Water Quality–Based Environmental Flow under Plausible Temperature and Pollution Scenarios

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in

*Hydrol. Eng.*, 

Report No: IIIT/TR/2019/-1

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November 2019
Water Quality–Based Environmental Flow under Plausible Temperature and Pollution Scenarios

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Abstract: This study aimed to estimate water quality–based minimum environmental flow (Eflow) of a river under the impact of different plausible scenarios. The water quality model QUAL2K was deployed to simulate levels of dissolved oxygen (DO) and biochemical oxygen demand (BOD) in a river during the dry season. Hypothetical scenarios of pollution were generated by varying BOD in contributing drains, and climate change scenarios were generated by altering air temperature over the study region. DO and BOD levels were simulated under the impact of various scenarios. Corresponding to each scenario, minimum Eflow throughout the river stretch—that is, the headwaters flow (quantity and quality) meeting desirable river water quality standards (as proposed by the Indian Central Pollution Control Board)—was explored. Water quality charts were developed for direct and user-friendly estimation of Eflos. The proposed approach was applied to the Yamuna and Bhadra rivers in India. The results reveal the inefficiency of existing river flow conditions in maintaining permissible water quality standards. Adverse effects of pollution load, upstream diversions, and climate change are highlighted. DOI: 10.1061/(ASCE)HE.1943-5584.0001780. © 2019 American Society of Civil Engineers.

Author keywords: Hypothetical scenarios; Dissolved oxygen (DO); Biochemical oxygen demand (BOD); QUAL2K; Yamuna; Bhadra.

Introduction

Environmental flow (Eflow) is defined as the quantity, quality, and timing of flow required for healthy functioning and sustenance of riverine ecosystems and the benefits that depend on them (Brisbane Declaration 2007). The estimation of Eflow requires consideration of several factors which affect the functioning of a river and its ecosystem. Broadly, these factors (Fig. 1) can be grouped into the following categories: hydrologic, hydraulic, biodiversity, habitat preference, socioeconomic and cultural, and water quality (Arthington et al. 1999; Lokgarivar et al. 2013; Richter et al. 1997; Soni et al. 2014; Tare 2011; Tennant 1976). The recommended Eflow is the flow that satisfies the requirements of all factors, or the maximum flow obtained from them.

Various methods have been developed to estimate Eflos considering single or multiple factors. Tharme (2003) grouped Eflow methodologies in four distinct categories: hydrological (based on historical natural flow data); hydraulic (based on the hydraulic geometry of rivers); habitat (based on niche or habitat preferences of target species); and holistic (based on integration of various information sources). Holistic methodologies are preferred nowadays. They include building block (King et al. 2008), flow restoration, (Arthington et al. 1999), flow events (Stewardson and Cottingham 2002), and downstream response to imposed flow transformation (King et al. 2003), all aiming to provide water requirements for sustenance of an entire river ecosystem rather than a few species or components. However, due to the absence of a proper individual framework for estimation of the water quality factor in Eflow, most holistic methods have neglected water quality when estimating Eflow. Although the recommended Eflow from these studies might be able to maintain a river ecosystem, the possibility of poor water quality means that the overall integrity of the river might still be adversely affected. Poor water quality due to increasing discharge of industrial and domestic effluents can lead to some serious issues in a river, such as an unbalanced ecosystem, fish mortality, eutrophication, contaminated drinking and public water supply, slow self-purification, toxicity, and aesthetic nuisances (Jha et al. 2007; Ostroumov 2005; Thomann and Mueller 1987).

The significance of incorporating water quality in existing holistic Eflow frameworks has been highlighted by recent studies (Acreman et al. 2014; Dhanya and Kumar 2015; King et al. 2008; Malan and Day 2004; Overton et al. 2014). While O’Keeffe et al. (2012) and Palmer et al. (2005) incorporated water quality in their Eflow estimation, they relied on water quality observations at a few specific sites (hotspots) rather than considering the water quality profile of an entire river system. Recently, Opdyke et al. (2014), Paredes-Arquiola et al. (2014), and Walling et al. (2017) deployed a modeling approach to estimate Eflos based on water quality. However, their methodologies assumed initial river water quality conditions to be constant whereas actual water quality conditions may change abruptly due to anthropogenic interference.

Clearly, existing methods may either overestimate or underestimate Eflow requirements, since they fail to adapt to changing water quality scenarios. This demands consideration of all plausible scenarios of water quality alteration arising from human-induced pollution and implies estimation of Eflow corresponding to each scenario. Moreover, Eflow based on water quality criteria may surpass the natural flow availability of a river system in the case of heavy pollution (as in Walling et al. 2017). In such cases, the provision of natural river flows to dilute the bulk of anthropogenic pollutants will not serve the purpose. Under such conditions, Eflow
methods considering water quality criteria should incorporate the possibility of various river pollution mitigation measures. Likewise, it is important to consider plausible fluctuations in water quality due to changing climate (Cox et al. 2015; Dyer et al. 2014; Mimikou et al. 2000; Rehana and Mujumdar 2011; Whitehead et al. 2009) and their impact on the water quality factor of Eflow (Walling et al. 2017).

Climate change has globally altered precipitation patterns (leading to changes in river flow) and caused air temperature fluctuations (leading to changes in water temperature). IPCC (2014) predicted an average air temperature increase of 2°C–4°C across the world, which will surely affect water temperature and impact dissolved gases content in river water, including dissolved oxygen content (Delpla et al. 2009). Similarly, predicted increases in the magnitude and frequency of extreme rainfall events (IPCC 2012; Kundzewicz and Gerten 2014; Mimikou et al. 2000) may lead to abrupt variations in future discharges. Overall, any changes in streamflow or temperature (due to climate change) will have a direct impact on the water quality factor. A few Eflow studies (Gul et al. 2010; Thompson et al. 2014) investigated Eflow requirements in climate change scenarios; however, they did not focus on the water quality requirement.

This study aimed to determine water quality–based Eflow in plausible scenarios of pollution loadings and changing climate. Here is presented a water quality modeling approach for deriving the quantity and quality of flow at the headwaters of a river stretch, meeting desirable river water quality constraints in the entire river stretch. The proposed approach was applied to two river systems, the Yamuna and Bhadra rivers in India. A water quality–modeling tool, QUAL2K, was selected to model dissolved oxygen (DO) and biochemical oxygen demand (BOD) over the study stretch during critically dry seasons. Desirable river usage and its corresponding water quality standards as proposed by the Indian Central Pollution Control Board (CPCB) (Table 1) were set as the water quality objectives. CPCB has classified river stretches into five classes (A, B, C, D, and E), with each class having a fixed quality on which a designated usage is based. In this study, Eflow required for maintaining the desirable CPCB river water class was determined and the impacts of various pollution and climate change scenarios on Eflow were investigated.

### Description of Study Regions

Two diverse river stretches in India, the Delhi segment of the Yamuna River and the Bhadravati segment of the Bhadra River, were selected for application. The Delhi segment of the Yamuna River represents river systems that are perennial and regulated and at high risk of pollution. On the other hand, the Bhadravati segment of the Bhadra River represents river systems that are nonperennial and regulated and under moderate risk of pollution.

**Yamuna River (Delhi Segment)**

The Yamuna River is the largest tributary of the River Ganga and originates in the Yamunotri Glacier of the lower Himalayas in the northern Indian state of Uttarakhand. Though the Yamuna is a perennial river, overextraction of its water from the barrages constructed in its course significantly reduces its flow, especially during the nonmonsoon season. Major extraction of river water takes place in the Hathimukid Barrage, where almost 90% of the river water is diverted through irrigation canals. The Yamuna, on its course through Delhi, the capital of India, is polluted by numerous industrial drains dumping polluted water into the river stretch. Untreated polluted water from incoming drains, along with very low river discharge due to upstream diversions, transforms the river stretch more or less into a polluted drain. The Delhi segment of the Yamuna River is polluted by 15 drains and the Hindon-Cut Canal [Fig. 2(a)]. In addition, water is extracted through the Agra Canal [17 in Fig. 2(a)] for irrigation. The CPCB has identified this stretch to be at the highest risk of pollution (Priority 1) (CPCB 2011). River water in this stretch falls in Class E (DO < 4 mg/L); the desirable category is Class D (DO ≥ 4 mg/L) (CPCB 2008, 2011).

In order to address the alarming decrease in Yamuna River water quality, in 1998 the Supreme Court of India appointed a High Power Committee, which recommended a provisional minimum flow of 10 m³/s in the Delhi stretch to maintain water quality. Later in 2003, the Water Quality Assessment Authority (WQAA) established by the Government of India set minimum flows in Indian rivers to conserve riverine ecosystems based only on hydrological factors, using a method similar to the Tennant Method (CWC 2007; Smakhtin 2006). For Himalayan rivers including the Yamuna, the WQAA recommended a minimum flow of 2.5% of 75% dependable annual flow (CWC 2007). Soni et al. (2014) considered the hydrological functions of rivers—sediment transport, algal choking, and the like—using hydraulic and hydrological data. They observed that a river needs a minimum 50%–60% of its natural flow for healthy functioning. Walling et al. (2017) considered water quality and proposed Eflow between 700 and 800 m³/s for CPCB river water usage classes. However, Eflows proposed by earlier researchers were either significantly too low to maintain the water quality factor or much higher than the natural availability of river flow. Given that water quality maintenance is a major issue in the

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**Table 1. Primary water quality criteria for various river water uses**

<table>
<thead>
<tr>
<th>Class</th>
<th>Use</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Drinking water source without conventional treatment but after disinfection</td>
<td>DO ≥ 6 mg/L; BOD ≤ 2 mg/L</td>
</tr>
<tr>
<td>B</td>
<td>Outdoor bathing (organized)</td>
<td>DO ≥ 5 mg/L; BOD ≤ 3 mg/L</td>
</tr>
<tr>
<td>C</td>
<td>Public water supply with approved treatment equal to coagulation, sedimentation, and disinfection</td>
<td>DO ≥ 4 mg/L; BOD ≤ 3 mg/L</td>
</tr>
<tr>
<td>D</td>
<td>Propagation of wildlife, fisheries</td>
<td>Not meeting A, B, C, and D criteria</td>
</tr>
<tr>
<td>E</td>
<td>Irrigation, industrial cooling, controlled waste disposal</td>
<td>DO ≥ 4 mg/L.</td>
</tr>
</tbody>
</table>

Source: Data from CPCB (2008).

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Delhi stretch of the Yamuna River, this study aimed to provide a realistic and feasible Eflow value that would satisfy the water quality requirement under hypothetical pollution and climate change conditions.

**Bhadra River (Bhadravati Segment)**

The Bhadra River is a tributary of the Krishna River and originates in Gangamula in the Western Ghats (Kundermukh Range) in the Chickamaglur District of Karnataka State. The river flows nearly 190 km from its origin and joins the River Tunga at Koodli, Karnataka, to form the River Tungabhadra. The Bhadra Reservoir is built across the Bhadra River, 50 km upstream of Koodli. The Bhadra flows through Bhadravati City, Karnataka, where it is polluted due to effluents from various industrial and domestic sources [Karnataka State Pollution Control Board (KSPCB), Sumithra and Narayana 2003]. Fig. 2(b) shows the reservoir, the river stretch considered in this study, and its effluent drains.

The Bhadravati segment of the Bhadra River is mostly polluted by three drains: Mysore Paper Mill (MPM) [D1 in Fig. 2(b)], Bhadravati City [D2 in Fig. 2(b)], and Visveshvarya Industrial Steel Limited (VISL) [D3 in Fig. 2(b)]. Apart from these drains, the 27-km study stretch is polluted by nonpoint sources in the form of overland flow from nearby towns and farms. The CPCB has identified this river stretch as one of the most polluted in India (CPCB 2011). River water in it falls in Class D (DO ≥ 4 mg/L); the desirable category is Class C (DO ≥ 4 mg/L; BOD ≤ 3 mg/L) (CPCB 2008, 2011). Eflow studies of the Bhadra River have been

Fig. 2. (a) Details of the Delhi segment of the Yamuna River; and (b) details of the Bhadravati segment of the Bhadra River.
based on hydrological factors and reveal the unavailability of flows from June to December to satisfy Eflow requirements (Babu and Kumara 2009). Thus, considering the problem of river pollution in the Bhadra stretch, together with the need to revisit the water release policies of the Bhadra Reservoir, it is imperative to adopt a scenario-based assessment of Eflow under the water quality constraint.

Methodology

In order to estimate Eflow based on water quality, the most important and fundamental step is the development of a water quality model. Water quality models are very useful in simulating the natural state of a river system and thus in predicting changes in the natural state under altered conditions. Water quality variables in a river stretch are highly influenced by (1) point or nonpoint sources of pollution joining in a river stretch, (2) flow and water quality at the headwaters of the river stretch, and (3) meteorological conditions, especially, air temperature (water temperature) and rainfall over the watershed (or resultant streamflow). Any change in these three factors will alter river water quality conditions, so various plausible scenarios for them (tested individually or combined) should be taken into account in scenario-based Eflow estimation. Fig. 3 is a schematic of the steps in scenario-based estimation of Eflows considering water quality. The detailed methodology adopted to estimate Eflow under various plausible scenarios is discussed next.

![Fig. 3. Generic flowchart for plausible pollution load and climate change scenario estimation of water quality Eflow.](image)

Table 2. Performance metrics used in the present study

<table>
<thead>
<tr>
<th>Metric</th>
<th>Equation</th>
<th>Range</th>
<th>Ideal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>( RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{x})^2} )</td>
<td>[0, ∞)</td>
<td>0</td>
</tr>
<tr>
<td>Correlation (R)</td>
<td>( R = \frac{n \sum_{i=1}^{n} y_i x_i - (\sum_{i=1}^{n} y_i) (\sum_{i=1}^{n} x_i)}{(\sqrt{n \sum_{i=1}^{n} y_i^2} - (\sum_{i=1}^{n} y_i)^2) \sqrt{n \sum_{i=1}^{n} x_i^2} - (\sum_{i=1}^{n} x_i)^2)} )</td>
<td>[-1, 1]</td>
<td>1</td>
</tr>
<tr>
<td>Coefficient of efficiency (E)</td>
<td>( E = 1 - \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} )</td>
<td>[-∞, 1)</td>
<td>1</td>
</tr>
<tr>
<td>Index of agreement (IOA)</td>
<td>( IOA = 1 - \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}^2 +</td>
<td>x_i - \bar{x}</td>
<td>^2)} )</td>
</tr>
</tbody>
</table>

Note: \( n \) = total values; in AT and WT relationship, \( y = WT \) and \( x = AT \), for calibration and validation of QUAL2K model, \( y = \) simulated; and \( x = \) observed.

Development of the Water Quality Model

QUAL2K is a one-dimensional steady-state, numerical river and stream water quality model (Chapra et al. 2006). It conceptualizes the river stretch as a number of segments (called reaches) that are further subdivided into smaller computational elements. Segmentation is based on uniform hydraulic characteristics and reaction rates. Each reach is sequentially linked via the transport mechanisms of advection and dispersion. The flow rates for each reach are computed using flow balance as shown in Fig. S1 (Supplementary Data). QUAL2K is frequently used for river water quality modeling (Chaudhary et al. 2018; Cox et al. 2015; Parmar and Keshari 2012; Rehana and Mujumdar 2011; Walling et al. 2017). For its calibration here, a sequential and reach-specific technique developed by Chaudhary et al. (2018) was adopted. Three performance metrics—index of agreement (IOA), correlation coefficient (R) and coefficient of efficiency (E)—were used to analyze model performance in simulating observed DO and BOD. Details are provided in Table 2.

The Delhi segment of the Yamuna River (21.9 km) was divided into 16 reaches based on river morphology. Information about the hydraulic characteristics of different stretches of the river is obtained from Parmar and Keshari (2012) and the Delhi Jal Board (2005). The cross-sectional width of the individual river stretches ranged from 60 to 272 m, their cross-sectional depth ranged from 0.4 to 6 m. The coefficients and exponents of the flow equations for the stream were obtained from Parmar and Keshari (2012). The coefficient (exponent) in the velocity-discharge relationship varied from 0.0169 to 0.4554 (0.029 to 0.6028) along the river stretches. Similarly, the coefficient (exponent) in the depth-discharge relationship varied from 0.0498 to 0.4411 (0.3146 to 0.8538). Water quality data—DO, BOD, and temperature of the point sources—were obtained from the CPCB (2005) and Parmar and Keshari (2012); river flow details were obtained from the Indian Central Water Commission (CWIC). The QUAL2K model for Yamuna River was calibrated for the dry season in March–June 2002 and validated for a dry period in February 2003.

The Bhadrawati segment of the Bhadra River was divided into four reaches based on river morphology. Information about hydraulic characteristics of the headwaters and stretches of the...
river were obtained from Rehana and Mujumdar (2011) and the Karnataka State Water Resources Development Organization (KSWRDO). An average bed width of 61.85 m and a longitudinal slope of 0.0016 were observed along the river stretches. Similarly, a Manning’s roughness coefficient of 0.0492 was obtained. Water quality data—DO, BOD, and temperature of the headwaters and pollution sources—were obtained from the KSPCB, Rehana and Mujumdar (2011), and Sumithra and Narayana (2003). Flow rates were obtained from the CWC. In order to conservatively account for the contribution of nonpoint pollution sources in the Bhadravati stretch, incremental flow between upstream and downstream was computed and further distributed throughout the stretch in order to obtain diffuse pollution load per unit distance. The water quality in this diffuse pollution source was assumed to have a high value of 30 mg/L for BOD and a low value of 4 mg/L for DO (Rehana and Mujumdar 2011). The QUAL2K model for the Bhadra River was calibrated for the dry season (February 15 through June 15) of 2007–2008 and validated for the dry season (February 15 through June 15) of 2009–2010.

**Relating Air Temperature and Water Temperature**

Various regression models were examined to determine a relationship between air temperature (AT) and water temperature (WT) specific to the study regions. Their performance was analyzed using RMSE, R, and E, which are detailed in Table 2. For the Yamuna stretch, average monthly WT data were obtained from the CPCB at two locations: Palla (15 km upstream of the Wazirabad Barrage) and Nizamuddin (14 km downstream of the Wazirabad Barrage) (CPCB 2006). Monthly AT data (minimum, maximum, and mean) were obtained from the Indian Meteorological Department (IMD) in Pune. Different regression equations were trained for the period 1999–2003 and tested for the period 2004–2005. For the Bhadra stretch, the linear regression equation developed by Rehana and Mujumdar (2011) was adopted: $y = 1.75 + 0.86x$ with $R^2 = 0.57$ over the river stretch, where $y = WT$ and $x = AT$ (°C).

**Generation of Plausible and Hypothetical Scenarios**

Average conditions during the dry season of March–June 2002 and March–June 2007–2008 were selected as the baseline for the Yamuna and Bhadra rivers, respectively.

**Future Air Temperature**

Data analysis provided a basis for selecting a range of plausible scenarios for variables influencing water quality. Scenarios for air temperature were based on observed changes in annual mean air temperature from 1988–1999 to 2000–2006 at different stations in the Bhadra region. They showed an increase ranging from 0.215°C to 1.39°C (Rehana and Mujumdar 2011). Basha et al. (2017) observed increasing air temperature over the Yamuna (0.2°C/decade) and Bhadra (0.1°C/decade) regions. IPCC (2014) suggested increases in average annual temperatures of more than 2°C and 3°C by the mid- and late 21st century, respectively, over South Asia in a high-emissions scenario. For these reasons, increasing temperatures of 2°C and 4°C from baseline were considered in this study. Generally, hypothetical scenarios assume variations within ±4°C in air temperature from baseline (McCabe and Hay 1995; Walling et al. 2017). Temperature decreases of 4°C and 2°C were also incorporated in order to investigate the effect of lower air temperatures on Eflow requirements.

**Headwaters Water Quality**

Headwaters pollution scenarios were generated by varying DO and BOD from their prescribed value to the maximum (DO) or the minimum (BOD). For example, if the minimum DO prescribed in a river stretch were 3 mg/L, the headwaters DO variations would be from 3 mg/L to saturated (the maximum) for that stretch. Similarly, if maximum BOD to be maintained in the stretch were 10 mg/L, the headwaters BOD variations would be from 0 (the minimum) to 10 mg/L. The present study aimed to maintain water quality standards in the entire river stretch, including the headwaters, so it was assumed that headwaters water quality would meet at least minimum requirement.

**Incoming Drain Pollution**

Pollution scenarios were obtained by increasing the BOD treatment level from 0% to 100% in the drains under baseline conditions. The treatment scenarios of increased BOD would not only aid in reducing river pollution but also encourage polluters to treat their pollutants before discharging them into the river. Additional DO treatment scenarios (DO enrichment) for drains would be taken up further if prescribed water quality requirements were not to be met, even after considering the scenario of complete BOD treatment.

This study adopted decreasing pollution scenarios by subjecting BOD in drains to treatment options ranging from 0% to 100% (at 20% increments) from observed baseline conditions. A scenario based on maximum permissible BOD discharge of 30 mg/L was also considered, taking into account Indian standards for wastewater discharge established by The Environment (Protection) Rules (1986).

**Scenario-Based Estimation of Eflow and Development of Water Quality Charts**

QUAL2K was run to simulate water quality in different scenarios of pollution load and air temperature. For each scenario, headwaters flow was varied until the desired water quality standards were met throughout the river stretch. The minimum headwaters flow satisfying the water quality requirement was the desired water quality–based Eflow for the corresponding scenario. Different scenarios of headwaters quality, BOD treatment in drains, and corresponding Eflow values were graphically represented in form of Eflow–based water quality charts. Given headwaters quality conditions and flow availability at the headwaters, the charts were used to estimate the level of BOD treatment required in the drains in order to meet the desired water quality requirement.

**Results and Discussion**

**Eflow for the Yamuna River (Delhi Segment)**

**Calibration and Validation of QUAL2K**

DO and BOD simulations for calibration (March–June 2002) and validation (February 2003) closely matched observations (Fig. 4). During the calibration period, high values of $R$ (0.994 DO; 0.961 BOD), $E$ (0.98 DO; 0.92 BOD), and $IOA$ (0.995 DO; 0.980 BOD) were observed. Similarly, during the validation period, high values for $R$ (0.994 DO; 0.961 BOD), $E$ (0.98 DO; 0.839 BOD), and $IOA$ (0.972 DO; 0.955 BOD) were observed.

**Relationship between Air Temperature and Water Temperature**

Among the three AT variables (mean, maximum, and minimum), minimum AT was found to more significantly correlate with average WT for the Yamuna river stretch. A power regression model $y = 63 – 495/x^{0.84}$, where $y = \text{mean monthly WT}$ and $x = \text{minimum monthly AT (°C)}$ showed the best fit to the observed data with the lowest $RMSE$ (3.604), high $R$ (0.815), and high $E$ (0.620).
Satisfactory results were obtained for the testing period with the power regression model \((RMSE = 2.930; R = 0.855; E = 0.676)\).

**Generation of Plausible Pollution Scenarios**

The minimum DO for River Class D per CPCB specification (CPCB 2008) is 4 mg/L; the saturation DO estimate from the QUAL2K model was 7.5 mg/L [Figs. 4(a and c)]. Hence, headwaters DO was varied 4–7.5 mg/L (in 0.5-mg/L increments) to generate the scenarios. Plausible drain pollution scenarios were generated considering different levels of BOD treatment ranging 0%–100%. As mentioned before, since the Yamuna is immensely polluted, further improvement in water quality standards considering drain DO enrichment scenarios of 1 and 2 mg/L in the incoming 100% BOD–treated drains is suggested.

**Scenario-Based Estimation of Eflow and Development of Water Quality Charts**

Eflows satisfying the Class-D (DO ≥ 4 mg/L) requirement in baseline and plausible hypothetical scenarios are discussed in the following paragraphs.

A graph of Eflow demand in different pollution scenarios under baseline conditions is shown in Fig. 5. As expected, demand decreases with increasing drain treatment and improvement in water quality conditions at the headwaters of the stretch. Evidently, headwaters DO improvements significantly reduce Eflow requirements when compared with those due to drain treatment. For the best possible scenario (headwaters DO = 7.5 mg/L; 100% BOD drain treatment), an Eflow value of 31.5 m³/s is recommended. However, taking into account the possible unavailability of even 31.5 m³/s during the low-flow period, DO enrichment scenarios were also applied, which further lowered the Eflow requirement to 16.25 m³/s (DO = 2 mg/L; 100% BOD treatment). The Eflow requirement rose to 500 m³/s when the worst headwaters quality and best drain treatment scenarios were combined. In this case, even with DO enrichment, Eflow decreased only to 335 m³/s.
The worst combination—untreated incoming drains (0% BOD treatment) and polluted headwaters (DO = 4.5 mg/L) demanded an Eflow of 960 m$^3$/s. Improvement in water quality conditions at the headwaters of the stretch lowered Eflow demand to 155 m$^3$/s, a difficult discharge to meet in low-flow seasons. Similarly, in order to maintain permissible BOD (30 mg/L) in drains, Eflow demand was increased from 94 to 710 m$^3$/s for different headwaters pollution scenarios.

Eflow demand in different temperature scenarios is shown in Fig. 6. The maximum increase in demand is for an increase of 4°C in air temperature. The most unfavorable condition (headwaters DO = 4.5 mg/L; BOD drain treatment = 0%), an increase of 450 m$^3$/s from the base value (46.9% increase in demand) is observed as shown in Fig. 6(a). Similarly, an increase of 0.75 m$^3$/s (4.6% increase in demand) from the base value is observed for the most favorable condition (DO at headwaters = 7.5 mg/L; BOD drain treatment = 100%; DO enrichment = 2 mg/L). Similarly, for a 2°C increase in air temperature, minimum Eflow requirements are observed to increase by 120 (12.5%) and 0.25 m$^3$/s (1.5%) from baseline for the most unfavorable and favorable scenarios, respectively [Fig. 6(b)].

The decrease in future air temperature lowered the Eflow requirement of the Yamuna River. For example, for the most polluted scenario (DO at headwaters = 4.5 mg/L; BOD drain treatment = 0%), Eflow decreased by 140 (14.6%) and 280 m$^3$/s (29.2%) from the baseline requirement with 2°C and 4°C temperature decreases, respectively [Figs. 6(c and d)]. For the least polluted scenario (DO at headwaters = 7.5 mg/L; BOD drain treatment = 100%; DO enrichment = 2 mg/L), Eflow decreased by 0.25 (1.5%) and 0.75 m$^3$/s (4.6%) with 2°C and 4°C temperature decreases, respectively [Figs. 6(c and d)]. Hence, the minimum Eflow requirements with temperature increases of 4°C and 2°C and temperature decreases of 2°C and 4°C were observed.

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Fig. 6. Eflow charts for Class-D water quality: (a) 4°C temperature increase; (b) 2°C temperature increase; (c) 2°C temperature decrease; and (d) 4°C temperature decrease.
decreases of 2°C and 4°C were 17, 16.5, 16, and 15.5 m³/s, respectively. A summary of Eflow values obtained at various stages for different scenarios is given in Table S1 in Supplemental Data.

**Eflow for the Bhadra River (Bhadravati Segment)**

**Calibration and Validation of QUAL2K**

DO and BOD simulations for the calibration and the validation period showed close fits to observed DO and BOD (Fig. 7). During the calibration period, high values for $R$ (0.99 DO; 0.86 BOD), $E$ (0.99 DO; 0.88 BOD), and $IOA$ (0.99 DO; 0.84 BOD) were observed. Similarly, during the validation period (February 2003), satisfactory values of $R$ (0.88 DO; 0.76 BOD), $E$ (0.66 DO; 0.53 BOD), and $IOA$ (0.92 DO; 0.84 BOD) were observed.

DO simulations [Figs. 7(a and c)] clearly showed that the river stretch always has a DO greater than 4 mg/L (CPCB Class-D requirement) while Class-C (which demands an additional BOD constraint) is desired. As shown in Figs. 7(b and c), BOD is quite high, with a maximum of 18 mg/L downstream of the MPM drain (25 km upstream of Koodli), whereas the rest of the stretch shows BOD values greater than 8 mg/L (approximately). As a result, the river fails to fall in the desirable Class-C category.

**Generation of Plausible Pollution Scenarios**

Since the minimum DO requirement of the river stretch is 4 mg/L and the saturation DO is approximately 7.5 mg/L [Figs. 7(a and c)], headwaters DO scenarios varied from 4 to 7.5 mg/L. Similarly, since the desired BOD requirement of the river stretch was 3 mg/L, headwaters BOD scenarios varied from 0 to 3 mg/L.

Drains, the major carrier of pollutants (in the form of BOD), were subject to BOD treatments ranging from 0% to 100%.

**Scenario-Based Estimation of Eflow and Development of Water Quality Charts**

An Eflow chart satisfying the water quality requirement for a Class-C River (DO > 4 mg/L; BOD ≤ 3 mg/L) was derived. Since variations in DO and BOD at the headwaters alter water quality conditions downstream of the Bhadra stretch, two Eflow charts were prepared by (1) varying headwaters DO to find Eflow values satisfying the Class-C DO requirement (DO > 4 mg/L) and (2) varying headwaters BOD to find the Eflow values satisfying the Class-C BOD requirement (BOD ≤ 3 mg/L). The maximum Eflow from the two charts was fixed as the desired Eflow for the stretch. Pollution mitigation measures in the form of drain discharge treatments were taken into account in deriving the Eflow charts, which are described in the following paragraphs.

**Eflow under Baseline Conditions**

Eflow charts for different headwaters and drain pollution scenarios under baseline conditions are shown in Fig. 8. Similar to the case of Yamuna River, the Eflow requirement decreases with improved headwaters quality and drain treatment. For the best scenario combination—headwaters DO = 7.5 mg/L; no headwaters BOD; 100% BOD treatment in drains—the minimum recommended Eflow value is 77 m³/s. For the most water-demanding scenario combination—untreated incoming drains and polluted headwaters (DO = 4.0 mg/L; BOD = 3.0 mg/L)—a high Eflow value of 3,170 m³/s is recommended to ensure class-C conditions. Improved

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**Fig. 7.** (a) Bhadra River: calibration period simulated DO; (b) calibration period simulated BOD; (c) validation period simulated DO; and (d) validation period simulated BOD profile.
headwaters quality lowers demand to 143 m³/s, however. The severe pollution conditions in the Bhadra segment demand a significantly high Eflow ranging from 106 to 236 m³/s, even to maintain the standard permissible BOD = 30 mg/L for different headwaters quality scenarios.

**Eflows in Different Hypothetical Climate Change Scenarios**

The impact of changes in future air temperature on Eflow requirements is shown in Fig. 9. Interestingly, changes in water temperature have the opposite effect in maintaining permissible BOD and DO (in Fig. 9). While an increase in temperature causes an increase in Eflow requirement under DO regulations, it causes a decrease in Eflow value under BOD regulations. According to Henry’s law of partial pressure, the solubility of any gas in water decreases with increasing temperature. This explains the decrease in oxygen content and hence DO with increasing temperature and vice versa. More Eflow is needed to maintain desirable DO in increased air temperature scenarios. In contrast, an increase in temperature accelerates the rate of decay of organic matter in rivers. Thus, BOD decreases with increasing temperature, lowering the Eflow demand to decompose organic matter and vice versa.

Although changes in air temperature have a direct impact on both DO and BOD, the magnitude of change varies. It is evident from Fig. 9 that, while BOD is sensitive to small variations in temperature, DO is not. The Bhadra River stretch is heavily polluted by drains carrying industrial effluents, which are the primary source of BOD. Thus, more Eflow is required to maintain permissible BOD levels than is required to maintain DO levels. BOD thus emerges as the deciding factor in determining Eflow over the Bhadra River stretch.

For the 4°C temperature increase scenario [Fig. 9(a)], the Eflow requirement for the most favorable condition (DO at headwaters = 7.5 mg/L; no headwaters BOD; BOD drain treatment = 100%) decreases to 73 m³/s (5.2% reduction) from the base Eflow value of 77 m³/s. Similarly, for the worst combination (DO at headwaters = 4 mg/L; BOD at headwaters = 3 mg/L; BOD drain treatment = 0%), Eflow decreases from 3,170 to 2,500 m³/s (21.1% reduction). Similar behavior is observed for the 2°C temperature increase scenario [Fig. 9(b)]. For the 2°C temperature decrease scenario [Fig. 9(c)], the Eflow requirement for the most favorable condition increases to 88 m³/s. Likewise, for the worst combination, Eflow increases to 3,700 m³/s. Impacts are similar for the 4°C temperature decrease scenario [Fig. 9(d)]. The minimum Eflow requirements for 4°C and 2°C increases and for 2°C and 4°C decreases are 73, 75, 88, and 92 m³/s, respectively (a summary of Eflow values obtained at various stages for different scenarios is given in Table S2 in Supplemental Data).

**Vulnerability of the Yamuna and Bhadra River Stretches in Maintaining Water Quality**

Estimation of Eflow based on water quality in different river stretches of the Yamuna and Bhadra rivers exposed the flaws in existing flow regulations and adverse effects of upstream diversions in maintaining permissible water quality standards. The pollution level is higher in the Delhi segment of the Yamuna River when compared with the Bhadradavi segment of the Bhadra River. Under baseline conditions, the Delhi segment of the Yamuna demands Eflow values ranging from 16.25 to 960 m³/s for different plausible pollution scenarios to meet CPCB Class-D water quality requirements. Similarly, under different plausible climate change conditions, the Eflow requirement for the Yamuna varies from 15.5 to 1,410 m³/s for various pollution scenarios. The inclusion of pollution treatment scenarios reduced the Eflow requirement. However, suggested Eflow values were much higher than the existing flow in the river throughout the year. This situation turns out to be critical during the dry season, when a flow of 1.5 m³/s is only available at the headwaters of the stretch. Under such low-flow

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**Fig. 8.** Eflow chart for Class-C river under baseline conditions satisfying: (a) BOD requirement; and (b) DO requirement.
Fig. 9. Eflow chart for Class-C river: (a) 4°C temperature increase; (b) 2°C temperature increase; (c) 2°C temperature decrease; and (d) 4°C temperature decrease.

*The Environment (Protection) Act 1986, Ministry of Environment and Forests, India
conditions, even for maintaining the standard permissible effluent discharge with BOD = 30 mg/L in drains, high Eflow values of 94–710 m³/s are required.

The Bhadravati segment of the Bhadra River demands Eflow values from 77 to 3, 170 m³/s for different pollution scenarios under the baseline condition to satisfy CPCB Class-C water quality requirements. Similarly, for hypothetical climate change conditions, Eflow demand varies 75–4,100 m³/s. Even the inclusion of pollution treatment scenarios in the Eflow estimation framework cannot ensure maintenance of desirable water quality standards under the existing flow conditions of 22 m³/s at the headwaters. Excessive extractions of flow from the Bhadra Reservoir are mainly responsible for low water availability at the headwaters of the stretch. Therefore, the existing release and extraction policies of the Bhadra Reservoir need revision taking into account the water quality requirements of the Bhadravati segment.

**Eflow Estimation Based on Hydrological and Hydraulic Factors**

Eflow estimates based on hydrological factors rely solely on the observed flow regime of the river, assuming that some percentage of mean flow is required to maintain a healthy stream environment. Fig. S2 (Supplemental Data) shows the mean monthly variation in observed natural (unregulated) flow upstream of the Hathnikund Barrage on the Yamuna River and upstream of the Bhadravati segment of the Bhadra River.

The Tennant (or Montana) method developed by Tennant (1976) is worldwide the most common and simplest hydrological method. It proposes minimum environmental flow based on percentages of annual average natural runoff varying from 10% to 200% depending on season (wet/dry) and desirable river health conditions. Table S3 (Supplemental Data) shows E-flow estimates based on different ratios of mean annual flow (MAF) according to Tennant method recommendations. In order to maintain good river health, 20%-40% of MAF is required depending on season. Hydrological Eflow recommendations for maintaining good health over the Yamuna River were estimated to lie between 986.4 and 2,959.3 m³/s; for the Bhadra River, they were estimated to lie between 16.3 and 32.6 m³/s. Tennant (1980) suggested a modification to the Tennant method in order to incorporate the intra-annual variability of Eflows by allocating percentages of mean monthly flow (MMF) to calculate Eflow requirement depending on flow season (high, intermediate, and low) as shown in Table S4 (Supplemental Data). Eflow estimates for the Yamuna and Bhadra rivers based on hydrological factors using Tennant’s method are shown in Table S5 (Supplemental Data). The minimum Eflow to be maintained in the river during the dry season is 3,945.7 m³/s for the Yamuna and 5.8 m³/s for the Bhadra.

Soni et al. (2014) estimated Eflows for the Yamuna River based on hydraulic factors such as flow required to transport sediments and algal choking. They recommended maintaining at least 50% of monsoon virgin flow (estimated to be 472 m³/s) for efficient sediment transport. Similarly, 60% of nonmonsoon virgin flow (estimated to be 72 m³/s) was recommended for avoiding algal bloom. Due to the unavailability of hydraulic data and literature on the Bhadra River stretch, Bhadra Eflows based on hydraulic factors were not investigated in the present study.

In the Yamuna River, Eflow based on hydrological factors exceeds the flow requirement of the water quality factor, indicating that virgin and natural flow is sufficient to maintain CPCB Class-D river water standards in the Delhi stretch. The treatment of BOD in drains reduces the water quality—based Eflow requirement. However, the river still needs a minimum 472 m³/s of water for transporting sediments and at least 72 m³/s for preventing algal growth. In the Bhadra River, natural flow variability is too low to dilute pollution in the downstream reaches, so the demand of the water quality factor in Eflow is notably higher than the hydrological flow requirement.

**Summary and Conclusions**

In this study, the importance of water quality in estimating Eflow was illustrated by the development of a water quality model to simulate various possible scenarios. The impacts of plausible hypothetical climate change (in the form of air temperature) and pollution load scenarios on the Eflow requirement of rivers were also explored. The model was applied to the polluted river stretches of the Yamuna and Bhadra rivers. These river systems exhibit diverse characteristics in terms of water availability, regulations, and pollution. Water quality–based Eflow charts were provided for both rivers considering various climatic and pollution load conditions. Eflow charts incorporating all possible climate change and pollution reduction scenarios will help to reduce uncertainty in Eflow estimation.

The following conclusions can be drawn from this study:

- Incorporation of the water quality factor in estimating Eflow can aid in maintaining the health of river ecosystems and the desired uses of river water.
- Both river flow quantity and quality at headwaters play vital roles in maintaining desirable water quality standards in the entire stretch.
- Water quality–based Eflow values show significant change under slightly altered conditions of pollution load and changing climate.
- Existing flows in the Yamuna and Bhadra rivers are unable to maintain water quality requirements.
- Development of water quality–based Eflow charts will provide a user-friendly way to estimate Eflow in plausible scenarios of pollution and climatic conditions. Eflow charts will make application of the present approach much easier.
- Although treatment of drains is a good way to reduce the Eflow water quality requirement, a minimum flow is still necessary to facilitate the natural functioning of a river stretch.
- Scenario-based estimation of Eflow partly incorporates the timing of allocating Eflow in a river (as discussed in the Brisbane Declaration 2007), where timing specifically refers to water quality variations during dry periods.
- Recommended Eflow values for the Yamuna and Bhadra river systems are sufficient to maintain permissible water quality standards throughout the year.
- In the case of the Yamuna River, natural virgin flow is sufficient to maintain desirable CPCB Class-D river water standards in the Delhi stretch. However, the water quality Eflow requirement is insufficient to maintain the river’s hydrological and hydraulic functions.
- Natural flow availability is too low to dilute pollution in the downstream reaches of the Bhadra River; as a result, the demand of the water quality factor of Eflow is notably higher than the hydrological flow requirement.

It is important that the findings of this study are constrained by a few limiting factors. The study focused only on the water quality factor of Eflows for estimation. However, maintenance of water quality alone may not guarantee a healthy river ecosystem. The actual Eflow value of any river stretch is the maximum flow needed to satisfy Eflow requirements considering different components, as shown in Fig. 1. The present study explored the impact of air
temperature fluctuations on Eflow, leaving direct impact of altered precipitation patterns unexplored. Hydrological modeling of river basins with down-scaled climatic variables (rainfall and temperature) from various climate models can be performed to explore the impacts of climate change on streamflow. It will reveal present and future water availability, which, as indicated in Fig. 1, should be considered in a holistic Eflow analysis. In the present study, the impact of future variations in temperature was incorporated in terms of hypothetical scenarios; down-scaled future scenarios of air temperature from climate models can also be included. Even for hypothetical scenarios, a longer term average would be a more appropriate way to establish a baseline. DO and BOD were selected for water quality modeling due to the unavailability of data for other variables. The focus was on maintaining minimum DO; however, some organisms can withstand short periods of low DO with little adverse effect. The complexity of modeling the water quality of an entire river reach is considerable. Nevertheless, the approach proposed here will help to regulate diversions and storage in reservoirs and barrages built in vulnerable river stretches, and will also help to formulate policies that take Eflow demands into account. The water quality Eflow charts derived in this study for two rivers will promote better river management decisions and treatment policies along with necessary Eflow requirements in any river stretch. They will aid understanding of existing water quality, river flow, and water extractions in river systems.

Acknowledgments

The authors would like to thank the Department of Science and Technology (India) for partly supporting this study through Grant No. SB/S3/CEE/045/2014 to Dr. C. T. Dhanya. The authors sincerely thank the editor and the anonymous reviewers for reviewing the manuscript and providing insightful comments. The authors also express thanks to the Indian Institute of Technology, Delhi, for supporting this work.

Supplemental Data

Tables S1–S5 and Figs. S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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