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Turbidity and suspended sediment in the Matakana River, Auckland

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Abstract

Turbidity is used as a surrogate measure for suspended sediment concentration in order to quantify the amount of sediment being transported by the Matakana River (Auckland, New Zealand), a river characterised by very high flow rates for such a small catchment. A highly significant relationship is obtained between the two variables. Much of the sediment is fine-grained with exposed riverbanks being a major sediment source, particularly in the lower reaches. During the very high floods that characterised the first half of 2023 in the Auckland region, upwards of 300 tonnes of sediment were transported in an hour, with the sediment peak tending to precede the flow peak.

Keywords

turbidity, suspended sediment concentration, bank erosion, 2023 storms

Introduction

Rivers deliver close to 13,000 million tonnes of sediment to the world's oceans every year (Syvitski *et al.*, 2005; Walling, 2008). The suspended fraction of that sediment load, by far the major component of the total, consists of the wash load (generally clays and silts) and that part of the bed-material load that is periodically swept into suspension from the stream bed (largely sands). As the latter element grows in significance, so the transport of suspended sediment becomes increasingly episodic.

Suspended sediment, particularly at the finer end of the scale, influences many aspects of the fluvial environment (Knighton, 1998). It affects physical properties of the flow, the quality of the water in rivers, and visual clarity (Davies-Colley *et al.*, 2014). It can act as a vector for the transport of pollutants such as phosphorus and heavy metals (Kronvang *et al.*, 2003). In sufficient quantities it can smother stream and estuary beds, thereby adversely affecting the resident fauna and flora (Bilotta and Brazier, 2008). Sediment delivered to Kaipara Harbour, Auckland, New Zealand, has significantly reduced the extent of sea grass, a habitat that is critical to snapper and shellfish communities (Simon *et al.*, 2016). Such an effect has implications for the New Zealand fluvial environment as a whole (Zabarte-Maeztu *et al.*, 2021). When deposited in large quantities suspended sediment can considerably reduce the carrying capacity and life expectancy of reservoirs. It is also indicative of the amount of erosion taking place in a catchment, an issue that has become of particular concern in the Auckland region (Irvine *et al.*, 2019; Hicks *et al.*, 2021). New Zealand as a whole delivers 200 million tonnes of sediment to the oceans annually (Ministry of the Environment and Stats NZ, 2018).

FOAM (Friends of Awa Matakanakana) is a community organisation set up in 2018, the principal concern of which is water quality in the Matakana and Glen Eden rivers (Auckland), particularly with respect to the amount of sediment being delivered by those rivers to Sandspit Estuary where shellfish beds are being affected. An initial requirement is to quantify the nature and scale of that sediment delivery. The Glen Eden River, which lies immediately to the west of the Matakana, is not considered here. In conjunction with the Healthy Waters Department of Auckland Council, an experiment was set up in 2021 on the Matakana River to investigate variations in suspended sediment concentration. The results of that initiative are the main focus of this paper.

Field area

The Matakana River has a drainage area of 15.4 km^2 and a length of 6.9 km at the measurement point in Matakana village (Figure 1). A short distance downstream of that point is a 7 m high bedrock cascade that acts as a local base-level and isolates the upstream river from any tidal influence. Despite that control on bed elevation, there is evidence that the Matakana River in its lower reaches has incised itself relatively recently. The potential for erosion in the catchment as a whole has increased markedly in the last 170 years with the widespread removal of native forest mainly for farmland and horticulture (Lindsay *et al.*, 2009; Temple and Parsonson, 2014; Grant, 2017), resulting in extensive sedimentation downstream in Sandspit Estuary and the shallow Kawau Bay. The high intensity rainfall that characterises the area (>1450 mm per annum) and the steep slopes in the upper catchment, where the main stem descends over 340 metres in 1.25 km, exacerbate the problem.

The Matakana River is not gauged but the Tamahunga River, which lies immediately to the northeast and experiences similar environmental conditions, has been gauged since 1978. It has a drainage area of 8 km^2 at the gauging station and a mean annual flood ($Q_{2.33}$) of 28 m^3 s^{-1}. Flow volumes in the Matakana River were estimated using established data for various rivers in the north Auckland region – Tamahunga River, Mahurangi Argonaut, West Hoe, Orewa River, and Rangitopuni River. Two different independent variables were used in the estimation process, drainage area (A_d) and link magnitude (M), where the latter is defined by the number of sources upstream of a particular point in the channel network. Link magnitude has been used successfully elsewhere to estimate flow parameters (Knighton, 1987). The resulting equations for high flows with a recurrence interval of 2.33 ($Q_{2.33}$) and 5 (Q_5) years are given in Table 1.

The discharge estimates for the Matakana River are in the range of 32 to 35 m^3 s^{-1} for $Q_{2.33}$ and 48 to 49 m^3 s^{-1} for Q_5. These values are higher than regional flood flow estimates for the same flood frequencies, respectively 27.9 m^3 s^{-1} and 39.5 m^3 s^{-1} (Henderson *et al.*, 2018), but the Matakana catchment has one of the highest rainfalls in the Auckland region (Hicks *et al.*, 2021) and the corresponding values for the gauged Tamahunga, a smaller catchment, are 28 m^3 s^{-1} and 41 m^3 s^{-1}. Whatever the estimation method these values are surprisingly high for a catchment of only 15.4 km^2, reflecting the influence of high intensity rainfall and steep topography on discharge generation. The correlation coefficients for the equations in Table 1 are relatively high but, because of the small sample size, the estimates must be regarded as indicative rather than definitive of the discharges in the catchment. Nevertheless, they do suggest that the river has a high erosive potential.

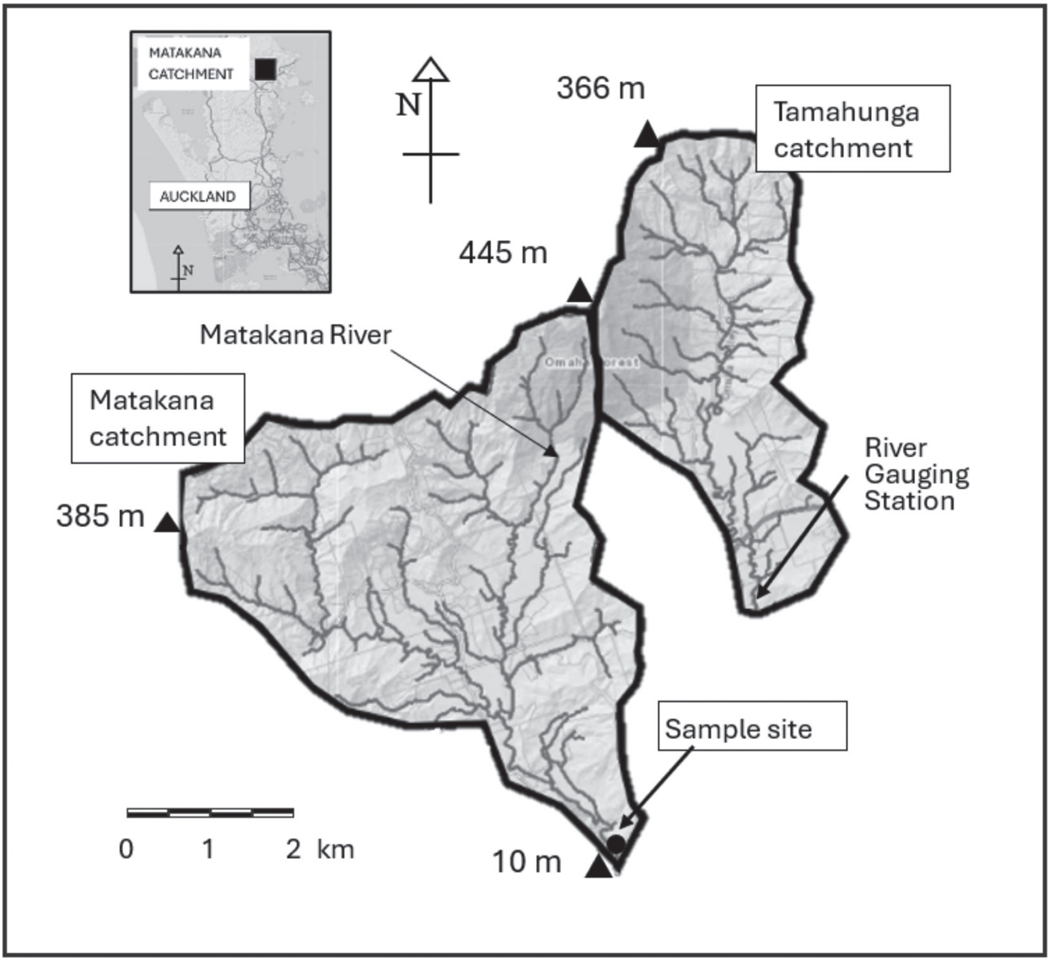

Figure 1 – The Matakana Catchment, with the measurement point and Tamahunga catchment indicated. The inset map shows the position of the catchments to the north of Auckland.

Table 1 – Equations to estimate $Q_{2.33}$ and Q_5 in the Matakana River using drainage area (A_d) and link magnitude (M) as independent variables. Note r is the estimate of the correlation coefficient.

$Q_{2.33} = 3.3\,A_d^{0.83}$ (r = 0.97)	$Q_5 = 4.5\,A_d^{0.85}$ (r = 0.97)
$Q_{2.33} = 23.8 + 0.43M$ (r = 0.85)	$Q5 = 33.6 + 0.60M$ (r = 0.87)

Method and results

Continuous measurements of suspended sediment are difficult to obtain, partly because of the lack of suitable instrumentation and partly because of the large temporal variability of the transport process itself. Surrogate measures are often used to circumvent this problem, and turbidity is one of the commonest and most reliable of these measures. Turbidity is an optical measurement of the transparency of a solution due to the scattering and attenuation of light by suspended particles, and continuous turbidity measurements have been shown to provide reliable estimates of suspended sediment concentration (Haddadchi, 2017). In this instance a Phathom S40-SWW turbidity sensor was installed. The sensor measures the attenuation of near-infrared light (880 nm) in four paths, applies a four-beam algorithm to calculate a Probe Signal, and is calibrated with representative samples of suspended material, 1800 corresponding to a concentration of zero. This superior multi-beam technology gave a reading every 11 minutes, a time interval chosen to ensure manageable data handling. The instrument was sited at Matakana Market Wharf in a 110 mm diameter stilling tube, in such a position that it was constantly immersed and free from public scrutiny at this popular tourist location. Recording began in May 2021.

Samples of suspended sediment were obtained with a home-made device modelled on the US DH-81 depth-integrating sampler, where a 1 litre sample bottle is lowered at a constant rate through the water column while attached to a rod. In this case the rod was 2.5 m long. Since it is assumed that finer particles are uniformly distributed throughout the water depth while coarser ones are concentrated towards the stream bed, representative sampling requires that the sampler nozzle reaches as close as possible to the stream bed. Here the sampler reached within 40 mm of the bed, except at the highest flows when sampling near the bed proved too dangerous with a hand-held device. Once obtained, each sample was sent immediately to a professional laboratory for analysis. Twenty-five samples were taken over a range of discharge conditions. Based on occasional discharge measurements along the lower Matakana, RIMU (Research and Evaluation Unit of Auckland Council) have devised a method whereby Matakana River discharges can be estimated from their Tamahunga River equivalents. Application of that method indicated that the sampling covered a flow range from 0.15 to 68 $m^3 s^{-1}$, the highest flow having a recurrence interval of about 7 years.

The laboratory, Aqualab of Auckland, using a Hach nephelometer, returned data for turbidity in FNU (Formazin Nephelometric Units) and total suspended solids (TSS) in mg l^{-1}. TSS is essentially suspended sediment concentration, since suspended sediment was overwhelmingly the dominant component and organic matter made a minimal contribution. As a check on the reliability of the field instrument which is calibrated in different units, its readings were correlated with the turbidity measurements made in the laboratory (Figure 2). The resultant linear correlation is highly significant at the 95 percent level with confidence limits for the correlation coefficient (ρ) of $0.98 \leq \rho \leq 0.99$, suggesting that the field instrument was giving consistent results over the measurement range. The field instrument did occasionally become fouled with filamentous algae and very fine silt, but regular cleaning, particularly before a sampling event, seems to have reduced inconsistency in the results.

The plot of TSS against field turbidity also produces a highly significant linear relationship (Figure 3), with 95 percent confidence limits of $0.95 \leq \rho \leq 0.99$. The scatter about the regression line is relatively small when compared with most plots of

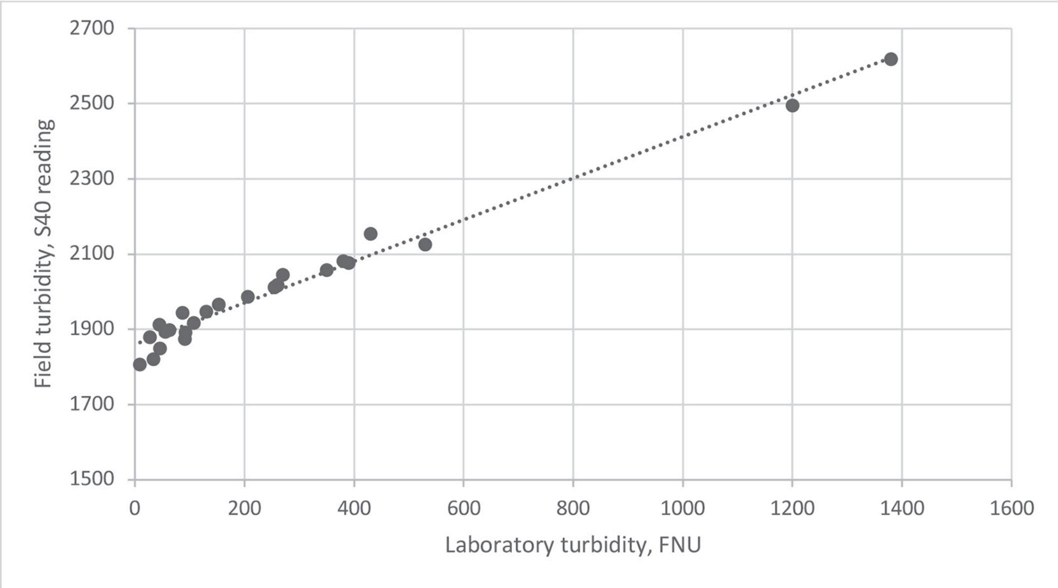

Figure 2 – The relationship between laboratory turbidity and the S40 turbidity reading.

suspended sediment concentration against discharge (Knighton, 1998). Even some plots of turbidity against suspended sediment can give rise to a widish scatter (Davies-Colley and Smith, 2001). There is some indication from pairs of readings that part of the scatter can be attributed to the flow phase (i.e., timing within a flood event) at which the sample was taken. On 21 March 2022 samples were taken 45 minutes apart, the first yielding a TSS of 900 mg l^{-1} when the discharge on the rising limb of the Tamahunga River was 6.3 m^3 s^{-1}, and the second yielding 770 mg l^{-1} at a peak discharge of 7.3 m^3 s^{-1}, a drop of 14 percent despite the higher flow rate (and it should be noted that peak flow in the Matakana River is about one hour later than that in the Tamahunga River). On 9 May 2023 a first sample was taken at 13:35 hrs on the rising limb of the highest measured flow during the monitoring period, with sediment concentration at 1840 mg l^{-1}, and a second at 17:15 hrs with sediment concentration significantly reduced at 600 mg l^{-1} as the flow receded. This pattern of behaviour, where the sediment peak precedes the river flow peak to give higher concentrations on the rising than the falling limb, is not uncommon and may indeed be a prevalent hysteretic effect (Williams, 1989). This clockwise hysteresis is symptomatic of the depletion of available sediment before the water discharge has peaked and is much more likely in small basins, such as the Matakana, where sediment sources are close to watercourses. Thus, despite the samples on the Matakana River being taken at a large variety of flow stages relative to the peak of an event, the amount of scatter in Figure 3 remains encouragingly low.

The hysteretic effect described above is typical of events in which wash load is a significant component of the transport process, reflecting the fact that the rate of wash load transport is determined largely by the rate of sediment supply rather than by the transporting capacity of the flow. In the Matakana catchment that supply probably comes from the erosion of cohesive riverbanks, from surface erosion close to

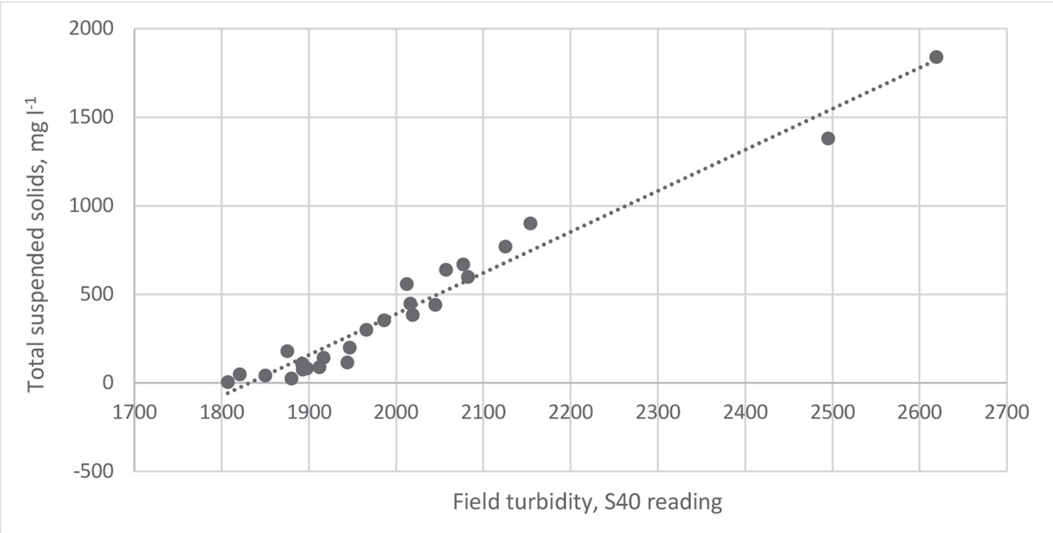

Figure 3 – The relationship between the S40 turbidity reading and total suspended solids.

existing streams, especially in the steeply sloping upper catchment where many small streams spring up during heavy rain, and from localised pipe networks that terminate in riverbanks. Also, fine sediment that frequently drapes the bed after settling out during low-flow periods provides a ready source when higher flows return. That wash load is an important transport mechanism along the Matakana is reflected in the fact that the river is often murky, at even moderate discharges, and in the composition of the load where particles ranging from coarse silt to coarse sand (0.05–1 mm) predominate. Unfortunately, sampling close to the stream bed was impractical during the highest discharges when transport of coarser fractions could have become important.

Evidence in the form of abandoned meander loops on the floodplain suggests that the Matakana River has experienced periods of entrenchment, possibly in the last century and a half when the forest cover was severely reduced and erosive potential increased. Such vertical incision has exposed elevated river banks to erosion, especially in the lower part of the river where alluvial and colluvial deposits derived from volcanic ash form a matrix. Hydraulic action against unvegetated banks and mass failures aided by undercutting are the main processes involved, material being either delivered directly to the flow or deposited temporarily at the bank foot to be entrained by later floods. In a reach 800 m upstream from the measurement point the river flows through a small, wooded reserve where bank erosion produced a log jam of large trees (Figure 4), a build-up that created large-scale eddying and accelerated bank scour in a positive feedback, forming embayments. This is not an isolated occurrence along this stretch of the river. Opinions vary as to the merits of woody debris in rivers but in this case it has exacerbated the amount of erosion. Overall, it is suspected that streambank erosion is a major contributor to the measured sediment load in the Matakana, a suspicion which echoes results from other North Island river systems (Simon *et al.*, 2016; Hughes *et al.*, 2021). In the Hoteo River catchment (also in the Auckland region) at least 72% of the total sediment yield comes from that source (Simon *et al.*, 2016).

Figure 4 – A log jam in the lower Matakana River in 2023, with significant erosion of the right bank.

Several storm events occurred during the measurement period, characteristics of which are shown in Table 2. The first half of 2023 proved to be an exceptionally wet period in Auckland's history (Fowler, 2023). The hydrographs for the Tamahunga River (Figure 5) illustrate the range of responses involved, the Matakana River is expected to follow a similar pattern of flows. The rainfall total for the 9 May 2023 event was markedly less than that for either the Auckland Anniversary (27 January 2023) or Cyclone Gabrielle (14 February 2023) events but high intensity rain for a short period falling on an already saturated surface produced a very rapid and large response that resulted in significant suspended sediment transport. The 27 January 2023 flood produced slightly less sediment load at the peak despite the higher discharge but, because it was a more sustained event, the total load transported was greater. Interestingly Cyclone Gabrielle, which caused such devastating effects elsewhere in the Auckland region, had a relatively small impact on the Matakana River. The cyclone generated a more sustained flood hydrograph but the event was less sharply peaked and the peak discharge itself was a lot lower. Turbidity data were insufficient to estimate the associated sediment load for that event but, judging from other information in Table 2, somewhere in the region of 150–200 t hr^{-1} at the peak is probably realistic. That such a short, sharp event as the 9 May 2023 flow can generate such a large sediment load is a clear indication of the erosion problem in the Matakana catchment.

Hicks *et al.* (2021) have derived equations for nine north Auckland basins to estimate event suspended sediment loads. The closest geographically and in size to the Matakana is the Orewa Stream. Substituting the peak discharges for the four events into the relevant equation (1), where S is event sediment yield in tonnes and Q_p is event peak discharge in litre s^{-1}, indicates that the event loads given in

Table 2 – Characteristics of significant flow events captured during the period of continuous turbidity monitoring in the Matakana catchment.

	21/5/22	27/1/23 Auckland Anniversary	14/2/23 Cyclone Gabrielle	9/5/23
Peak Tamahunga Discharge, $m^3\ s^{-1}$	7.4	46.7	25.4	40.5
Time to peak, hr	2.5	7.3	22.3	2.5
Duration of flood hydrograph, hr	8	26	39	11.8
Total event rainfall, mm	79.5	173	177	109
Maximum rainfall intensity, mm hr^{-1}	40	42	16	46
* Total event suspended sediment load, t	90	1050	Insufficient data	860
* Peak suspended sediment load, t hr^{-1}	30	330	Insufficient data	370

*Estimated from the TSS/turbidity relationship, the peak load representing the amount transported over 1 hour about the discharge maximum

Table 2 for the Matakana River are 1.5 to 1.8 times those expected in the Orewa Stream, which is not surprising given that the Orewa Stream has a smaller drainage area (9.7 km^2), a lower rainfall and less steep topography. Indeed, the event loads generated in the Matakana are more akin to those associated with larger basins, such as the Wairoa River with a drainage area of 114 km^2.

$$S = 7.07 \times 10^{-5}\ Q_p^{1.45} \quad (1)$$

Conclusion

Turbidity has provided a consistent surrogate for suspended sediment concentration in the Matakana River, the relationship between the two variables being highly significant. The small scatter about the regression line is encouraging and can partly be attributed to the flow phase at which a sample was taken, with the rising limb of the hydrograph producing higher concentrations. That behaviour is typically associated with small basins and regimes in which wash load is important, the rate of sediment supply being a critical factor in the transport process. Streambank erosion is probably the main source of that supply, especially along the lower part of the Matakana where steep river banks are exposed and localised log jams can accelerate the erosive process. The Matakana River has a spectacularly high and responsive discharge for such a small catchment, and transports a relatively large suspended sediment load at peak flows. Under a changing climate scenario with more extreme rainfall events, those characteristics do not augur well for future erosion in the basin.

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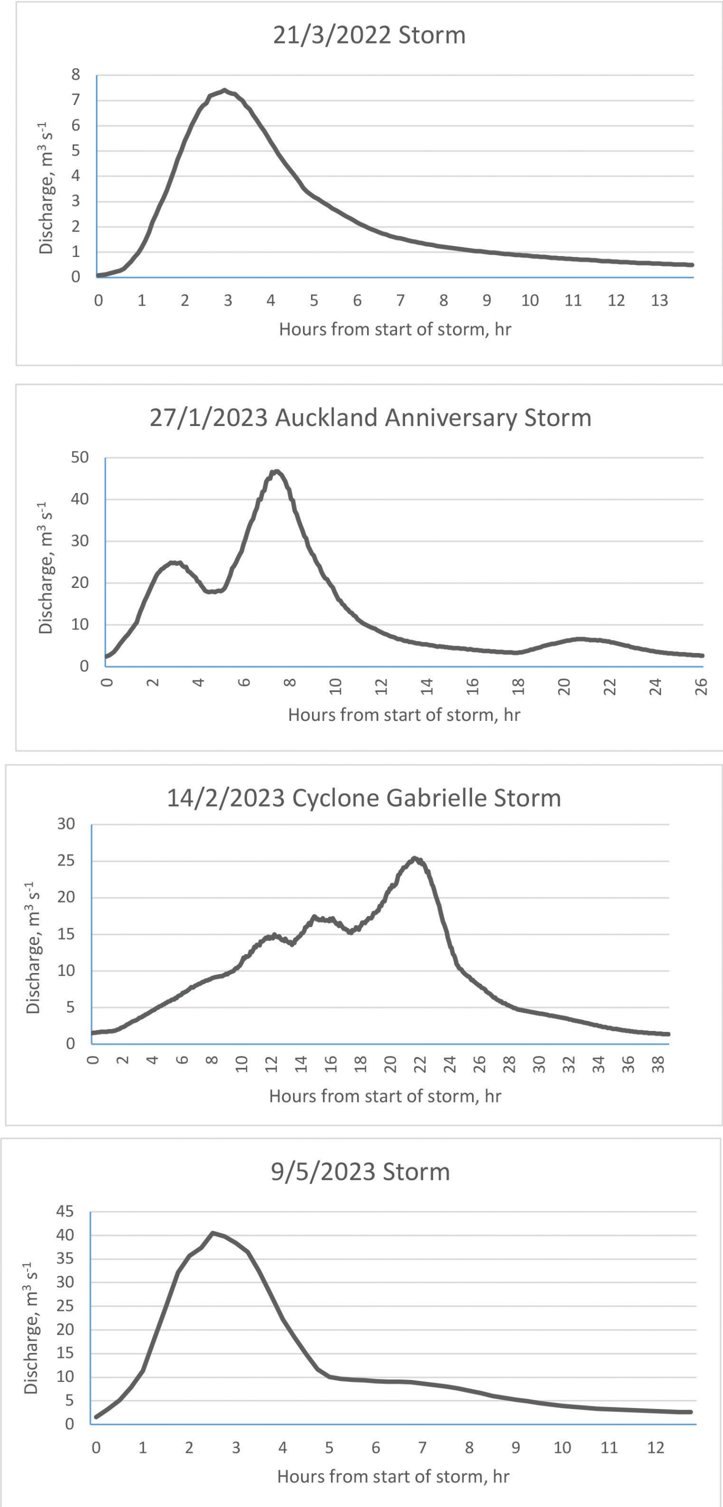

Figure 5 – Hydrographs for the Tamahunga River.

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