LDCP FRAMEWORK FOR SETTING LOAD LIMITS IN URBAN CATCHMENTS

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ABSTRACT

Setting enforceable quality and quantity limits is a key purpose of the National Policy Statement for Freshwater Management (NPS FM). Setting limits in terms of catchment loads is supported by NPS FM. Therefore, it is important that stakeholders have a reliable means to determine the catchment load levels for various pollutants and accordingly set the limits. In urban catchments, the fate and transport of different pollutants depends on a number of conditions including catchment characteristics, weather conditions, stormwater management practices, and chemical properties of pollutants. The observed water quality displays variability depending on temporal and spatial scales of the data, which are controlled by sampling frequency and range. This makes it difficult to determine load limits at daily or weekly or monthly frequency.

In this paper, we present a "Load Duration and Catchment Prioritization" (LDCP) framework approach to characterize water quality and enable limit settings. This framework determines loading capacities for each sub-catchment. It accounts for how stream flow patterns affect changes in water quality over the course of a year. Using this framework, the frequency and magnitude of water quality standard exceedances, allowable loadings, size of load reductions, and catchment (or sub-catchment) prioritization are determined.

The underlying premise of the LDCP framework is correlation of water quality impairments to flow conditions. It helps identify maximum loads for a given time unit (day or week or month) which account for the variable nature of water quality associated with different stream flow rates. This framework provides a reasonable way to define allocations which reflect differences in the types of sources that may be dominant under various flow conditions. Allocations represent those portions of a receiving water's loading capacity attributed to point sources or to nonpoint sources and natural background. Hence, it is useful to understand the load seasonality as well as the effect of temporal scale on load variability and water quality violations.

In the LDCP framework, each sub-catchment can be ranked according to the relative water quality improvement needed based on pollutants of concern, pollutant loadings, impairments in receiving waters, and regulatory requirements. This helps to develop a Catchment Prioritization Index (CPI) for each sub-catchment area. The CPI represents the relative water quality improvement needed for each sub-catchment on a scale from 1-5 with 5 indicating the highest need for improvement.

A major advantage of LDCP framework in loading capacity development is the ability to provide meaningful connections between allocations and implementation efforts. Because the flow duration interval serves as a general indicator of hydrologic condition (i.e., wet versus dry and to what degree), allocations and reduction targets can be linked to source areas, delivery mechanisms, and the appropriate set of management practices.

KEYWORDS

Urban Catchment, Load Limits, Load Reduction, Catchment Prioritization

PRESENTER PROFILE

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1 INTRODUCTION

The National Policy Statement for Freshwater Management (NPS-FM) provides national direction under the Resource Management Act 1991. It requires councils to set objectives and limits for fresh water quality and quantity (MfE, 2014). In rural catchments, contamination mostly arises from farm land. In contrast, contaminants in urban catchments are derived from a number of sources including road surfaces, building roofs and walls, industrial sites, and other impervious surfaces including pavements, driveways and parking areas as well as atmospheric deposition. Contaminant composition and quantity varies according to activities and land use. Contaminant loads are typically greater in urban sub-catchments where residential, commercial and industrial land uses predominate and in sub-catchments with roads carrying high vehicle numbers compared with rural sub catchments. Due to these differences, it is not suitable to apply common load limits for different catchments.

A few cities in New Zealand use a Contaminant Load Model (CLM) which is an annual stormwater contaminant load (spreadsheet-based) model (Council, A.R., 2010 and Golder Associates, 2014). It calculates loads based on land use areas and representative loading rates. It is a simple mathematical model where source load is equal to the source area times the source yield. The total load is simply the sum of individual source loads within a designated area. This model has numerous limitations including –

- Results are estimates of annual contaminant loads from large heterogeneous urban areas. The estimates are based on average pollutant loads. The spatio-temporal dynamics of loadings from sub-catchments is not captured.
- Water quality characterizations for various flow conditions, rather than a single flow such as average daily flow value of the water way, are not considered.
- Applying the model to smaller catchments (less than 20 ha) leads to incorrect estimates.

- If pervious area is more than 20% of the total area of the catchment, the model results are uncertain.
- The CLM does not provide any guidance for selecting suitable stormwater management options (treatment devices) for a particular catchment.

As a result, CLM cannot be used as a basis to determine loading capacity or set load limits at different flow regimes, and hence set target for sub-catchment specific improvements to meet National Policy Statement – Freshwater Management (NPS-FM) requirements.

To address the above gaps, we propose a new framework as described in the following section.

2 PROPOSED FRAMEWORK

2.1 OVERVIEW

The fate and transport (or concentration and distribution) of different pollutants within catchments depends on a number of conditions including characteristics and weather conditions, urban management practices, and chemical properties of pollutants. As a result, water quality in the receiving waters is subject to temporal and spatial variability. Accordingly, observed water quality data may also display variability depending on temporal and spatial scales of the data. The temporal variability in observed data is essentially controlled by sampling frequency. City, District and Regional Councils regularly (monthly, weekly, or at a higher frequency) monitor concentrations of different pollutants in different sites within streams and rivers to make sure that pollution concentrations/loads are not above water quality standards. In contrast to flow monitoring, water quality data might not be sufficient to effectively characterize the spatial and temporal variability of the catchment in terms of loading. Therefore, it is important that stakeholders have a reliable means to analyse the load levels for various pollutants.

The proposed "Load Duration and Catchment Prioritization (LDCP)" framework characterizes water quality concentrations at different flow regimes across the catchment. Using this framework, the frequency and magnitude of water quality standard exceedances, allowable loadings, and size of load reductions are easily presented and can be better understood. Most importantly, this method accounts for how stream flow patterns affect changes in water quality over time. The resultant output shows the percentage time or duration interval for which a given value of a pollutant load is equaled or exceeded within a particular sub-catchment.

LDCP framework helps in developing loading capacities for each sub-catchment. The loading capacity is defined as the maximum amount of loading that a water can receive without violating water quality standards. The loading capacity provides a reference, which helps guide pollutant reduction efforts needed to bring a water into compliance with standards. Reduction estimates can be developed for each zone, which serve to guide problem solving discussions on appropriate management strategies.

The underlying premise of LDCP framework is correlation of water quality impairments to flow conditions. This approach is particularly applicable in catchments where stream flow is an important factor in the determination of loading capacities. The use of this framework helps identify maximum daily load which accounts for the variable nature of water quality associated with different stream flow rates. With this approach, the maximum daily load can be identified for any given day based on the stream flow.

Basic hydrology represents a logical starting point to identify the loads. Loads are directly proportional to flows. Water quality parameters are often related to stream flow rates. Surface runoff following rain events can be one of the most significant transport mechanisms of sediment and other nonpoint source pollutants. Precipitation is the driving mechanism responsible for storm flows and associated surface runoff. For instance, sediment concentrations typically increase with rising flows as a result of factors such as channel scour from higher velocities. Thus, flow patterns play a major role when differentiating diffuse loads from point source loads.

Flow patterns for streams can be highly variable due to various catchment characteristics and weather conditions. Flow data can be analyzed to evaluate the hydrologic conditions (e.g. wet or dry conditions and to what degree) and interpret the associated water quality data. A flow duration curve (FDC) is typically used to examine the cumulative frequency of historic flow data over a specified time period and to relate flow values to the percent of time those values have been equalled or exceeded). The use of "percent of time" provides a uniform scale ranging between 0 and 100. Thus, the full range of stream flow data is considered. Low flows are exceeded a majority of the time, while high flows are exceeded infrequently (USEPA, 2007).

Flow duration curves are a type of cumulative distribution function. The flow duration curve represents the fraction of flow observations that exceed a given flow at the site of interest. The plotting of a flow duration curve requires the sorting of daily discharge rates from the highest to the lowest value, and the plotting sorted data, with flow on y-axis and percent of time flow is equaled or exceeded on x-axis. Using this convention, flow duration intervals are expressed as a percentage, with zero corresponding to the highest stream discharge and 100 corresponding to the lowest (i.e., drought conditions). Other sorted flow regimes assigned in the duration curves are 10, 40, 60, and 90 percentiles. In this way, flow duration curves provide the added benefit of looking at the full range of flow conditions.

Use of flow duration curves can help examine general catchment response patterns. Flow duration curve analysis identifies intervals, which can be used as a general indicator of hydrologic condition (i.e., wet versus dry and to what degree). Flow duration curve intervals can be grouped into several broad categories or zones. These zones provide additional insight about conditions and patterns associated with the impairment.

A common way to look at the flow duration curve is by dividing it into five zones [USEPA 2007] - high flows, moist conditions, mid-range flows, dry conditions, and low flows. These five zones can be used to explain catchment characteristics and flow patterns according to hydrologic conditions. Based on these zones, streamflow can be separated into base-flow and surface-runoff components.

Once a flow duration curve is constructed, it serves as the foundation for developing the load duration curve. The curves are developed by multiplying stream flow rate with the numeric water quality target for the pollutant of concern. The loading capacity, which sets the maximum daily load on any given day, is determined by the flow on the particular day of interest. The result provides a visual display of the relationship between stream flow and loading capacity in each sub-catchment. The use of duration curve zones can help provide a simplified summary through the identification of discrete loading capacity points by zone. The zones can be used to define allocations, which represent those portions of a receiving water's loading capacity attributed to point sources or to nonpoint sources. Based on the duration of flow and load data, this framework is useful to understand the effect of temporal scale on load variability (seasonal variations) and water quality violations.

Please note that the duration curve alone does not consider specific fate and transport mechanisms, which may vary depending on catchment or pollutant characteristics. Such processes may include sediment attenuation, plant uptake of nutrients, chemical transformations, or bioaccumulation.

Ambient water quality data, taken with some measure or estimate of flow at the time of sampling is used to compute an instantaneous load. Using the relative percent exceedance from the flow duration curve that corresponds to the stream discharge at the time the water quality sample was taken, the computed load can be plotted in a duration curve format. By displaying instantaneous loads calculated from ambient water quality data and the daily average flow on the date of the sample (expressed as a flow duration curve interval), a pattern develops, which describes the characteristics of the water quality impairment under various flow conditions. Loads that plot above the curve indicate an exceedance of the water quality criterion, while those below the load duration curve show compliance.

Once the loading capacities for each sub-catchment are identified, the next step to identify the order of relative need for water quality improvement across all the sub-catchments is quantified by Catchment Prioritization Index (CPI). The CPI value indicates the degree of water quality impairment in the sub-catchment and provides a means to facilitate the targeting of mitigation measures (Cho and Park, 2013). A higher CPI value indicates that proportionately more mitigation measures are required to improve water quality as compared to lower CPI values. The values are calculated by multiplying normalized pollutant loads for every sub-catchment with weight of each pollutant according to its location across the five zones of flow patterns. Highest weight (5) is given to loads observed in "High Flows" zone as these loads are generated from diffuse sources of pollution. Lowest weight (1) is given to loads observed in "Low Flows" zone as these loads are discharged from point sources of pollution. In reality, more mitigation measures are required to reduce diffuse pollution as compared to point source pollution. Hence, higher weights are associated with flow zones corresponding to diffuse pollution.

2.2 BENEFITS OF THE LDCP FRAMEWORK

The LDCP framework provides a reasonable way to define allocations because it allows adjustments, which reflect differences in the types of sources that may be dominant under various flow conditions. Allocations represent those portions of a receiving water's loading capacity attributed to point sources (waste load allocations) or to nonpoint sources and natural background. For instance, in effluent dominated streams wastewater treatment facilities (WWTFs) exert a significant influence on water quality at low flows. Therefore, the allocation or portion of the loading capacity attributed to WWTFs can be greater in the low flow zone. Similarly, runoff from nonpoint sources tends to dominate water quality under high flow conditions. Thus, the allocation or portion of the loading capacity for nonpoint sources can be greater under moist and high flow conditions using this framework.

In general, load duration curves are useful to understand the effect of temporal scale on load variability and water quality violations. In this framework, catchment water quality characterizations are based on overall flow conditions rather than on a single flow event. Hence, this framework provides a good opportunity for determination of appropriate loading reduction targets.

The utility of duration curve zones for pattern analysis can be further enhanced to characterize wet-weather concerns. Stream discharge measurements on days preceding collection of the ambient water quality sample may also be examined by comparing the flow on the day the sample was collected with the flow on the preceding day. Any one-day increase in flow (above some designated minimum threshold) is assumed to be the result of a surface runoff event (unless the stream is regulated by an upstream reservoir).

A major advantage of this framework is the ability to provide meaningful connections between allocations and implementation efforts. Because the flow duration interval serves as a general indicator of hydrologic condition (i.e., wet versus dry and to what degree), allocations and reduction targets can be linked to source areas, delivery mechanisms, and the appropriate set of management practices. The use of duration curve zones (e.g., high flow, moist, mid-range, dry, and low flow) allows to define allocations, which can be used to summarize potential implementation actions that most effectively address water quality concerns.

The Catchment Prioritization Index (CPI) could be used as a risk assessment index by catchment managers to help locate critical source areas of contaminants within catchment. CPI directs catchment managers to the possible problem areas of contamination in the catchment, thus enabling those areas to be assessed and resources to be focused in an efficient manner.

The primary strengths of the proposed framework are in the minimal data requirements, simplicity, and as an illustrative model.

2.3 APPLICATION

The proposed LDCP framework was applied to the Hutt River catchment.

2.3.1 HUTT RIVER CATCHMENT DESCRIPTION

The Hutt River is a steep alluvial river that starts in the Tararua Ranges and enters Wellington Harbour at Petone. The river drains mountainous terrain in the southern Tararua and Rimutaka Ranges and streams and rivers from the Eastern and Western Hutt hills. The catchment covers an area of 655 km^2 and contains the Hutt River East and West, the Akatarawa, Pakuratahi and Mangaroa Rivers. All of these rivers feed into the Hutt River.

2.3.2 MONITORED DATA

Flow and water quality data were obtained from the publicly available data portal hosted by Greater Wellington Regional Council [GWRC 2017]. Data was collected for one year duration (1st December 2015 to 30th November 2016). The flow data was obtained from locations – Hutt River at Taita Gorge, Hutt River at Birchville, and Mangaroa River at Te Marua. Water quality data (E.coli in cfu/100ml) was collected from locations – Hutt River at Birchville, Mangaroa River at Te Marua, Waiwhetu Stream at Whites Line East, and Akatarawa River at Hutt Confluence.

2.3.3 MODEL SETTINGS

In this study, MIKE 11 (DHI, 2004) was used to simulate the flow of the Hutt River along with the discharges of its tributaries (such as Akatarawa River and Mangaroa River).

MIKE 11 is a modelling system for the simulation of flows, water levels, sediment transport and water quality for rivers, flood plains, irrigation systems, estuaries and other water bodies (Wang et al., 2009). MIKE 11 computes unsteady water levels and flow in rivers and estuaries using an implicit, 1D, finite-difference formulation. A rainfall-runoff (RR) model and hydrodynamic (HD) model for the Hutt River were developed in MIKE 11. The HD model was developed and refined over a number of years, for flood investigation purposes. As part of a separate exercise to develop a flood forecasting system for the Hutt, a rainfall-runoff model was developed using the RR model. The RR model was calibrated and verified based on measured data including rainfall, evaporation, water level and discharge. The model calibration was carried out against the flow data recorded at different locations along the Hutt River (mentioned in Section 2.3.2). So the runoff data could be obtained using the rainfall-runoff model. Both the RR and HD models were run together over the period 1st December 2015 to 30th November 2016, with rainfall records as the input, to generate sub-catchment and river flows for the period.

2.3.4 RESULTS AND DISCUSSION

The simulated flows from the calibrated model were used to generate the flow duration curves and corresponding load duration curves. The water quality criterion used for generating the load duration curve was 540 E. coli cfu/100 ml [Larned et al. 2016]. Observed water quality loads were computed by multiplying the stream flow at the time when the water quality data was recorded by the concentration data.

The resultant load duration curve (as shown in Figures 1 to 4) for each of the four locations was categorized into five zones – one representing high flows (0-10%), another for moist conditions (10-40%), one covering mid-range flows (40-60%), another for dry conditions (60-90%) and one representing low flows (90-100%). This categorization allowed us to examine the pattern of impairment across all flow conditions. Observed pollutant loads were plotted in the figures as red diamond markers. The loads were observed to be spread across zones. This implied potentially different sources of pollutant loads. For instance, in Figure 3, the observed loads (in red diamonds) exceeded the standard loads in three zones. Loads in "Dry Conditions" zone indicated that these loads were generated from point sources of pollution. The pollutant delivery related to runoff from impervious areas with light rain, or from saturated soils would have caused pollutant loads to exceed standards in "Moist Conditions" or "Mid-range Flow".

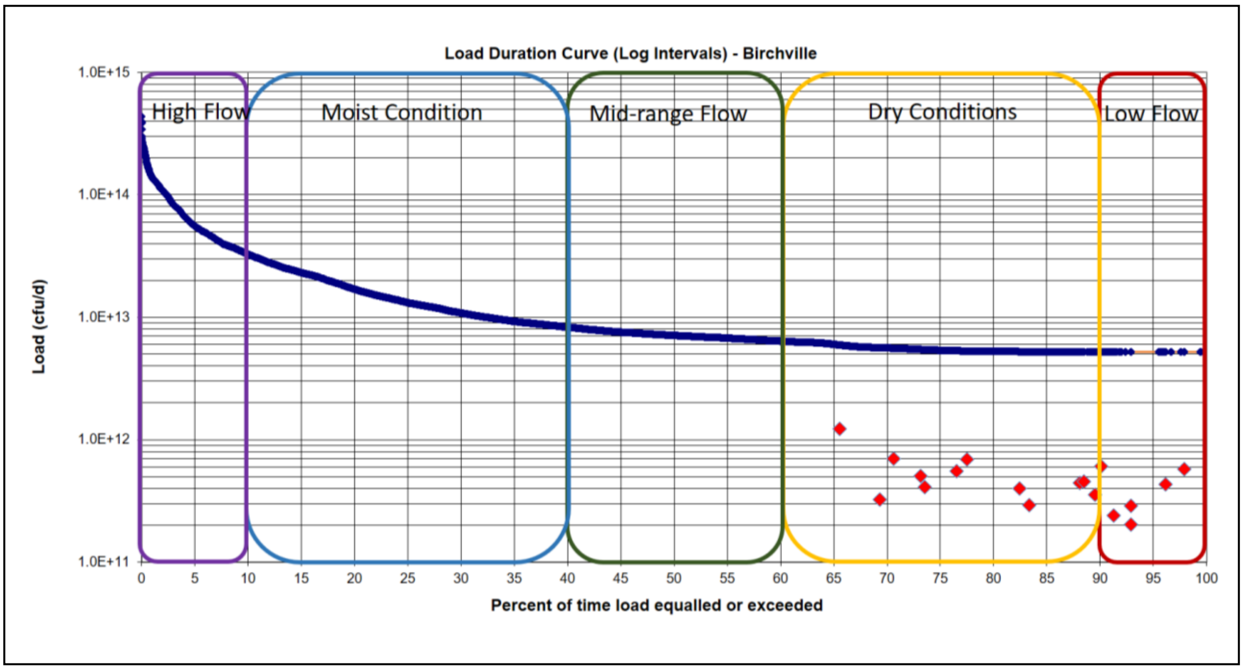

Figure 1: Load Duration Curve for Birchville sub-catchment

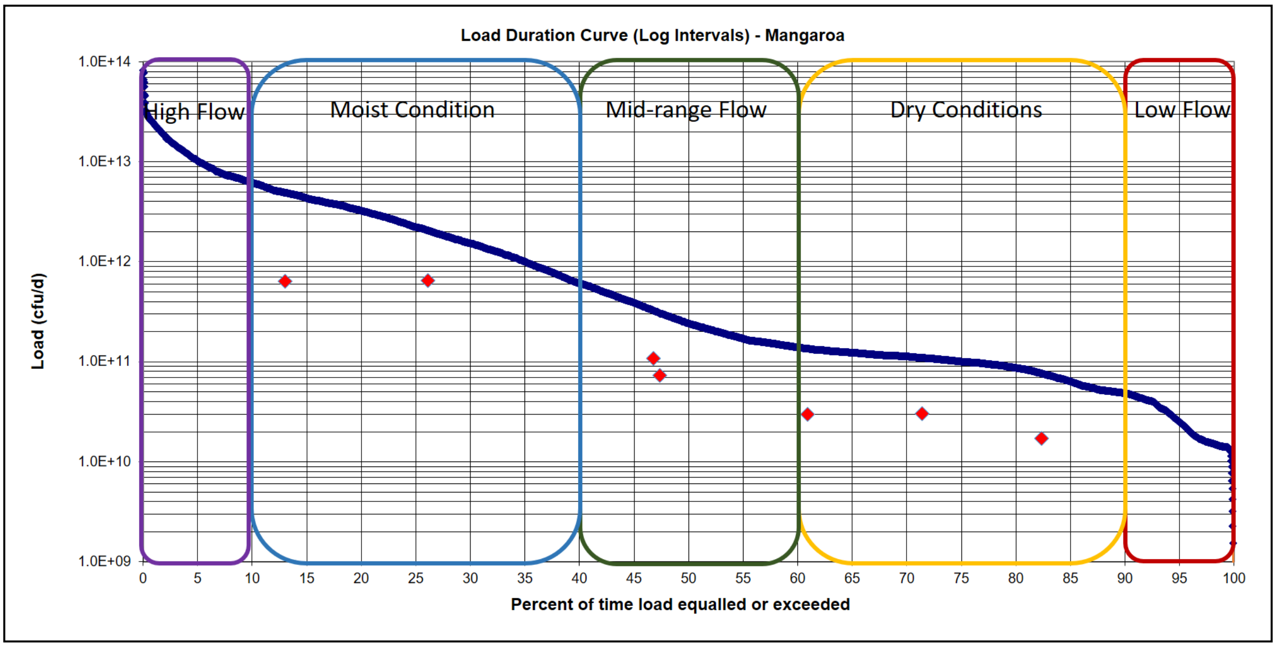

Figure 2: Load Duration Curve for Mangaroa sub-catchment

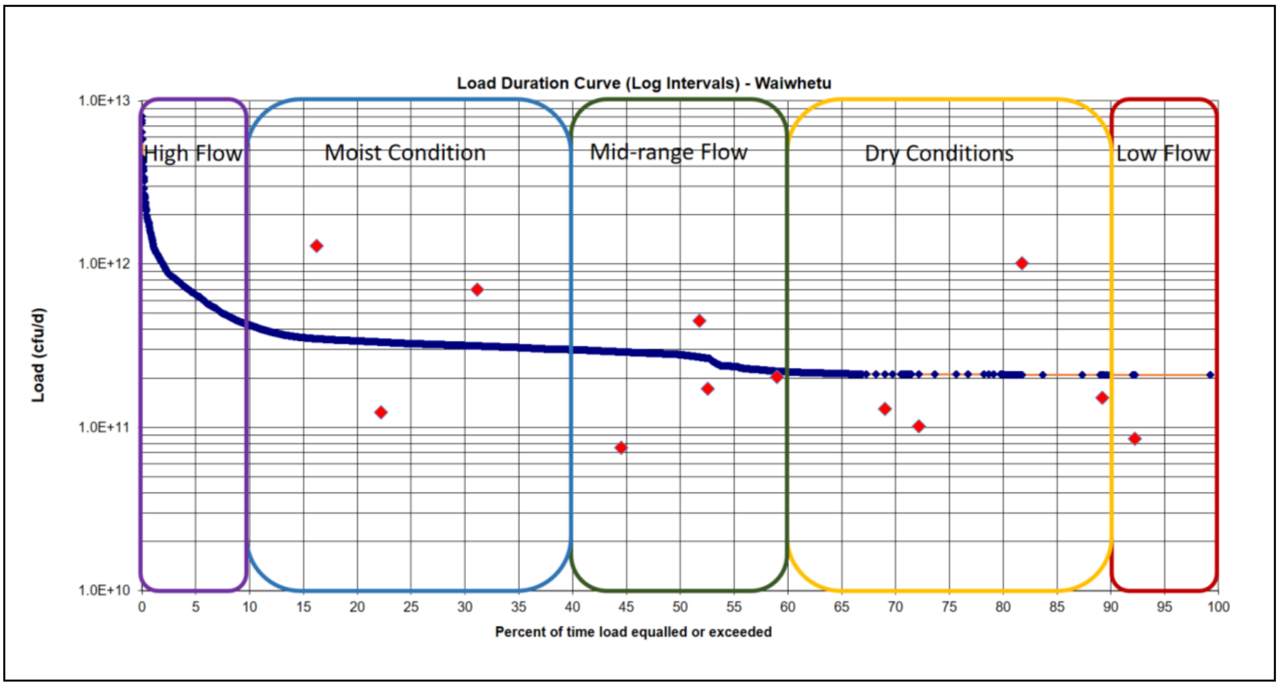

Figure 3: Load Duration Curve for Waiwhetu sub-catchment

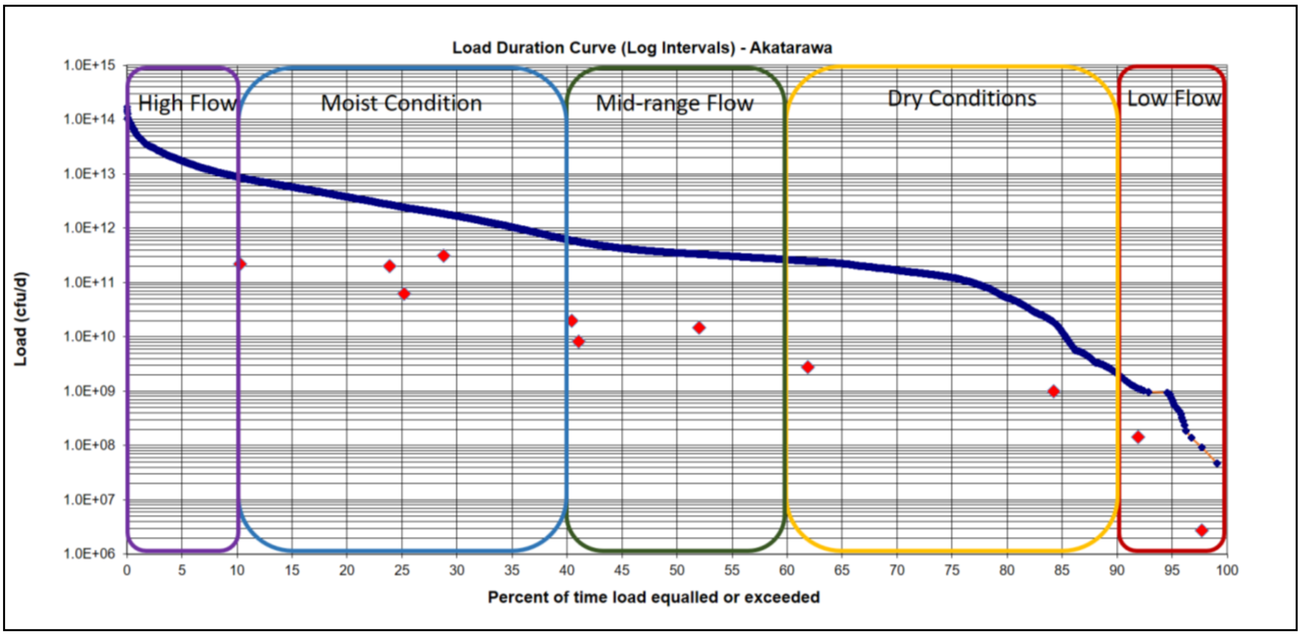

Figure 4: Load Duration Curve for Akatarawa sub-catchment

To identify the order of relative need for water quality improvement across the four sub-catchments, CPI was computed (Table 1).

Table 1: CPI for Hutt River Sub-catchments

Sub-catchment	CPI Value
Birchville	1.73
Mangaroa	3.78
Waiwhetu	3.12
Akatarawa	3.93

As loads were observed only in "Dry Conditions" and "Low Flows" in the Birchville sub-catchment, it received the lowest CPI value. The loads in Akatarawa sub-catchment were observed in four of five zones similar to Waiwhetu sub-catchment. However, in Akatarawa sub-catchment, the loads proportionately increased from "Low Flow" zone to "Moist Condition" zone. In contrast, the loads were evenly spread across the four zones in Waiwhetu sub-catchment. This indicated that stream flow has a higher influence on water quality changes in the Akatarawa sub-catchment as compared to Waiwhetu sub-catchment, where higher levels of loads are discharged from possible point sources. In the order of priority, the Akatarawa sub-catchment (with the highest CPI value) should receive more mitigation measures to improve water quality as compared to the Birchville sub-catchment (lowest CPI value).

3 CONCLUSIONS

In this paper, we presented a "Load Duration and Catchment Prioritization" (LDCP) framework approach to characterize water quality in the catchment. The framework was applied on Hutt River catchment to showcase its potential. This framework determined loading capacities for the selected sub-catchments of Hutt River. It accounted for influence of stream flow patterns on water quality in the river over the course of a year. Catchment Prioritization Index (CPI) value was computed for the selected sub-catchment areas to rank them according to the relative water quality improvement needed. These results highlight where catchment managers can prioritize efforts to reduce pollutant loads and set catchment specific enforceable water quality limits to meet the requirements of the National Policy Statement for Freshwater Management.

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