Application of a hydrological method for determining monthly environmental flow in Code River, Indonesia

Adam Rus Nugroho

1Department of Environmental Engineering, Universitas Islam Indonesia, Jl. Kaliurang Km.14.5, Sleman, D. I. Yogyakarta, Indonesia, 55584
adam.rusn@uii.ac.id

Abstract. The declining groundwater in Yogyakarta could potentially affect the Code River baseflow, thus lowering the river streamflow. Consequently, the riverine ecosystem would suffer from a low quantity of streamflow. The quantity standard of streamflow can be determined by calculating the environmental flow. In this study, the environmental flow requirement (EFR) for the Code River is determined by applying an enhanced version of the most-used hydrological method, namely the Modified Tennant Method based on Multilevel Habitat Conditions III (MTMMHC-III). The EFR in the Code River could be calculated successfully by the MTMMHC-III with a satisfactory temporal variability. The EFRs are the lowest during July to October in the normal years, July to September in the wet years, and July to December in the dry years. The EFRs are highest during January to April in the normal and dry years and January to May in the wet years. However, the EFR might become too low in the dry years, especially from the beginning of the dry season (May) until the early wet season (December), with only 4-11% of the average annual flow. Ultimately, the MTMMHC-III method is a better hydrological method than the original Tennant Method and Q95 method.

1. Introduction

Environmental flow is defined as the required flow for sustaining aquatic ecosystems, which, in turn, will support human life aspects [1]. Water is required not only for humans but also for the natural ecosystem. In this modern industrial era, the water for the ecosystem is less important than for humans. This means that water abstraction for human needs often leaves the river with a low amount of water. Hence, environmental flow assessment, most of the time, is associated with low flow.

The low level of streamflow introduces many problems to a riverine ecosystem. Low flows can control the extent of the physical aquatic habitat, mediate changes in habitat conditions, affect the exchange of energy in riverine ecosystems, and restrict the connectivity and diversity of the habitat [2]. Low flow is also linked to poor water quality, explained by its assimilative capacity and dilution capability [3,4]. The assimilative capacity refers to the water’s self-purification ability to degrade pollutants. The natural assimilative capacity of water is usually assumed to increase in a higher flow due to more dissolved oxygen and microorganisms. Additionally, more pollutants are diluted in a higher flow, giving a lower pollutant concentration.

In hydrology, low flow is associated with groundwater storage. In a dry season, when rainfall does not occur for a long period, the streamflow discharge is composed entirely of the baseflow, that is, the river inflow from groundwater storage [5]. Consequently, the quantity of groundwater becomes crucial for sustaining the riverine ecosystem in a dry season.
The declining groundwater level is known to be a critical water resources issue in the Yogyakarta region. The growth of tourist accommodation in Yogyakarta City has led to the increasing groundwater abstraction and the declining groundwater table level. In 2013, it was reported that the groundwater level had decreased by ±3 m on average compared to the groundwater level in 1984 [6]. In 2018, it was known from a groundwater model simulation that for the next ten years, the groundwater level will decrease by up to 1.2 m in the main road of Malioboro, the most famous tourist spot in Yogyakarta [7]. Given the groundwater problem, the low flow of the Code River might dynamically change in the future.

Concerning the issues that can potentially emerge with low river flows, it is essential to determine the environmental flow in the Code River, aiming for its sustainability. There are four categories of environmental flow assessment methods: hydrological, hydraulic rating, habitat simulation, and holistic methods [8]. With the currently available data resources for the Code River, it is only possible to assess environmental flow by the simplest method, which is the hydrological method. Additionally, the hydrological method is appropriate for the planning level of water resource development or when determining the preliminary flow targets [8]. Therefore, this study aims to calculate the environmental flow requirement (EFR) in the Code River using hydrological methods.

2. Study Area

The Code River is a small river basin with a catchment area of 40 km² located in the Special Region of Yogyakarta Province, in Java, Indonesia (Figure 1). The river has been important for Yogyakarta’s society since the 1980s [9] and has been acknowledged by society for its aesthetic value [10] and tourism potential [11]. The Code River travels 41 km from the Merapi Mountain to the Opak River in the south and has two streamflow gauging stations, one in the Pogung area (midstream) and the other in the Kaloran area (downstream). The midstream basin is the municipal area of Yogyakarta City, while the downstream basin is a less populated area.

Yogyakarta Province has tropical savanna (Am) and tropical monsoon (Aam) climate types, as defined by the Köppen climate classification. The tropical climate makes a region typically has only wet and dry seasons. The region of Yogyakarta has dry months from May to October (peak in August) and wet months from November to April (peak in January or February). The recorded annual rainfall occurring in the Yogyakarta region was between 400 and 3600 mm. The average temperature in the Yogyakarta region varies from 22 °C to 27 °C.

Figure 1. Code River location in Yogyakarta, Indonesia.
3. Materials and Methods

3.1. Data
The data used in this study is the streamflow data in the Kaloran gauge station (Figure 1) downstream of the Code River. The data were obtained from the Research Center for Water Resources under the Indonesian Ministry of Public Works and Housing. The daily streamflow data of the downstream Code River observed by Kaloran gauge station were available for 1994–2018 with four years (2006–2009) missing (Figure 2).

![Figure 2. Time-series of Code River average monthly flow at Kaloran gauge station (downstream).](image)

3.2. Low flow index
Stalnaker and Arnette [12] recommended some specific flow percentiles to support various ecological processes. The flow duration curve (FDC) flow distribution is used to determine the percentile of flow exceedance. In Indonesia, the government regulation for the river (PP RI No. 38/2011) states that the maintenance flow (Indonesian term for environmental flow) is determined as Q_{95}. The Q_{95} is defined as the flow which is exceeded 95% of the time. The Q_{90} and Q_{95} are frequently used as low flow indicators and have been widely used to set the minimum environmental flow [13]. In this study, Q_{95} as the low flow index is compared to the main method, a modified Tennant Method.

3.3. Modified Tennant Method
The most frequently used hydrological method for assessing environmental flow is the Tennant Method [8]. The Tennant Method assumes that some proportion of the average annual flow (AAF) is required to sustain the biological integrity of a river ecosystem. Based on field data collected from 11 rivers in Montana, Nebraska, and Wyoming, and additional data from hundreds of gauged flow regimens in 21 states, Tennant [14] recommended the percentage values of AAF predicted to sustain predefined ecosystem attributes for the North-Central USA region (Table 1).

The Tennant Method’s main limitation is that its application in streams other than those where it was developed may provide inaccurate environmental flow standards [12]. One of the spatial issues is the stream’s physical characteristics. It has been pointed out that Tennant’s original dataset only represented low gradient streams with less than 1% slope [15]. Hence, the original Tennant Method is not suitable for the Code River, along which most reaches have slopes of more than 1%.

Many modifications of the Tennant Method have been proposed to accommodate better variations in hydrologic regimes in various geographic areas [8]. Li and Kang [16] classified the modified Tennant Method (MTM) into: 1) MTM based on a single habitat condition (MTMSPHC), 2) MTM based on multilevel habitat conditions (MTMMHC), and 3) MTM based on specific bio-physical requirements (MTMBPR). The MTMMHC is used to determine the environmental flow for several levels of habitat conditions, from poor to optimum, just like the original Tennant Method.
Table 1. Environmental flow as % of average annual flow (AAF) recommended by the original Tennant Method [14].

| Flow Classes                  | Recommended flows (% AAF) |
|-------------------------------|---------------------------|
|                               | Oct-Mar (non-flood season) | Apr-Sep (flood season) |
| Flushing or maximum           | 200                        | 200                     |
| Optimum                       | 60-100                     | 60-100                  |
| Outstanding                   | 40                         | 60                      |
| Excellent                     | 30                         | 50                      |
| Good                          | 20                         | 40                      |
| Fair or degrading             | 10                         | 30                      |
| Poor or minimum               | 10                         | 10                      |
| Severe degradation            | 0-10                       | 0-10                    |

This study applied the MTMMHC-III proposed by Li and Kang, who claim it to be more reasonable than the previously modified Tennant Methods [16]. The MTMMHC-III solves the temporal variability problem by dividing water years based on the guaranteed rate (GR) of the average monthly flow (AMF) series instead of the average annual flow (AAF) series like the previous MTMs. The MTMMHC-III also solves the spatial variability problem by making sure of two points. First, the influence of extreme inter-annual flow events and uneven intra-annual distribution can be avoided by the upper boundary of the optimum environmental flow. Second, the minimum environmental flow can change with the flow regime. The following steps are required to apply the MTMMHC-III by considering the temporal (steps 1-3) and spatial (step 4) variability:

1) select natural daily flow series and group the data into 12 months,
2) calculate the AMF for every year by taking the average of daily flow data in each month,
3) divide the AMF series into wet years (GR<25%), normal years (25%<GR<75%), and dry years (GR>75%) based on the guaranteed rate (percentile) of the AMF,
4) the corresponding environmental flow in different water years is calculated by equation (1).

\[ E_{n}(i,j) = Q_{90(i,j)} + (n-1) \left( Q_{90(i,j)} - Q_{90(i,j)} \right)/9, \quad n = 1, 2, \ldots, 10 \]  \hspace{1cm} (1)

Where \( E \) is the environmental flow requirement (EFR) with flow class \( n \) from 1 to 10 (\( E_1 \): minimum; \( E_2 \): fair; \( E_3 \): good; \( E_4 \): excellent; \( E_5 \): outstanding; \( E_6-E_{10} \): optimum); \( i \) represents months (January to December); \( j \) refers to the water year (wet, normal, or dry); \( Q_{90} \) and \( Q_{50} \) are the 90% and 50% flow exceedance of the daily flow series, respectively.

The MTMMHC-III also improves scalability by reducing the classification number between the minimum environmental flow (\( E_1 \)) and optimum environmental flow (\( E_6-E_{10} \)). However, this scalability setup is established mainly for large rivers with even inter-annual flow distribution [16]. Because the Code River has a small catchment (40 km²) and high flow variability (monthly coefficient of variation = 0.67–1.44), it is unnecessary in this study.

4. Results and Discussion

4.1. Monthly flow characteristics

The average monthly flow (AMF) and the other monthly flow statistics are shown in Figure 3. The dry season occurs from May to October, while the wet season occurs from November to April. The \( Q_{95} \) flow at the beginning of the dry season (May) is below 1.0 m³/s, and it decreases more in the next few months, with the lowest \( Q_{95} \) (0.1 m³/s) in August and September. The \( Q_{95} \) increases slowly from October until the end of the year. November and December still have low flow variance despite the wet season. This
low flow variability showed that the tropical region’s environmental flow standard should be dynamic with different months or seasons.

The flow variability in the Code River is high in most months (Figure 3a). The coefficients of variation (CV) for each month, respectively from January to December, are: 0.77, 0.67, 0.71, 0.76, 1.43, 0.71, 0.92, 1.07, 1.07, 1.16, 1.11, and 1.27. These values showed that the variability is the highest during the dry season and the beginning of the wet season. This also indicates that the onset of the wet season has high variability. The monthly flow duration curve (Figure 3b) also indicates the high variability in most of the months in the dry season (May–October) by the irregular curves around the 10% percentile.

Figure 3. Intra-annual monthly flow (a) statistics and (b) flow duration curve (FDC) of Code River.

4.2. Environmental Flow Requirement (EFR)

The MTMMHC-III method to calculate the EFR from Li and Kang [16] is applied for the streamflow of the Code River downstream. The results are shown in the percentage of annual average flow (AAF) and divided into three water year groups, namely normal years (Table 2), wet years (Table 3), and dry years (Table 4). The AAF for determining the percentages in the tables is calculated by averaging the AAF series of all years. It is recommended to update the EFR calculation every year by calculating the new AAF with additional observation data, so the accuracy of the EFR will be improved.

It is important first to determine the EFR of normal years since it is the most frequent occurrence of all time. The dry years come second in importance, as it is critical to apply the EFR in the dry season, especially on small basins such as the Code River. Finally, the wet years are important concerning the temporal variability, as many hydrological methods focus only on low flow. It is often ignored that in a wetter condition, the standard of EFR can be set higher to provide better ecosystem sustainability.

Moreover, the high variability in some river basins should also be a concern.

The 1994–2018 streamflow data calculation suggests that the minimum EFR (E1) in a normal water year is 32–73% AAF during the wet season and 18–44% AAF during the dry season. Overall, the EFR in normal years is the lowest from July to October, with a minimum EFR of 18–25% AAF or 0.40–0.55 m³/s. Moreover, the minimum EFR in dry years becomes only 4–5% AAF or 0.08–0.11 m³/s from July to December (Table 4 and Figure 4a). The minimum EFR is the flow that should be satisfied to sustain the short-term survival habitat for aquatic organisms [14]. The calculated EFR in the dry season might be too low to conserve the habitat’s suitability for aquatic organisms. However, it requires a field study using physical approaches, such as the habitat simulation method (e.g., PHABSIM), to confirm this.

The optimum EFR is used to explain how much water a basin needs to achieve the best conservation of the ecosystem. The MTMMHC-III defines the optimum EFR as E6, E7, E8, E9, and E10. The Eo, or the lower bound of the optimum EFR for the Code River in the normal years, is at 55–95% AAF during the wet season and 32–56% AAF during the dry season. In the wet years, the Eo is at 114–178% AAF during the wet season and 83–152% AAF during the dry season. In the dry years, the Eo becomes 7–53% AAF during the wet season and 6–18% AAF during the dry season. The calculation of the actual EFR showed
that, in the dry years, $E_s$ (Figure 4b) does not differ very much from $E_i$ (Figure 4a). This could go against the purpose of $E_i$, which is intended as an optimum quantity of flow.

### Table 2. EFR standard (% of average annual flow) for Code River in normal water years.

| Class | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $E_1$ | 52  | 73  | 73  | 59  | 37  | 44  | 25  | 20  | 22  | 18  | 32  | 41  |
| $E_2$ | 57  | 77  | 78  | 62  | 41  | 46  | 28  | 23  | 24  | 21  | 37  | 46  |
| $E_3$ | 62  | 82  | 82  | 65  | 45  | 49  | 32  | 26  | 27  | 24  | 41  | 50  |
| $E_6$ | 66  | 87  | 86  | 68  | 48  | 51  | 36  | 29  | 29  | 27  | 46  | 55  |
| $E_5$ | 71  | 91  | 91  | 70  | 52  | 53  | 39  | 32  | 31  | 30  | 51  | 59  |
| $E_6$ | 76  | 96  | 95  | 73  | 56  | 56  | 43  | 36  | 33  | 33  | 55  | 64  |
| $E_7$ | 81  | 101 | 100 | 76  | 60  | 58  | 47  | 39  | 36  | 35  | 60  | 69  |
| $E_8$ | 86  | 105 | 104 | 78  | 64  | 60  | 50  | 42  | 38  | 38  | 65  | 73  |
| $E_9$ | 90  | 110 | 109 | 81  | 68  | 63  | 54  | 45  | 40  | 41  | 69  | 78  |
| $E_{10}$ | 95 | 115 | 113 | 84  | 71  | 65  | 58  | 48  | 42  | 44  | 74  | 82  |

### Table 3. EFR standard (% of average annual flow) for Code River in wet water years.

| Class | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $E_1$ | 129 | 118 | 132 | 95  | 93  | 74  | 71  | 71  | 66  | 93  | 74  | 66  |
| $E_2$ | 135 | 129 | 141 | 103 | 105 | 79  | 74  | 74  | 70  | 100 | 84  | 76  |
| $E_3$ | 142 | 140 | 151 | 112 | 117 | 84  | 76  | 76  | 73  | 108 | 94  | 86  |
| $E_6$ | 149 | 152 | 160 | 120 | 129 | 89  | 79  | 79  | 77  | 116 | 104 | 95  |
| $E_5$ | 155 | 163 | 169 | 128 | 141 | 94  | 81  | 81  | 80  | 124 | 114 | 105 |
| $E_6$ | 162 | 174 | 179 | 137 | 153 | 98  | 84  | 84  | 84  | 132 | 125 | 115 |
| $E_7$ | 168 | 186 | 188 | 145 | 165 | 103 | 87  | 87  | 87  | 140 | 135 | 124 |
| $E_8$ | 175 | 197 | 198 | 154 | 177 | 108 | 89  | 89  | 91  | 147 | 145 | 134 |
| $E_9$ | 182 | 208 | 207 | 162 | 189 | 113 | 92  | 92  | 94  | 155 | 155 | 143 |
| $E_{10}$ | 188 | 219 | 216 | 171 | 201 | 118 | 94  | 95  | 98  | 163 | 165 | 153 |

### Table 4. EFR standard (% of average annual flow) for Code River in dry water years.

| Class | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $E_1$ | 27  | 25  | 41  | 21  | 9   | 11  | 4   | 4   | 4   | 5   | 4   | 4   |
| $E_2$ | 28  | 28  | 43  | 24  | 10  | 13  | 5   | 5   | 4   | 5   | 5   | 4   |
| $E_3$ | 28  | 31  | 46  | 27  | 12  | 14  | 6   | 5   | 6   | 6   | 6   | 5   |
| $E_6$ | 29  | 33  | 48  | 30  | 13  | 16  | 7   | 6   | 5   | 6   | 7   | 6   |
| $E_5$ | 29  | 36  | 51  | 33  | 15  | 17  | 8   | 7   | 6   | 7   | 8   | 7   |
| $E_6$ | 30  | 39  | 53  | 36  | 16  | 19  | 9   | 8   | 7   | 9   | 8   | 8   |
| $E_7$ | 31  | 42  | 56  | 39  | 17  | 20  | 10  | 9   | 7   | 8   | 10  | 9   |
| $E_8$ | 31  | 44  | 58  | 42  | 19  | 22  | 11  | 10  | 8   | 8   | 11  | 10  |
| $E_9$ | 32  | 47  | 60  | 44  | 20  | 23  | 12  | 11  | 8   | 9   | 12  | 10  |
| $E_{10}$ | 32 | 50  | 63  | 47  | 22  | 25  | 14  | 12  | 9   | 9   | 13  | 11  |
4.3. Comparison with the other methods

The EFR in the dry years is similar to the EFR calculated by the monthly $Q_{95}$ method. Although there are two other ways to calculate $Q_{95}$ [17], these only provide a single value in a year: 0.10 m$^3$/s (minimum monthly $Q_{95}$) and 0.23 m$^3$/s ($Q_{95}$ of all data). Additionally, the $Q_{95}$ methods do not have any classes for EFR, so it always has the same values on all EFR classes defined by the Tennant Methods. In summary, the MTMMHC-III method has an advantage in adding the variability of water years and the different EFR values for ten classes.

The original Tennant Method is also compared in this study. The lack of intra-annual temporal variability in the original Tennant Method explains why MTMMHC-III is better than the original Tennant Method. The original Tennant Method only gives a single EFR value for one year, just like the $Q_{95}$ methods. However, the Tennant Method is still better than the $Q_{95}$ methods because the Tennant Method provides different values for several EFR classes. The original Tennant Method has a minimum EFR similar to the $Q_{95}$ and MTMMHC-III dry water year for May-December (Figure 4a). It also has an optimum EFR similar to the average measure of the MTMMHC-III normal water year. The EFR calculation in MTMMHC-III, which incorporates the $Q_{50}$ and $Q_{90}$, is suitable for rivers with different flow regimes. In summary, the MTMMHC-III method has an advantage in terms of the water years variability and the spatial variability compared to the original Tennant Method.

5. Conclusion

This study applied the modified Tennant Method by Li and Kang [16], namely MTMMHC-III, to determine the monthly environmental flow requirement (EFR) in the Code River. The MTMMHC-III has three modifications to improve the original Tennant Method: temporal variability, spatial variability, and EFR criteria scalability. Due to the characteristics of the basin, only the first two points are applied in the Code River. This method has two kinds of temporal variability: the intra-annual variability and the water year variability.

The EFR in the Code River could be calculated successfully by the MTMMHC-III method with a satisfactory temporal variability. However, several points should be noted:

- The EFRs are the lowest during July to October in the normal water years, July to September in the wet years, and July to December in the dry years. October is the lowest in the normal water year, and September is the lowest in the wet and dry water years.
- The EFRs are the highest during January to April in the normal and dry years and January to May in the wet years. The peaks for all water year groups are in March.
- The EFR in the dry water years might become too low, especially from the beginning of the dry season (May) until the early wet season (December), with only 4-11% of AAF.
- In the dry water year, the optimum EFR ($E_6$) does not differ very much from the minimum EFR ($E_1$). This indicates a difficulty in setting an optimum EFR with the poor flow in dry years.
The last two points are the problems in determining the flow standard to conserve the riverine ecosystem in the Code River. With this finding, the EFR standard should be determined more carefully in the Code River. It may also suggest that such a problem would arise for other small river basins with high variability like the Code River.

Due to its improved temporal and spatial variability, the MTMMHC-III method is proven to be better than the original Tennant Method and the Q95 method adopted by the Indonesian regulation. It is therefore recommended to consider this method as a simple method for determining the EFR in Indonesia.

In general, this study contributes to environmental flow studies in Indonesia, which are still lacking. However, this study is only a preliminary assessment of the environmental flow in the Code River. Many aspects should be considered in the future environmental flow assessment in the Code River. The hydrological method may be enough in this early stage with the data limitation. However, to improve the result’s linkage to the ecosystem or the target of environmental flow, whenever the resources are possible, it is recommended to apply a habitat simulation or a more advanced method for assessing the environmental flow.

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