Discussions and ClosuresClosure to“Water Quality–Based Environmental Flowunder Plausible Temperature and Pollution Scenarios

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We thank the respected discussers for appreciating the relevance of the present work, critically analyzing it, and bringing forth the possible constraints in its applicability. This discussion provides us an opportunity to elaborate the point related to the scope and applicability of original work, especially with focus on the hydrological community that otherwise would possibly remain unclarified. Because there are two discussions of our paper, we have addressed them in two different sections.

Response to the Discussion by Vinod Tare, Gautam Roy, and Suresh Kr Gurjar

In this study, we have included the *water-quality factor* in *Eflow* estimation, in addition to other factors, for the two Indian rivers. The quantity and quality of flow estimated represent the desirable standards to maintain the water quality factor of Eflow only. However, maintenance of water quality alone may not guarantee a healthy river ecosystem. Therefore, the actual Eflow value of any river stretch should be the maximum flow needed to satisfy Eflow requirements considering different factors, as shown in Fig. 1 (in the original article).

We follow the definition of Eflow as per the Brisbane Declaration 2019 (IRF 2019), that the Eflows must be described in terms of quantity, timing, and quality of freshwater flows needed to sustain aquatic ecosystems. Therefore, the Eflows estimated by the previous definition will not be a single value, but rather be a range of values for a range of scenarios. Such an extensive estimation of Eflow of any river stretch requires a humongous amount of data, which covers all the plausible scenarios over the river. In the present study, we have described and estimated Eflows as the *quantity* and *quality* of river flow required during the *low-flow* or *dry* season. Water quality requirements are often violated during the low-flow seasons; therefore, we have limited our analysis only to low-flow season. However, the same procedure can be adopted to estimate the water-quality factor of Eflow for other seasons also (though often, the flow quantity is usually high enough to satisfy the Eflow requirements in these seasons, and hence Eflow may be automatically satisfied). Additionally, it is important to understand that we are estimating the quantity and quality of river flow required to maintain the water quality requirements of river as per different Central Pollution Control Board (CPCB 2008) river water quality usage classes. The target objective is that the quantity and quality of the estimated flow should satisfy the water quality standards for the propagation of wildlife and fisheries (Class D) in the case of the Yamuna river and should maintain the drinking water source after conventional treatment and disinfection (Class C) in case of Bhadra river, during the dry season. For example, in Fig. 5 of the original article, Eflow chart under baseline conditions for maintaining CPCB Class D requirement over Delhi stretch of Yamuna river, show the desired headwater river flow (on the *Y*-axis) and desired headwater river water quality (on the *X*-axis). Therefore, we are not describing Eflow by flow quantity (one parameter) in terms of flow quality (another parameter); but rather we are describing Eflow as both the quality and quantity of flow necessary to meet the target water quality objectives (which is either CPCB Class D or Class C river water quality requirements). Further, we agree with the discussers that "flow quantities that may be required to meet desired water quality standards or other purposes are usually termed compensation flows (Acreman and Dunbar 2004) or dilution flows (Soni et al. 2014) and not Eflows." In this study, we call the flow required to be the water quality factor of Eflow, which is different from compensation flows and dilution flows, because it does not merely suggest a flow value, but also prescribes a water quality value of the flow suggested. Moreover, this study does not encourage to merely dilute or compensate the river flows; therefore, in contrary to compensation flows and dilution flows, we have considered different water quality treatment scenarios in the polluting point sources of the river and estimated the water quality factor of Eflow for each of those scenarios. Therefore, we have described the flow required to maintain the water quality as the water quality factor of Eflow.

Dissolved oxygen (DO) and biochemical oxygen demand (BOD) parameters are often considered as surrogate health indicators of the river ecosystem and are widely used to evaluate water pollution and quality of water bodies to support aquatic life and perform its natural functions. DO is indispensable for survival of aquatic ecosystems and is widely affected by introduction of organic materials (in form of BOD) in rivers. The reduction in DO concentration in rivers marks most fatal consequences such as unbalanced ecosystem, fish mortality, eutrophication, odor, toxicity, and other aesthetic nuisances (Thomann and Mueller 1987). Similarly, the level of BOD in river indicates the approximate amount of biodegradable organic matter present in water and serves as an indicator parameter for the extent of river water pollution. Therefore, DO and BOD parameters were only considered in the present study. Other parameters like chemical oxygen demand, turbidity, dissolved organic nitrogen, ammonia nitrogen, nitrate-nitrogen, phosphorus, pathogens, phytoplankton, total inorganic carbon, and algae also play role in river water quality modeling. However, their contribution to the total river water pollution is largely site-specific and depends on the incoming pollution sources. Over the Delhi segment of Yamuna river, water quality parameters, DO, and BOD have been in prime focus (Chaudhary et al. 2018, 2020; Kazmi and Hansen 1997; Jha et al. 2007; Paliwal et al. 2007; Parmar and Keshari 2012; Sharma and Singh 2009; Walling et al. 2017). The inclusion of other parameters would surely aid in representing the pollution levels in river in a more scientific way; however, due to data unavailability it was not possible in the present study. Moreover, the present study focuses on developing a generic framework incorporating the factor of water quality in Eflow estimation. The parameters of water quality can be modified according to the data availability of the study region. We agree with the discussers that the CPCB river water classes are not exhaustive and possess limited representation of the desirable Eflow quality requirements of the rivers. For example, as per CPCB Class D, 4 mg/L of DO is required to be maintained in the river for propagation of wildlife and fisheries; however, the exact DO requirement may vary from species to species. The water quality constraints as per CPCB river classes are the desired river water quality requirements of any river, which can be the same for multiple rivers or stretches. However, the quantity and quality of water required at the headwater of any river stretch in order to maintain the desired river water quality class is going to be different, because it would depend on the in-situ river water quality conditions, i.e., contribution from point/diffused pollution sources, inflow and abstraction of flow in river, hydraulic characteristics of river stretch, and reaction rates. Moreover, it is not necessary that the water quality requirements and their designated usage be same for the entire river stretch. Therefore the desirable water quality needs to be specifically determined for the river stretch in analysis, and that may be beyond the CPCB river water quality requirements.

Note that in addition to DO, BOD, pH, and free ammonia, the discussers mention “sustenance of river ecosystems involves many other water quality parameters—from elementary physical-chemical properties such as temperature, turbidity, and salinity to essential ingredients and harmful pollutants—that are not included in the CPCB” Class D River water quality guidelines. Therefore, there is need to revise and provide more comprised water quality standards for different water usages of CPCB river classes.

As pointed out by the discussers, sediments are fundamental drivers of river ecosystems, especially for alluvial river stretches, and is an important factor to be considered in estimating Eflow. Ideally, sediments and geomorphological concerns should be included while determining Eflow of any river stretch (Tare et al. 2015). Therefore, we have modified the schematic representation in Fig. 1 of the original manuscript as shown in Fig. 1. Note that Fig. 1 is merely a generalized and comprised version of various factors to be considered in Eflow determination; many other factors can be still added as per their importance over the river stretches under consideration.

The discussers have correctly pointed out the error in the flow data values of the Yamuna river. In the case of Yamuna flow data, the units of flow have been overlooked by the authors. The corrected units of Yamuna River flow values are cusecs (ft^3/s), in contrary to flow units of cumecs (m^3/s) which was erroneously written in the original article. Additionally, we have converted cusecs (ft^3/s) flow values into cumecs (m^3/s) and stated in this closure.

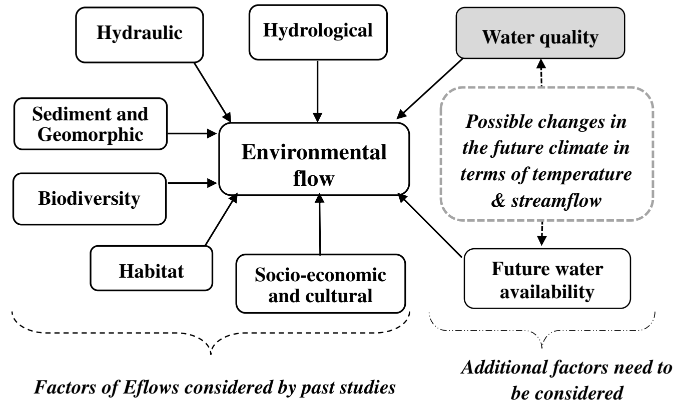

Fig. 1. Various factors that should be considered in the estimation of Eflow. The factor proposed to be considered in the present study is shaded.

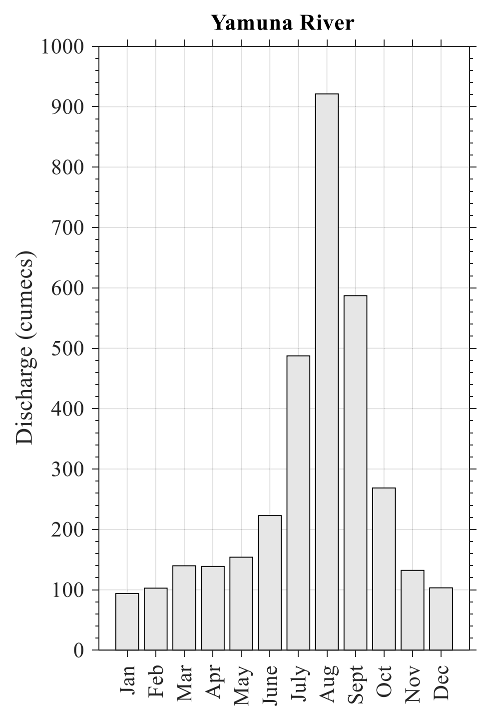

Fig. 2. Observed unregulated flow at the upstream of Hathinikund barrage on the Yamuna river over the period of 1995–2004. Units of flow are in cumecs.

Fig. 2 shows the observed unregulated flow at the upstream of Hathinikund barrage on the Yamuna river over the period of 1995–2004. The flow values are shown in Fig. 2 show close match to the data of the discussers. Detailed corrections can be found in Chaudhary et al. (2020).

The discussers have correctly stated that “in India, generally pollution mitigation at source or before discharging into water bodies is what is recommended in such cases, and where such mitigation is not affected, the polluter pays principle is applicable to compensate for damages (Dari and Sharma 2014).” In order to consider this, we have included different pollution treatment scenarios of BOD contributed by pollution drain sources in our water quality modeling exercise. Moreover, the study has also considered a 100% BOD treatment scenario, wherein the entire BOD is removed and the water is enriched with DO post-BOD treatment. Note that river water quality is often significantly influenced by anthropogenic pollution sources (Tare 2014), which may, of course, change rapidly over time. Considering this factor, a water quality model was developed over the different river stretches to predict/simulate the water quality conditions under a varied set of initial river water quality condition or pollution load conditions. Although the pollution loads are going to change in the future, the model developed and the reaction rates determined would still be applicable. Therefore, the water quality factor of Eflow can possibly be determined under plausible scenarios of future changing pollution loads using the water quality model. The water quality factor of Eflow estimated in the present study is different from the quantitative compensation flows, as the former is both qualitative and quantitative. We thank the discussers for their appreciation and understand that there is considerable complexity in estimating the Eflow over any river stretch. The present study was an attempt to estimate water quality factors of Eflow during the low-flow season. We also agree with Tare (2014) that controlling pollution sources by adopting a reuse and recycle policy is better than rather following the principle of dilution is the solution to pollution.

Response to the Discussion by Dipteek Parmar and A. K. Keshari

The water quality modeling approach adopted in the present study is elaborated for more clear understanding. QUAL2K, a one-dimensional numerical river water quality model is selected in the present study. DO and BOD are selected as the target water-quality variables for maintaining CPCB river water quality standards in the selected river stretches. Initially, the river stretch is divided into smaller segments called river reaches and the water quality model is calibrated during a low flow season period. The model parameters considered for calibration are oxygen reaeration rate, BOD hydrolysis rate, and BOD oxidation rate. More details about the selection of model parameters used in calibration can be found in Chaudhary et al. (2018), Parmar and Keshari (2012), Rehana and Mujumdar (2011), and Walling et al. (2017). The QUAL2K model is calibrated using sequential calibration technique with reach-specific parameter estimates as proposed by Chaudhary et al. (2018). The performance of DO and BOD simulations and in situ observations are compared using three different performance metrics. The calibrated model is further validated for a different time period (dry season) and the performance of model in simulating DO and BOD is further investigated. On observing satisfactory performance measures, the QUAL2K model is used to generate water quality conditions under different pollution load and hypothetical temperature change scenarios. In order to find minimum flows satisfying desired water quality requirements, headwater flow value is invariably determined by a method of successive approximation using a trial method so as to meet the desired water quality standards throughout the river stretch.

Scenarios of treatment of BOD in the drains have been explored in the present study, which will be useful in maintaining the water quality standards in the entire river stretch. However, we wanted to investigate the impact of BOD removal on the water quality factor of Eflow; therefore, we varied the BOD treatment from 0% to 100% at intervals of 20%, which gave a more comprehensive study of impact of BOD treatment on water quality factor of Eflow. However, from an application aspect, scenarios of 35%, 70%, 85%, and 95% BOD removal are more realistic and can be explored in the future. The discussers have also given three other scenarios for management over the Yamuna river stretch. Moreover, it is also necessary to mention here that it would be better to have treatment plants at the outfall of drains into the river.

The QUAL2K model is calibrated using sequential calibration technique using reach-specific parameter estimates as proposed by Chaudhary et al. (2018). The sequential and reach-specific calibration approach adopted for calibration of QUAL2K model is data intensive as it requires DO and BOD estimates at the end of each reach and sequentially estimates the model parameters separately, i.e., each reach is considered for calibration one at a time. This accounts for heterogeneity in model parameters throughout the river stretch. However, while using such numerical or statistical based calibration framework, issues related to identifiability or uncertainty of model parameters in the calibration framework may arise. Therefore, it is more appropriate to measure as many model parameters as possible in the field.

Note that apart from DO and BOD, there are the additional criteria of free ammonia for a Class D river, total coliform organisms count, and pH for Class C river as per CPCB river classifications. Similarly additional criteria like electrical conductivity, and boron and sodium absorption ratios exist for Class A, B, and E river classifications.

Over the Delhi segment of Yamuna river, there exist other minor drains in Delhi region. These are LPG Bottling Plant Drain, Shahdara Drain and Tuglakabad Drain, Kalkaji Drain, Sarita Vihar Bridge and Sarita Vihar Drains, and Tehkhand Drain (Parmar and Keshari 2018).

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