Indicators of Hydrologic Stress in Massachusetts

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Introduction

There is considerable interest in the use of indicators and indices to describe the behavior of complex water and environmental systems and to assess the environmental status and impacts at the national and regional level (Rogers et al. 2005). There is a history of indicators being used in national and regional water resources assessment within the U.S.. For example, the U.S. Water Resources Council compiled a comprehensive water supply and demand database in the Second National Water Assessment (U.S. Water Resources Council 1979). The assessment was designed to assist federal and local agencies in establishing and implementing water resource policies and programs by cataloging regional and subregional water availability and use. The nation’s water supply, use, and critical water problems were presented for the then-current situation in 1975 and also projected 10 and 25 years in the future (the years 1985 and 2000).

Gleick (1990) introduced an unweighted index to evaluate the climate change vulnerability of water systems within the 18 water resource regions of the U.S. His index is composed of five indicators of regional vulnerability: storage ratio, demand ratio, hydropower use, ground-water overdraft, and streamflow variability. Relying on previous work and scientific judgment, Gleick established warning levels or thresholds for each of the indicators. The total number of indicator warnings is reported as the overall vulnerability of that region.

The U.S. Environmental Protection Agency (U.S. EPA 1997) developed a large set of indicators to evaluate the environmental health of U.S. watersheds. Indicators were used to characterize the condition of watersheds and their vulnerability to future problems. Vogel et al. (1999) use indicators of reservoir yield, reliability, resiliency, and vulnerability to assess the potential impacts of climate change on reservoirs in the U.S. by region. Climate change and population growth projections have led to increasing concern over freshwater availability and the sustainability of water-use in the US. Other U.S. studies which employ hydrologic indicators in regional comparisons include the studies by Lane et al. (1999), Roy et al. (2005), and Hurd et al. (1999). Recently, Weiskel et al. (2007) developed and applied a hydrology-based indicator framework that incorporates human water use as an integral component of the terrestrial water balance over a wide range of spatial and temporal scales.

Hydrologic indicators characterize the hydrologic behavior of a basin by describing key aspects of the hydrologic regime with a small number of easily calculated
statistics. Indicators attempt to reduce the complexity of the water resources system and facilitate spatial comparisons among basins or examination of temporal changes within a basin.

While consumptive use indicators such as the withdrawal ratio indicate the relative amount of available water that is used, it does not describe the impact of water use on streamflow. Streamflow statistics can describe the magnitude, variation, and timing of a hydrologic regime, but without a long period of record that includes pre-development periods, it is difficult to determine how the streamflow has been altered or what the causes of alteration are.

Previous analyses vary in spatial scale as well as choice of indicators, though in all cases the spatial scale of the analysis is much larger than attempted here. National scale studies range from county-level analysis (Roy et al., 2005) to large major-basin delineations (Gleick, 1990; Hurd et al., 1999; Lane et al. 1999). The level of spatial and temporal aggregation of data within a study is often determined by data constraints. Spatial aggregation results in information loss regarding the amount of local variation. Assessments performed on large spatial scales will capture average conditions within the spatial unit but will mask the variability found in headwater streams which are more susceptible to flow alterations from water withdrawals and urbanization.

Massachusetts is generally considered a water-rich state; previous water resource assessments classify the Northeastern U.S. as a low vulnerability region for water supply and consumptive use indicators (U.S. Water Resources Council, 1979). In recent years, however, concern has grown in Massachusetts regarding low-flow and dry-stream conditions during the summer, and the resulting impacts on aquatic biota. In part, low summer flows can be attributed to limited storage in the glacial-valley aquifers that supply many Massachusetts streams with baseflow, and also the strong seasonal cycle in recharge to these aquifers. However, modeling studies and data collection have shown that human water-use patterns (withdrawals and return flows) also contribute to summer low flows (Zarriello and Ries, 2000; DeSimone, 2004).

A recent study in Massachusetts (Massachusetts Water Resources Commission, 2001) developed stress designations for all rivers within the state based entirely on available streamflow data from gaged sites. (This was the only electronic streamflow data available statewide at that time). This imposed three significant limitations on the 2001 stress designations (as was noted in the MWRC 2001 document at the time). First, the relative contribution of natural basin characteristics and human factors—such as water use—to low flows could not be distinguished. Second, ungaged basins could not be assessed. Third, since streamflow gaging stations are generally located on larger streams, the effects of water use on headwater streams could not be determined. The goal of the present study is to reassess the potential effects of human water use on streamflows in Massachusetts using newly available data and methods which enable us to estimate these effects in ungaged and headwater basins at very small spatial scales.

**Methods**

The Sustainable Yield Estimator (SYE) application (Archfield et al., 2008) provides reliable estimates of time series of daily streamflow at a user-specified point along any Massachusetts river, whether or not streamflow data is available. The resulting streamflow time series corresponds to the unimpacted flow regime. Consider a site
which has no streamflow record, which we term an “ungaged site”. Regression equations based on physical basin characteristics are used to derive the flow duration curve under natural (no water use) conditions for the ungaged site. The SYE application then chooses an appropriate index watershed with a reliable stream gage which is used to convert the flow duration curve into a 44-year (1961-2004) daily-flow time series at the ungaged site using what is termed a QPPQ transform method (see Archfield et al. 2008). Annual withdrawal and discharge data are available for each discharge and withdrawal point in the ungaged basin from 2000 – 2004. These annual values are averaged and disaggregated to a one-year time series of daily flow. Net daily water use is subtracted from natural streamflow to get impacted streamflow for the period of record (Archfield et al, 2008).

The use of the SYE allows a direct temporal comparison of natural and water-use-impacted streamflow for any location in Massachusetts. Streamflow statistics were calculated using natural and impacted streamflow time series. Ratios of impacted streamflow to natural streamflow are used as indices to describe the magnitude of hydrologic alteration. Human water use can affect the magnitude, frequency, and duration of streamflows. Seven streamflow statistics were chosen from a larger candidate pool to characterize all three of these flow regimes aspects. Statistics of flow magnitude include the mean annual flow, median January, and August flows and the annual 7-day minimum low flow. Together these four statistics describe the long term average flow, seasonal flow conditions and annual low-flow conditions. The “low pulse count” is defined as the number of annual occurrences where streamflow is less than the 25th percentile of unimpacted daily flow for the period of record. Low pulse duration is the median length of time (number of days) that a low-pulse event occurs. Each statistic was calculated annually using impacted and unimpacted streamflow. The ratio of the median impacted statistic to the median unimpacted statistic (for the 44-year period of record) was then used to examine the relative severity of water use impacts across watersheds. A ratio of one indicates a watershed in which there are no water use effects indicated. For the flow magnitude statistics, a ratio below one indicates a net depletion in streamflow due to water withdrawals, while a ratio greater than one indicates a net augmentation or excess of streamflow above unimpacted conditions.

Headwater basins with water withdrawals are particularly prone to hydrologic stress. In humid regions, these effects are mitigated downstream from the withdrawal point as the drainage area increases and other tributaries enter the stream. In order to capture headwater streamflow alterations and the variation of basin stress through the stream network, a fine-scale basin delineation was created for the entire state of Massachusetts.

Watersheds were delineated directly upstream of stream junctions of third order streams or higher. Delineating above junctions prevents averaging effects at the mixing point. Headwater watersheds which were smaller than 2 mi² were combined with the next downstream hydrologic unit in order to comply with areal constraints of the SYE. This delineation algorithm resulted in 1,550 nested sub-basins covering the state of Massachusetts. These units also nest within the USGS Hydrologic Unit Code (HUC) system of 12-, 10-, and 8-digit HUCs. The 1,550 nested sub-basins each average about 6 sq. mi., compared to the approximately 40 sq. mi. area of the 254 Massachusetts 12-digit HUCs.
Results

Preliminary results for the Concord River basin are presented for illustration in Figures 1-4. The Concord River drainage basin spans 337 mi² in a primarily suburban area northwest of Boston. There are 294 surface and groundwater withdrawals from public water supply or community wells and 49 permitted wastewater discharge points, including 35 groundwater discharges (Figure 1). The average annual streamflow for natural conditions is 689 cfs and annual withdrawals average 45.6 cfs for the entire basin. Figure 2 illustrates the dimensionless ratios of the impacted streamflow divided by natural (no water use) streamflow for the following flow statistics: (a) Mean Annual Flow, (b) Median January Flow, (c) Median August Flow, (d) Annual 7-day Low Flow, (e) Low Pulse Count, and (f) Low Pulse Duration. Figure 2a illustrates that on an annual basis, water-use has only a small impact on streamflow. Median annual impacted flows showed a 3.5% depletion with few localized exceptions. Summer and low-flow magnitudes showed much greater response to water-use. Ratios of impacted August median flow to natural August median flows ranged from 0, indicating a 100% depletion to 1.01, or a 1% surcharge in two watersheds. Low-pulse count was not greatly affected by water use but low-pulse duration was increased in many watersheds as shown in Figure 2e and 2f. Decreases in low-flow magnitude coupled with a prolonged low-flow duration signals a basin that could have stressed aquatic ecosystems.

The use of the SYE allows this analysis to be done at any spatial scale greater than 2 sq. mi. in Massachusetts. The following experiments show that the choice of spatial scale can affect the results of such an analysis. Headwater watersheds have naturally more...
Figure 2. Indicators of water-use impacts on streamflow. Indicators are presented as dimensionless ratios of the impacted streamflow vs natural (no water use) streamflow for (a) Mean Annual Flow, (b) Median January Flow, (c) Median August Flow, (d) Annual 7-day Low Flow, (e) Low Pulse Count, and (f) Low Pulse Duration.
variable streamflow patterns from basin to basin, and also show the greatest relative response to water withdrawals. These basins are particularly vulnerable to low flow stress from pumping during the low-flow season (June – September). These effects may be mitigated downstream as storage increases in the watershed. Figure 3 illustrates the nondimensional water stress indicator for the 7-day low flow for basins over a broad range of spatial scales. As shown in Figure 3, watersheds up to 30 mi² showed the most dramatic variations in low-flow stress. When results are spatially aggregated the resulting focus is on downstream conditions, masking the high degree of spatial variation in headwater regions. Figure 4 illustrates the nondimensional water stress indicator for the 7-day low flow for using the fine-scale spatial aggregation shown previously in Figure 2 as well as using the larger USGS 12-digit Hydrologic Units. Figure 4 clearly demonstrates the importance of the spatial scale on assessing low flow stress within a basin. The example basin is very spatially heterogeneous, hence it is important to consider an high level of spatial detail in order to accurately reflect hydrologic stress. Unimpacted headwaters sit adjacent to the most severely depleted areas. Figure 4 highlights that the analysis at the HUC 12 scale results in a nearly uniform average condition across the basin. While the HUC-12 level of aggregation (or larger HUC’s) may be useful for regional or large scale studies, Figure 4 shows that it could be misleading for analyses intended to benefit state- or local– level water planning and policy decisions.

![7-Day Low Flow Diagram](image)

Figure 3: Small basins are more highly impacted due to water withdrawals. Spatial aggregation averages out this variability.
Figure 4 - Indicators of water-use impacts on streamflow. Indicators are presented as dimensionless ratios of the impacted 7-day low streamflow vs natural 7-day low streamflow. Right hand figure uses fine scale basin delineation shown earlier in Figures 2 and left hand figures uses the larger HUC-12 regions.

Conclusions

This study introduces an approach to mapping hydrologic stress within the state of Massachusetts using recent innovations in the estimation of time series of streamflow at ungages sites (Archfield et al., 2008) and innovations in our ability to delineate watersheds at extremely high resolution (2 - 15 mi²). Our results document the importance of mapping hydrologic indicators using much finer levels of spatial detail than most previous studies, such as those by Gleick (1990), Lane et al. (1999), Hurd et al. (1999), Roy et al. (2005) and many others.

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References


