acutely low surface water level or flow with an associated frequency and duration which may occur during periods of extreme drought below which there will be a significant negative impact on the biota of the surface water which includes associated wetlands. An elaborate description of MFLs can be found in Neubauer et al. (2008) and SJRWMD (2010). For earlier studies on minimum flows, interest readers are encouraged to consult reports elsewhere (Stalnaker, 1990; Poff et al., 1997; Nilsson, 2000; Bunn and Arthington, 2002).

As shown in Fig. 1, the first step in low flow selection with the FL approach was to obtain the long-term (>20 years) discharge data and then to construct the FDC using the Hydstra model developed by Kisters Inc. (http://www.kisters.net/hydstra-features.html). Once a FDC was constructed, a low flow was obtained from the FDC. As an example, the low flow was 1 $m^3 s^{-1}$ from the FL approach (80% exceeded) based on Fig. 2. This low flow was within the range proposed by Laaha and Bloschl (2007). These authors argued that a low flow can be selected from a FDC within the lower (70%) and upper (99%) percentage bounds.

In this study, we have used the FL category from MFLs as a criterion for selecting low flows based on the following reasons: (1) the 7Q10 approach is suitable for extreme low flow conditions that exceed 95–99.5% of the time on the flow duration curve (Smakhtin, 2001). These extremes usually occur during severe droughts with short duration and very long return intervals; and (2) the FL

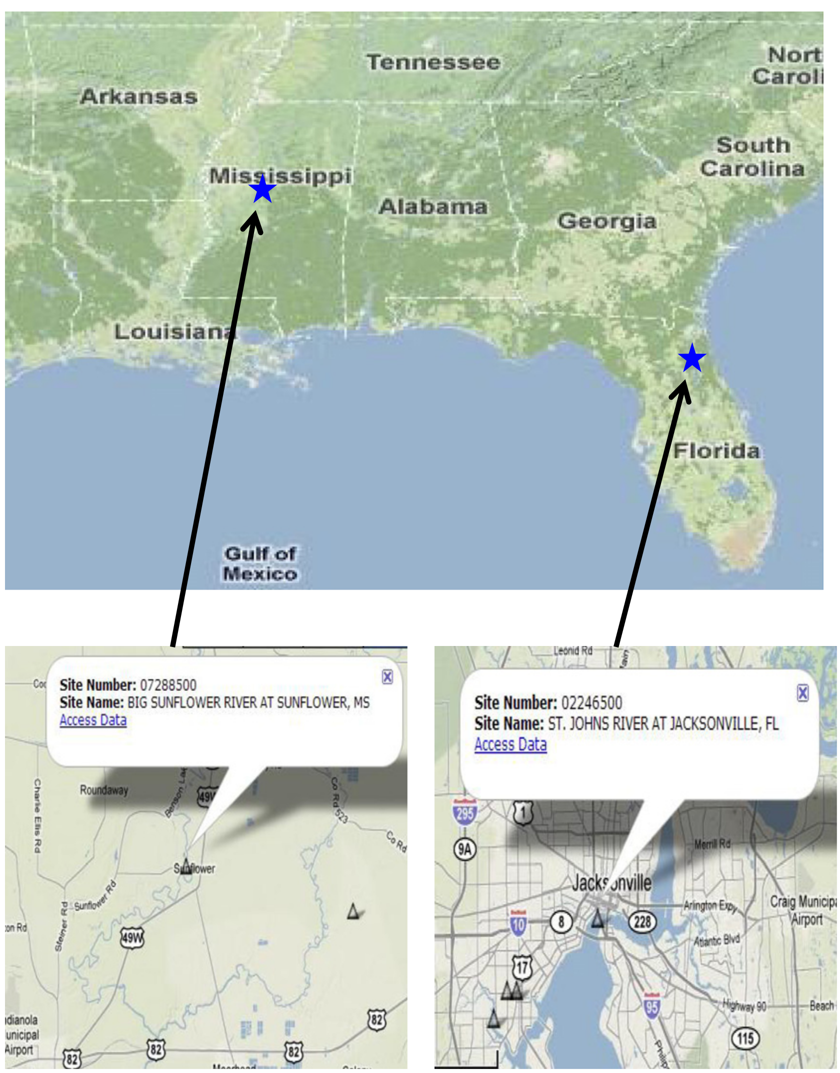

Fig. 3. Location of USGS surface water monitoring stations at the freshwater environment (Big Sunflower River) and the estuarine environment (St. Johns River) used in this study.

Table 1
Comparison of low flows estimated from the 7Q10 and FL (frequent-low) approaches at the estuarine and freshwater environments.

Year	7Q10		FL (Frequent-Low)	
	Low flow (m^3/s)	% of time a low flow equaled or exceeded	Low flow (m^3/s)	% of time a low flow equaled or exceeded
	USGS #02246500 in St. Johns River at Jacksonville, Florida Estuarine Environment			
1981–1991	−424	96	−26	80
1991–2001	−500	96	−44	80
2001–2011	−667	98	−71	80
	USGS #02246500 in Big Sunflower River at Sunflower, Mississippi Freshwater Environment			
1935–1945	4.4	100	5.9	80
1945–1955	2.4	100	5.8	80
1955–1965	2.3	99	4.0	80
1965–1975	2.6	99	4.0	80
1995–2005	0.8	99	3.9	80

approach is within the low flow selection range and the FL category has clearer quantified the effects of low flow on floodplain, biota, and ecosystem. Additional advantages and disadvantages of the 7Q10 and FL approaches were depicted in Section 3. It should be noted that the MFLs program may not explicitly propose to use the frequent low category as a criterion to select low flows as we proposed in this study.

2.2. Study site and data analysis

Data used in this study were obtained from the USGS surface water monitoring stations. Two different geological locations in the southeast USA were selected (Fig. 3): one was from Florida, which represents an estuarine environment, and the other was from Mississippi, which represents a freshwater environment. The USGS monitoring station #02246500 (Latitude 30°19′20″, Longitude 81°39′56″) located in the St. Johns River at Jacksonville, Florida was selected for the estuarine environment. This location has a drainage area of 22921 km^2 and a mean annual rainfall of 1.31 m, and a mean annual temperature of 19 °C. The minimum, mean, and maximum flows are, respectively, −1959.47, 188.40, and 3397.92 $m^3\ s^{-1}$. Land use in this environment is dominated by residential, agriculture, and forestry. The USGS monitoring station #07288500 (Latitude 33°32′50″, Longitude 90°32′35″) located at the Big Sunflower River, Sunflower, Mississippi was selected for the freshwater environment. This location has a drainage area of 1986 km^2 and a mean annual rainfall of 1.24 m, and a mean annual temperature of 18 °C. The minimum, mean, and maximum flows

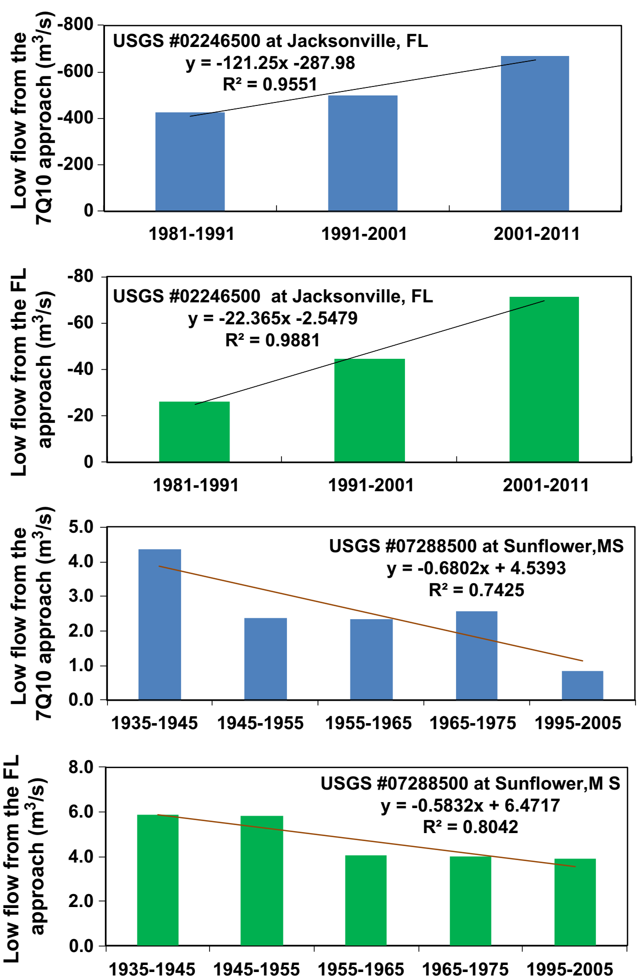

Fig. 4. Low flows estimated from the 7Q10 and FL approaches at the Big Sunflower River, Mississippi and the St. Johns River, Florida with period of data records in a 10-year increment.

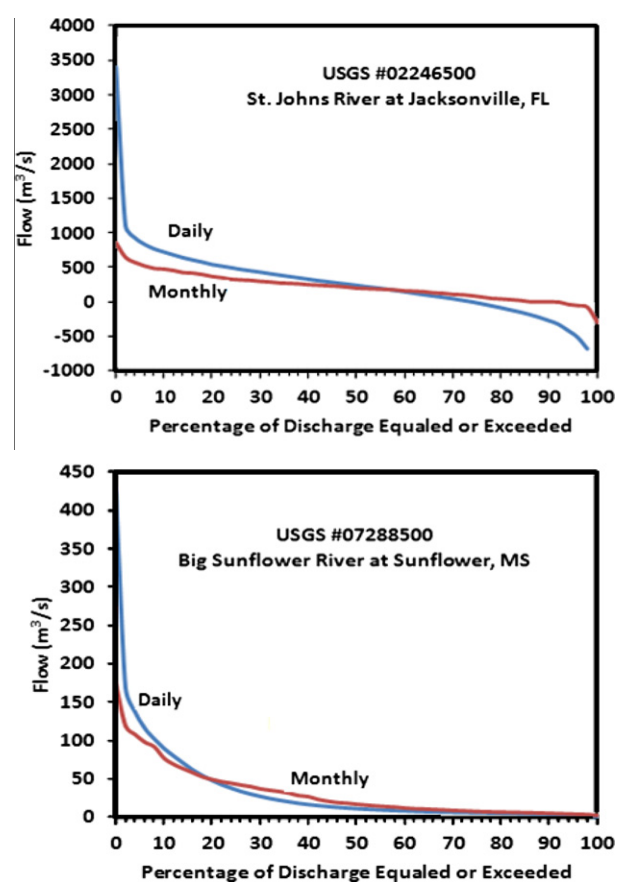

Fig. 5. Flow duration curves estimated from the FL approach for daily and monthly mean data at the Big Sunflower River, Mississippi and the St. Johns River, Florida.

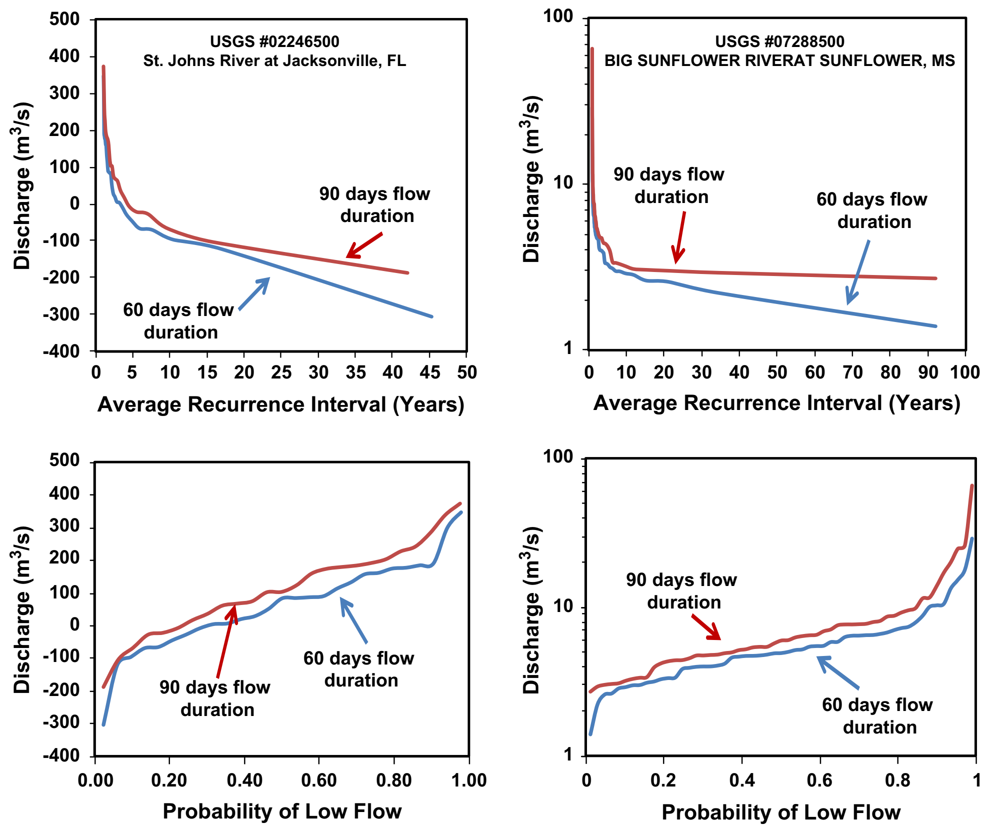

Fig. 6. Low flow recurrence probabilities and recurrence intervals for the 60- and 90-day low flow durations at the Big Sunflower River, Mississippi and the St. Johns River, Florida.

are, respectively, 0.26, 30.38, and 424.74 $m^3 s^{-1}$. Land use in this environment is dominated by agriculture and forestry. These two stations have flow data with the periods of records ranged from 40 to 75 years. Comparison of these two environments allows assess the feasibility of the FL approach in low flow selections.

The FDC analysis was used to identify a particular low flow value for a given site and period of data records, whereas the LFFC analysis was employed to determine low flow recurrence probabilities and intervals. These analyses were accomplished with the Hydstra Model (Version 10.3.2). Hydstra Model is a commercial software package that has capabilities, among others, to analyze hydrologic characteristics (e.g., river discharge and stage, groundwater flow and level, baseflow separation, and precipitation), water quality, and other ecological and environmental factors that have time-series data, to perform duration curve and frequency distribution analysis on hydrology and water quality data, and to identify recurrent intervals in response to climate change, and to perform data acquisition, data importing and exporting, data management, data analysis, modeling and simulation, and automated task scheduling. In this study, the HYFLOW function from the Hydstra Model was employed for FDC analysis, while the HYLOWFL function from the Hydstra Model was utilized for LFFC analysis. The HYFLOW function extracted the tabular output using the brute-force method: all observed values were stored in a list and sorted. This list was then treated as a frequency histogram, and values were interpolated to obtain the desired quantiles. A flow-weighted distribution was produced also, in which the quantile was calculated by finding the item in the list where the cumulative value was equal to the quantile multiplied by the total flow for the entire list. When plotted or printed, this distribution showed the percentage of the total flow that was caused by flows exceeding the nominated value. The HYLOWFL function performed a low flow analysis, showing the probability and annual recurrence interval for a variety of low flow periods (McMahon and Mein, 1986). Eight standard probability and recurrence distributions such as Gumbel, Pearson Type III, and log normal distributions are available for analysis in HYLOWFL. The HYLOWFL was also used to obtain the low flows for the 7Q10 approach by setting the low flow duration at 7 days with a 10-year period of data records.

3. Results and discussion

3.1. 7Q10 vs. FL

Comparison of the low flows from the 7Q10 approach with those from the FL approach for the period of data records with a 10-year increment at the two different surface water environments was given in Table 1. The percentages of the time that each low flow equaled or exceeded were also provided in this table. It should be noted that there were only 5-year flow data for the period from 1971 to 1981 in the estuarine environment (i.e., the St. Johns River at Jacksonville, Florida) which could not be used to obtain the low flow with the 7Q10 approach (as this approach requires a 10-year dataset) although this may not be the case with the FL approach. The same was true for the period from 1974 to 1985 in the freshwater environment (i.e., the Big Sunflower River at Sunflower, Mississippi). Thus, the low flows for these two periods were not provided in the table.

Table 1 showed that for the period of data records with a 10-year increment, the percentages of the time a low flow equaled or exceeded varied from 96% to 100% with the 7Q10 approach, but was constant (80%) with the FL approach. The variations in percentage with the 7Q10 approach could be a disadvantage in water

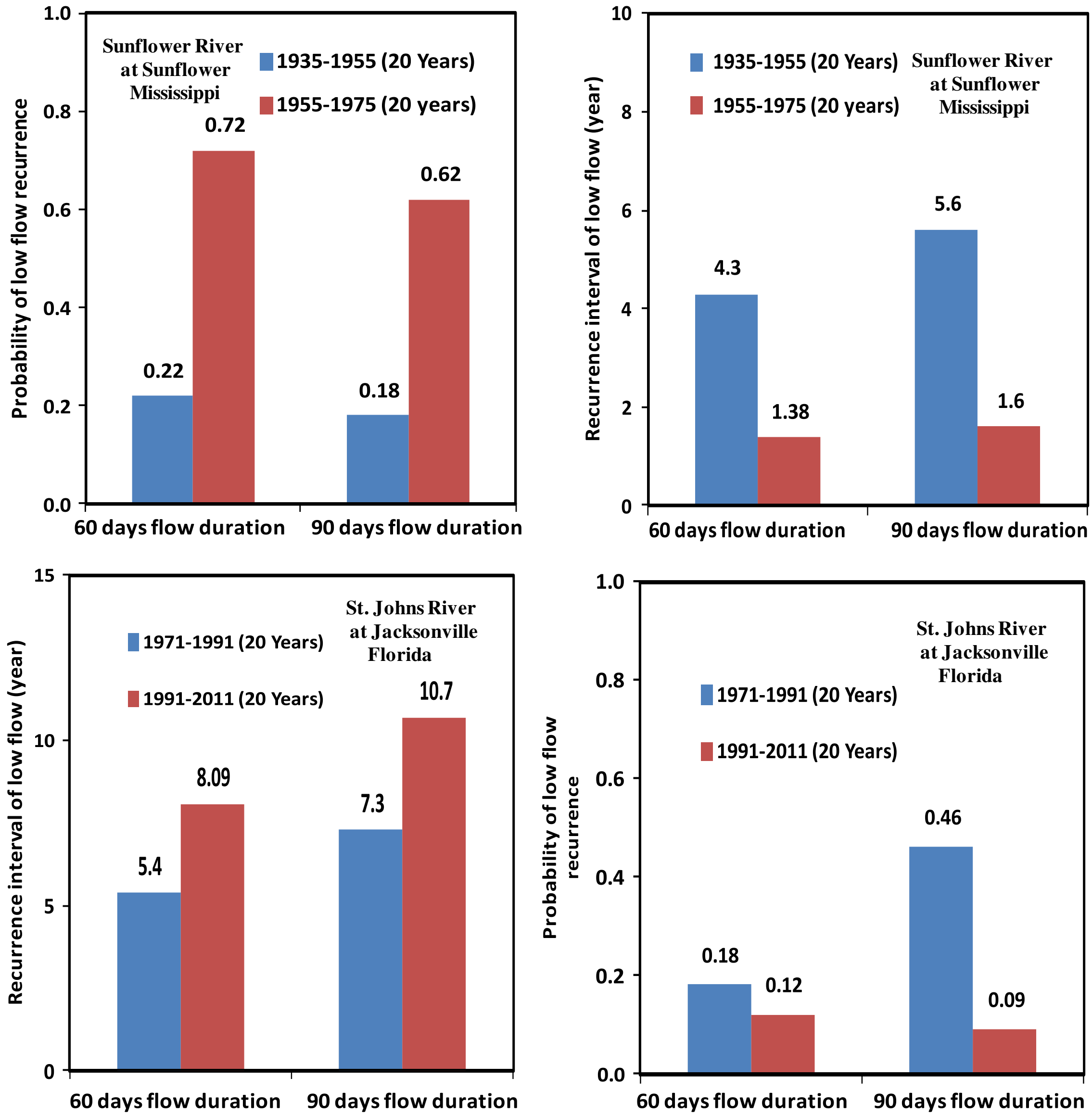

Fig. 7. Recurrence probability and interval of low flow for the 60- and 90-day low flow durations in a 20-year increment at the Big Sunflower River, Mississippi and the St. Johns River, Florida.

resource management. In certain circumstances, when the percentages are near 100%, the low flows could be near-zero or extremely low (e.g., 0.2 m^3/s with daily data from entire period of record at Big Sunflower River). Such extremely low flows could be difficult to use for establishing criteria to prevent streams from significant harm to biological and ecological communities in watersheds. The significant harm referred to a temporary loss of water resource functions, which result from a change in surface or ground water hydrology that takes more than 2 years to recover (Cichra et al., 2007). In contrast, the FL approach (as defined above) is associated with biological and ecological impacts in watersheds. The low flows from the FL approach (80% on the FDC) are unlikely to be near-zero and will be always larger than those from the 7Q10 approach (Smakhtin, 2001). Overall, the 7Q10 approach is a LFFC-based low-flow index while the FL approach is a FDC-based index. Therefore, the percentage of the time a low-flow exceeded based on 7Q10 is variable while that based on FL is constant. In addition, the 7Q10 approach by definition cannot be used when the period of data records is less than 10 years.

Table 1 further revealed that in general, the low flows changed from site to site and varied with period of data records within each site. For the estuarine environment, the low flows estimated from both approaches decreased (more negative) as time elapsed with a 10-year increment. For example, the low flows were −424 and −26 m^3/s, respectively, from the 7Q10 and FL approaches for the period from 1981 to 1991, but were −667 and −71 m^3/s, respectively, from the 7Q10 and FL approaches for the period from 2001 to 2011. The decreases in low flow from 1981 to 2011 in this estuarine environment were about 1.6-folds from the 7Q10 approach and about 2.7-folds from the FL approach. A linear relationship was found between the low flow and the 10-year increment with the correlation coefficients (R^2) of 0.9551 for the 7Q10 approach and of 0.9881 for the FL approach (Fig. 4). The decrease in low flow as time elapsed from 1971 to 2011 implied that the backflow (tidal influence) from the ocean to the St. Johns River increased while the foreflow from the river to the ocean decreased. Result suggested that the St. Johns River has become drier with a tendency of salted water intrusion during the last four decades. Although the exact reasons for this phenomenon remain to be investigated, the possible explanations would be the increase in ground and surface water usages from the extensive development of urbanization and agricultural industry along the river. Additionally, the climate change, wet-dry multi-decadal cycle, and see-level rise could be the other reasons for the river becoming drier with salted water intrusion.

Analogous to the case of the estuarine environment, the low flows from both the 7Q10 and FL approaches decreased, in general, as time elapsed with a 10-year increment for the freshwater environment (Table 1). For instance, the low flows were, respectively, 4.4 and 5.9 m^3/s from the 7Q10 and FL approaches for the period from 1935 to 1945, but were, respectively, 0.8 and 3.9 m^3/s from the 7Q10 and FL approaches for the period from 1995 to 2005. The decreases in low flow from 1935 to 2005 were 5.5-folds from the 7Q10 approach and 1.5-folds from the FL approach. A linear relationship also was observed between the low flow and the 10-year time increment with correlation coefficients (R^2) of 0.7425 for the 7Q10 approach and of 0.8042 for the FL approach (Fig. 4). Result indicated that the Big Sunflower River has become drier during the last seven decades due to the heavy groundwater usage for agricultural industry in addition to climate change.

3.2. Low flow characteristics

Fig. 5 shows the FDCs obtained from the FL approach for the two different surface water environments selected in this study, using the daily and monthly mean data with the entire period of data records. Based on the FDCs shown in this figure, the low flows with daily and monthly mean data were, respectively, −86.93 and 41.43 m^3/s for the estuarine environment and were, respectively, 4.81 and 6.04 m^3/s for the freshwater environment. It is thus apparent that low flows varied from site to site. The low flow from the monthly mean data was 41.43 m^3/s for the estuarine environment, but was only 6.04 m^3/s for the freshwater environment. The former was about 7-folds larger than the latter. This occurred because of the variations in hydrological conditions at different surface water environments.

With the entire period of data records and daily mean values, the low flow recurrence probabilities and intervals for the 60- and 90-day low flow durations at the two different surface water environments were constructed (Fig. 6). The low flow recurrence probability and interval for a given low flow duration can be deduced from this figure. For example, when the low flow was 4.81 m^3/s (Fig. 5) for the freshwater environment at the Big Sunflower River, its recurrence probability and recurrence interval were, respectively, 0.48 (or 48%) and 2.1 years for a 60-day low flow duration (Fig. 6).

To elaborate the recurrence probabilities and intervals of low flows at the two different surface water environments, we have further divided the period of data records into a 20-year increment for each environment. This increment allowed enough time-span to examine the variations of recurrence probability and interval of a low flow (Fig. 7). It should be noted that there were only 15-year flow data available for the period from 1975 to 2011 at the freshwater environment (Big Sunflower River), which has not been used to analyze for the periods from 1975 to1985 and from 1985 to 2005 due to insufficient data.

For the freshwater environment, the recurrence probability of the low flow increased as time elapsed from 1935 to 1975 for both the 60- and 90-day low flow durations, whereas the recurrence interval of the low flow decreased as time elapsed during the same period and the same low flow durations (Fig. 7). The recurrence probability of the low flow for the 60-day low flow duration was 22% from 1935–1955 and 72% from 1955–1975, whereas the recurrence interval of the low flow for the same low flow duration was 4.3 year from 1935–1955 and 1.38 years from 1955–1975. Similar trends were obtained for the estuarine environment. In other words, the low flows occurred more frequent in both surface water environments as time elapsed in a 20-year temporal scale. This finding further confirmed that the St. Johns River in Florida and the Big Sunflower River in Mississippi have become drier during the past decades.

4. Conclusions

In this study, a new approach, or the frequent-low (FL) approach, for low flow selections was developed based on the frequent-low category used in the minimum flows and/or levels programs. This approach was compared to the conventional 7Q10 approach prior to its applications using the flow data from two different surface water environments, one was the estuarine environment and the other was the freshwater environment. It should be noted that both the FL and 7Q10 approaches can also be viewed as the low flow indices. The FL approach is essentially the Q80 index derived from the FDC analysis, while 7Q10 is a low-flow index based on LFFC analysis.

The disadvantages in applying the 7Q10 approach for low flow selections were that in certain circumstances, the low flows selected from this approach could be near-zero. Such extremely low flows would hinder its use for establishing criteria to prevent streams from significant harm to biological and ecological communities. In contrast, the FL approach is associated with the biological and ecological impacts and the low flows selected from this approach (80% on the FDC) are unlikely to be near-zero and will be always larger than those from the 7Q10 approach (Smakhtin, 2001). Additionally, the 7Q10 approach cannot be used when the period of flow data records is less than 10 years while this may not be the case for the FL approach.

In general, the low flows changed from site to site and varied with period of data records within each site. For the estuarine environment, the decrease in low flow as time elapsed implied that the backflow (tidal influence) from the ocean to the St. Johns River increased while the foreflow from the river to the ocean decreased. A linear relationship was found between the low flow and the 10-year increment with very good correlation coefficients. Result suggested that the St. Johns River has become drier with a tendency of salted water intrusion during the last four decades. Similar result was obtained for the freshwater environment, i.e., the Big Sunflower River has become drier during the last seven decades.

Our study from the FL approach further revealed that the recurrence probability of low flow increased while the recurrence interval of low flow decreased as time elapsed at both surface water environments. This finding suggested that low flows at these two environments occurred more frequent as time elapsed. In light of this finding, actions like water resource conservation and hydrological system protection are needed to keep the minimum stream flows required to prevent significant harm to water resources in these surface water environments.

Acknowledgement

The author thanks the former colleagues from the St. Johns River Water Management of Florida for their valuable comments and suggestions.

References

Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ. Manage. 30, 492–507.

Cichra, C.E., Dahm, C.N., Locke, A., Shaw, D.T., Stewart, M. 2007. A Review of "Proposed Minimum Flows and Levels for the Upper Segment of the Hillsborough River, from Crystal Springs to Morris Bridge, and Crystal

Springs" January 30, 2007 Peer Review Draft. Southwest Florida Water Management District, 2379 Broad Street, Brooksville, FL 34604-6899.
Engeland, K., Hisdal, H., Beldring, S., 2006. A Comparison of Low Flow Estimates in Ungauged Catchments using Regional Regression and the HBV-model. NVE Report, Norwegian Water Resources and Energy Directorate, Oslo, Norway.
Gustard, A., Young, A.E., Rees, G., Holmes, M., 2004. Low flows, drought and operational hydrology. In: van Tallaksen, L.M., Lanen, H.A.J. (Eds.), Hydrological Drought: Processes and estimation methods for stream flow and groundwater developments in water science, vol. 48. Elsevier, NL.
Harris, J., Middleton B.J., 1993. Calculations of low flows for selected South African rivers and implications for water quality. In: Proceedings of the Sixth South African National Hydrology Symposium, Pietermaritzburg, SA, vol. 2, pp. 655–664.
Laaha, G., Bloschl, G., 2007. A national low flow estimation procedure for Austria. Hydrol. Sci. J. 52, 625–644.
McMahon, T.A., Mein, R.G., 1986. River and reservoir yield. Water Resource Publication, CO., 368 pp.
Midgley, D.C., Pitman, W.V., Middleton, B.J., 1994. Surface water resources of South Africa 1990. Water Research Commission Report No 298/5.1/94, Pretoria, South Africa.
Neubauer, C.P., Hall, G.B., Lowe, E.F., Robison, C.P., Hupalo, B.R., Keenan, L.W., 2008. Minimum flows and levels method of the St. Johns River Water Management District, Florida, USA. Environ. Manage. 42, 1101–1114.
Nilsson, C., 2000. Minimum river flow. Rivers 7, 171–174.
Pennington, D., 2011. Water supply challenges for the delta of Mississippi. In: Oral Presentation at the Water for Fish and Farmers Conference, Stoneville, MS. September 13–14, 2011.
Poff, N.L., Allan, D., Bain, M.B., Darr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: a paradigm for river conservation and restoration. Bioscience 47, 769–784.
Reilly, C.F., Kroll, C.N., 2003. Estimation of 7-day, 10-year low-stream flow statistics using baseflow correlation. Water Resour. Res. 39, 1236.
Riggs, H.C., Caffey, J.E., Orsborn, J.F., Schaake, J.C., Singh, K.P., Wallace, J.R., 1980. Characteristics of low flows. J. Hydraul. Div., Proc. Am. Soc. Civil Eng. 106, 717–731.
SJRWMD, 2010. St. Johns River Water Management District, Chapter 40c–8, F.A.C. Minimum Flows and Levels. St. Johns River Water Management District, Palatka, Florida, 32178. January, 2010.
Smakhtin, V.U., 2001. Low flow hydrology: a review. J. Hydrol. 240, 147–186.
Stalnaker, C.B. 1990. Minimum flow is a myth. In: Bain, M.B. (Ed.), Ecology and assessment of warm water streams: workshop synopsis. Biological Report, 90(5). U.S. Fish and Wildlife Service, Washington, DC.
Sun, G., McNulty, S.G., Myers, J.A.M., Cohen, E.C., 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. J. Am. Water Resour. Assoc. 44, 1441–1457.
Telis, P.A., 1992. Techniques for estimating 7-day 10-year low flow characteristics for ungauged sites on streams in Mississippi. USGS Water-Resources Investigations Report 91-4130, 143 pp.
Vogel, R.M., Fennessey, N.M., 1995. Flow duration curves. II. A review of applications in water resource planning. Water Resour. Bull. 31 (6), 1029–1039.
WMO, 1974. World Meteorological Organization, 1974. International Glossary of Hydrology, WMO, Geneva.