Assessing Turitea sediment starvation: impacts of the Turitea dams on sediment characteristics in the Turitea Stream, Palmerston North

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Contents

1. Overview

The focus of this report is on the hypothesised sediment starvation in the Turitea, connected with the stream bedload. Bedload is here defined as that material normally transported along a riverbed, comprising sand and gravel, also known as traction load. This material is transported via contact with the river bed (rolling, sliding, saltating), as opposed to being moved in suspension as suspended or wash load. This report reviews the impacts of reservoirs on the coarse fraction of sediment in stream systems and provides recommendations to assess the impacts of potential sediment starvation in the Turitea system downstream from the reservoirs in the catchment. The focus on bedload is intentional, since virtually all of this material will be captured by the Turitea dams, while an indeterminate proportion of suspended load will continue to be transported. Sediment starvation is therefore most likely to be observed and most pronounced in the stream's bedload. In turn this substrate also provides important habitat for aquatic fauna, thus any change in substrate composition due to sediment exhaustion is likely to impact stream habitat. It is not, therefore, within the remit of this report to discuss the impact or measurement of suspended load in the Turitea.

2. Review

Dams trap sediment and alter flood peaks and flow regime and accordingly profoundly change the character and function of river (Kondolf, 1997). Installation of dams in river systems inevitably has an impact on the river bedload, since (i) this material becomes trapped in the reservoir upstream, and (ii) the flow regime of the river downstream is changed, influencing the magnitude and frequency of sediment transporting flow events. Curtis *et al*. (2010) indicate that the impacts of flow regulation on the stream system are strongly controlled by the balance between (i) sediment supply and (ii) sediment transport capacity. Since the stream bedload is trapped, transport capacity potentially

increases downstream of a dam as water released from the dam possesses the energy to move sediment, but has little sediment load (Kondolf, 1997). Kondolf (1997, p.535) refers to this as 'hungry water' because the excess energy typically results in channel incision via scouring of the bed, i.e. bed degradation (Petts, 1979; Williams & Wolman, 1984; Gilvear, 2004). This bed degradation has also been observed to result in a substrate coarsening below dams (Angradi *et al*., 2006) and development of a less mobile armour layer in gravel bed rivers (Grant, 2012), which reduces bed mobility (Pohl, 2004). Once an armour layer is well developed, bedload transport rates will be reduced. Vericat and Batalla (2005) found that bedload transport rates were 35% lower in the regulated lower Ebro River (NE Spain), which they attributed directly to the development of an armour layer in that system.

An immobile armour layer develops by scouring of the more mobile component of the bed by smaller flows with increased competence (excess energy due to diminished load), leaving an immobile, coarser, armour layer behind, which is not mobilised by the modified flows downstream from the dam (Kondolf, 1997; Pohl, 2004). This progressive winnowing concentrates the coarser fraction (Williams & Wolman, 1984). The process of bed degradation can be slow in gravel bed rivers, since they are active a small fraction of the time, compared with sand-bed channels which are in a constant state of flux (Grant, 2012). Curtis *et al*. (2010) estimated that the complete geomorphic adjustment of the West River channel to reduced flow imposed by regulation would take c.100 years, which is consistent with Petts' (1980) observation in UK regulated rivers and Williams and Wolman's (1984) observations in the USA. Furthermore, Grant (2012, p. 173) suggests that in gravel-bed rivers the magnitude of bed elevation change due to impoundment is "generally relatively small…1 m or less of degradation", due to the armouring process. He notes that the armouring process increases the D_{50} (median grain size), requiring flows of increasing competence to mobilise sediment on the riverbed. As indicated above, the armouring process is facilitated both by a reduction in peak flows and sediment supply from upstream as a consequence of the dam. Grant (2012) suggests that coarsening of the gravel bed downstream of dams occurs within 5-10 years. Thus, while degradation and geomorphic adjustment may be protracted, winnowing of fines generating an under-loose armour layer may occur relatively rapidly following dam construction. This implies that the effects of sediment exhaustion may occur within c. 10 years of impoundment. It is therefore likely that such an effect be observed in the Turitea. However, it is important to note that degradation will only occur if the post-dam flow regime is competent to mobilise the finer fraction of the bedload in the first place (Schmidt and Wilcock, 2008), furthermore, in larger systems, the adjustment time in which an armour layer develops may be considerably longer, in the Ebro river, Vericat *et al*. (2006; 2008) observed an active, mobile bed 40 years following dam construction.

The extent to which the coarsening and armouring of the riverbed is propagated downstream is dependent upon the replenishment of sediment to the mainstem of the river. A system with abundant unregulated tributaries will replenish sediment in the mainstem of the river fairly quickly (cf. Curtis *et al*., 2010). For example, Grant (2012) cites a PhD study observing coarsening for c.3 km downstream of a dam in the Clackamas River, Oregon (Wampler, 2004), although he suggests typically coarsening is observed downstream for c.10-20 km. Bedload is replenished not only by tributary inputs, but also by bank erosion: Petts (1979) observed channel widening downstream of some dams. This is intuitive, since armouring of the bed immobilises it, which increases the potential for lateral erosion and mobility, reworking floodplain sediment, replenishing sediment load downstream. However, if flows are sufficiently reduced, channel narrowing may in fact occur, leading to a range of possible scenarios in an impounded river, dependent on precise flow regime and sediment supply and properties (cf. Petts, 1979). The diversity of river system response to dams has

also been highlighted by Dade et al. (2011, p.249), who state that, "the exact way and rate at which a bedload-dominated river reach adjusts to changes in regulated discharge is likely to depend on sediment supply". Accordingly some studies observe no degradation of the riverbed downstream of a dam (e.g. Grams and Schmidt, 2005), or relatively minimal change (e.g. Magilligan *et al*., 2008). A range of responses of stream systems to dams is usefully summarised by Petts and Gurnell (2005) and classified by Brandt (2000).

3. Assessing sediment starvation

3.1 Prospect

Sediment starvation in the Turitea is likely to have occurred if the regulated flow has sufficient excess energy to scour the riverbed (cf. Kondolf, 1997), without replenishment of sediment from local sources such as tributaries and / or bank erosion. This would result in the development of an immobile armour layer (Pohl, 2004). Given the size of the stream, it is probable that the channel has by now adjusted to the modified flow and sediment transport regime, although the extent to which it has attained a degree of equilibrium is conditional upon the magnitude and frequency of competent flows. Therefore, the extent of the impact of the dams should be discernible in the river's bedload if there has not been replenishment of the load from bank erosion or tributary input. There are very few significant tributaries in the Turitea that would substantially replenish bedload (Figure 1), which means replenishment is probably dependent upon bank erosion. However, there is one exception in the 'Greens Road' tributary, which has been observed to deliver finer grained bedload to the trunk stream (Plate 1). The extent to which the impact of sediment starvation extends downstream is dependent upon the effectiveness of sediment delivery from such local sediment sources. In large river systems, the effect of dams may extend >100 km downstream (cf. Williams and Wolman, 1984), but in small systems, the impact of the dam may be much more localised. For example, Petts *et al*. (1993) found the effects of a dam in the headwaters of the River Rede in the UK to be limited to within 2 km of the dam site. The effects of sediment starvation in the Turitea may not necessarily extend far along the river's course. Assessment of the impacts of the dams must take into account the possible localised effects, which requires an appropriate experimental design.

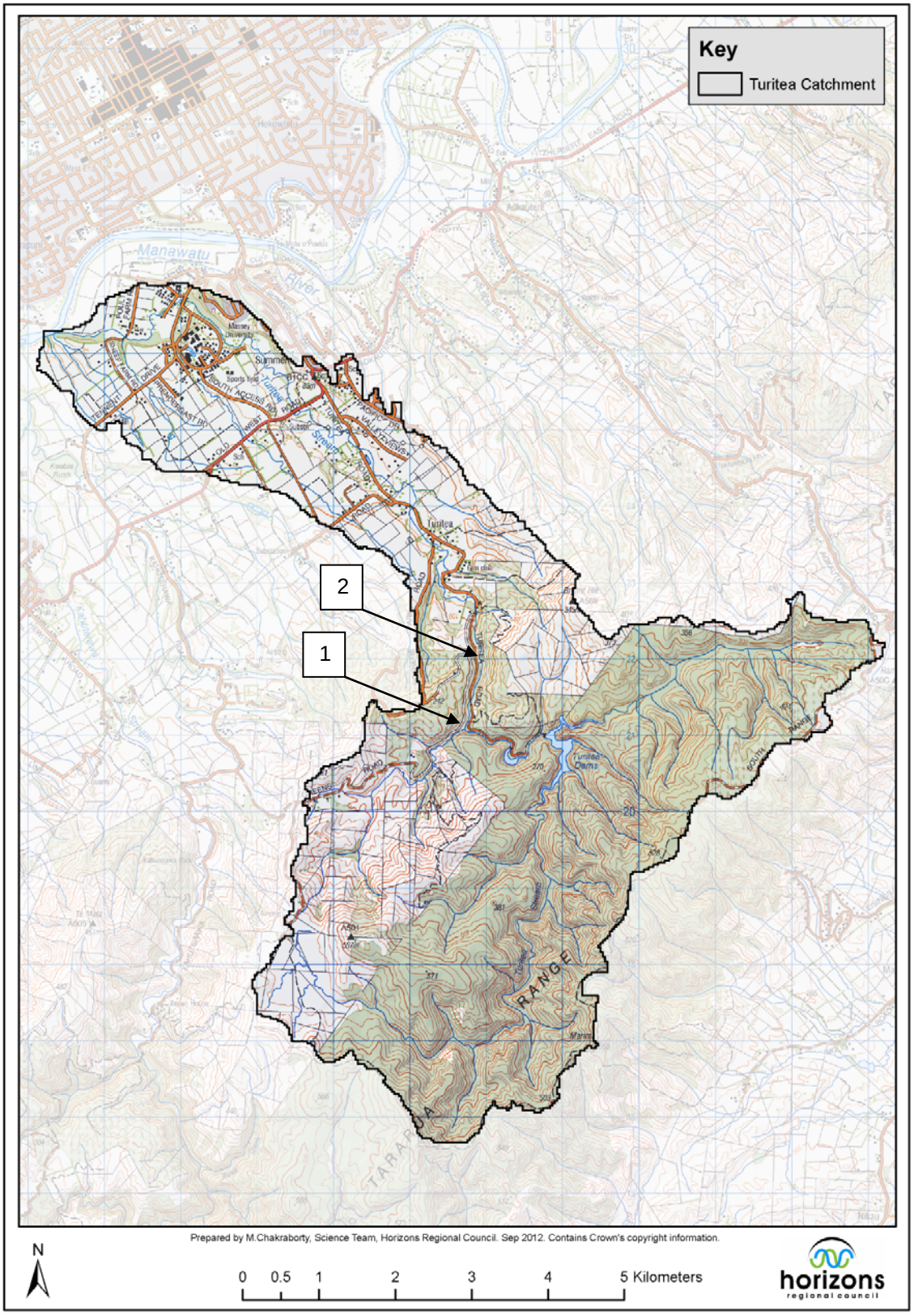

Figure 1. Turitea catchment map, locations of Plates indicated by numerals.

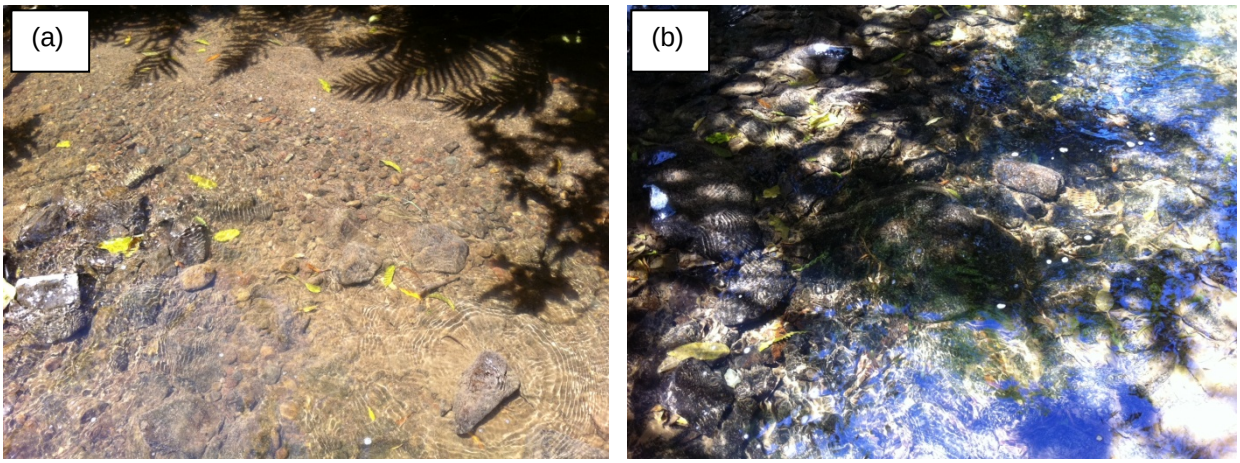

Plate 1. (a) Finer bed substrate in the Greens Road tributary, compared with (b) the coarser armour in the trunk stream at the confluence of trunk and tributary, cf. Fig. 1. This indicates some replenishment of bedload takes place via the Greens Road tributary (Photo: ICF 27 November 2012).

3.2 Approach

Since there are no pre-impoundment grain size data, nor any equivalent sized tributaries with which to compare sediment in the regulated mainstem, to assess the extent of sediment starvation in this river, I recommend an approach that samples riverbed sediment upstream and downstream of the reservoirs. This will enable comparison of grain size characteristics of the stream bed in the Turitea in an unmodified state (upstream of dams) to quantify the effects downstream. The difficulty in this approach is that grain size character does change naturally in a downstream direction, in other words differences in grain size between upstream and downstream sites would be expected. Bedload tends to become finer and potentially more rounded in a downstream direction, due to the effects of abrasion and selective transport (e.g. Knighton, 1998). However, if significant sediment starvation has occurred, i.e. finer bedload has been flushed out without replenishment from local (e.g. bank) sources, any downstream fining trend is likely to be disrupted and a coarse armour will plot as a positive anomaly above expected downstream trends. It should be noted that, while not an equivalent size to the mainstem of the Turitea, the left-bank tributary that feeds in to the Turitea alongside Greens Road could also be sampled, since this is likely to be a key source of bedload replenishment. Downstream trends in bed sediment character may also be disrupted naturally by the gorge reach of the mainstem downstream from the dams, since sediment is likely to be flushed through this reach, with minimal storage capacity (cf. Plate 2).

Plate 2. Gorge reach, mainstem Turitea. Not only does this reach act as an effective conveyor of sediment, but it also limits opportunity for bedload replenishment, since the river is confined by bedrock. Substantial replenishment of bedload is therefore unlikely to be evident until farther downstream where the river channel abuts floodplain and terraces (Photo: ICF 27 November 2012).

The extent to which an armour layer is developed in the riverbed downstream of the dams can also be assessed by comparing findings upstream and downstream of the reservoirs. Wallick *et al*. (2009) suggest that an armouring ratio of 1 (i.e. ratio of $D_{50[surface]}$: $D_{50[substrate]}$) indicates a high sediment supply and little armour development, i.e. there is no discernible difference between the grain size of the armour and subsurface sediment. The greater the ratio, the greater the difference, and the better developed the armour layer. Bunte and Abt (2001) suggest that where the ratio is greater than 2, excess transport capacity can be inferred. If sediment starvation in the Turitea is pronounced, armour ratios downstream of the dams would be expected to be larger than those upstream. This metric defining impact of the dams is not affected by downstream trends in bed sediment character.

Since downstream affects of dams on stream character are conditioned by flow properties, it would also be advantageous to quantify hydraulic variables such as shear stress to ascertain the likely mobility of clasts in the streambed. This could then be linked with the flow record to determine the likely frequency of bedload mobilisation. This approach would be analogous with that taken by Pohl (2004), based on deriving section averaged shear stresses for a given flow, compared with critical shear stresses for entrainment of given grain sizes. This would also permit quantification of the extent of bed mobility. A sediment starved reach is unlikely to display a high degree of mobility, since all that remains is a coarse armour or lag deposit. Therefore sites upstream might be expected to display a higher degree of mobility (i.e. clasts more readily transported) than those downstream of the dams if there is a sediment deficit below the dams.

3.3 Method

3.3.1 Surface grain size

Surface grain size characteristics should be measured using a ½ phi interval pebble template / gravelometer (cf. Wallick *et al*., 2009). Kondolf *et al*. (2003) recommend Wolman's (1954) pebble count to sample approximately (at least) 100 surface clasts from exposed bars or the river bed. A sample size of 100 stones was found by Wolman (1954) to produce consistent median grain sizes for multiple counts by one operator and among different operators. Accuracy in the tails of the distribution can be achieved by sampling 200-400 stones (Fripp and Diplas, 1993) and Rice and Church (1996) found no further increase in precision in samples >400. Since the median grain size is the focus, 100 stones will be sufficient to sample. Sampling may be random (the big toe method, where the stone under the big toe of the forward foot is sampled as the operator walks backwards and forwards across the area of bed to be sampled). Alternatively, sampling can proceed along a line or grid, sampling the stone under every nth cm along a tape, for example (cf. Wallick *et al*., 2009). This works best where the tape can be laid on a dry surface. A random approach is probably better when sampling submerged stones underwater. The key point is to be consistent and ensure as random and unbiased a sample as possible. Inevitably there will be some degree of coarse bias in this approach, because larger particles are easier to pickup than smaller, but this bias should be consistent across all sites.

Surface grain size should be sampled from as many discrete locations as possible to generate a robust dataset from which trends in sediment character can be determined. The locations of each 100-stone sample location should be recorded to enable plotting of grain size at that site vs. distance downstream. Sampling of 100 clasts should be from discrete, homogenous areas / patches within the active riverbed, such as an exposed bar surface, or within a discrete area of submerged bed and not a

composite say of pool and riffle and bar (cf. Kondolf *et al*., 2003). The nature of the location (bed or bar and type of bar) should be recorded because sediment in the wetted channel may be coarser than that on the bar platforms where present. Sampling should proceed downstream at regular intervals to be determined. It may be necessary to increase the distance between sample sites in the lower reaches, particularly once it becomes apparent that bedload has become replenished, but I would recommend a complete sampling of the river to serve as a baseline for future work, since it is possible that the system is not yet in equilibrium and is continuing to degrade / armour its bed. A downstream progression of sediment starvation is possible, depending on the extent of replenishment taking place. Suggested sample locations are marked on Figure 2. These should extend some distance up the mainstem of the Turitea.

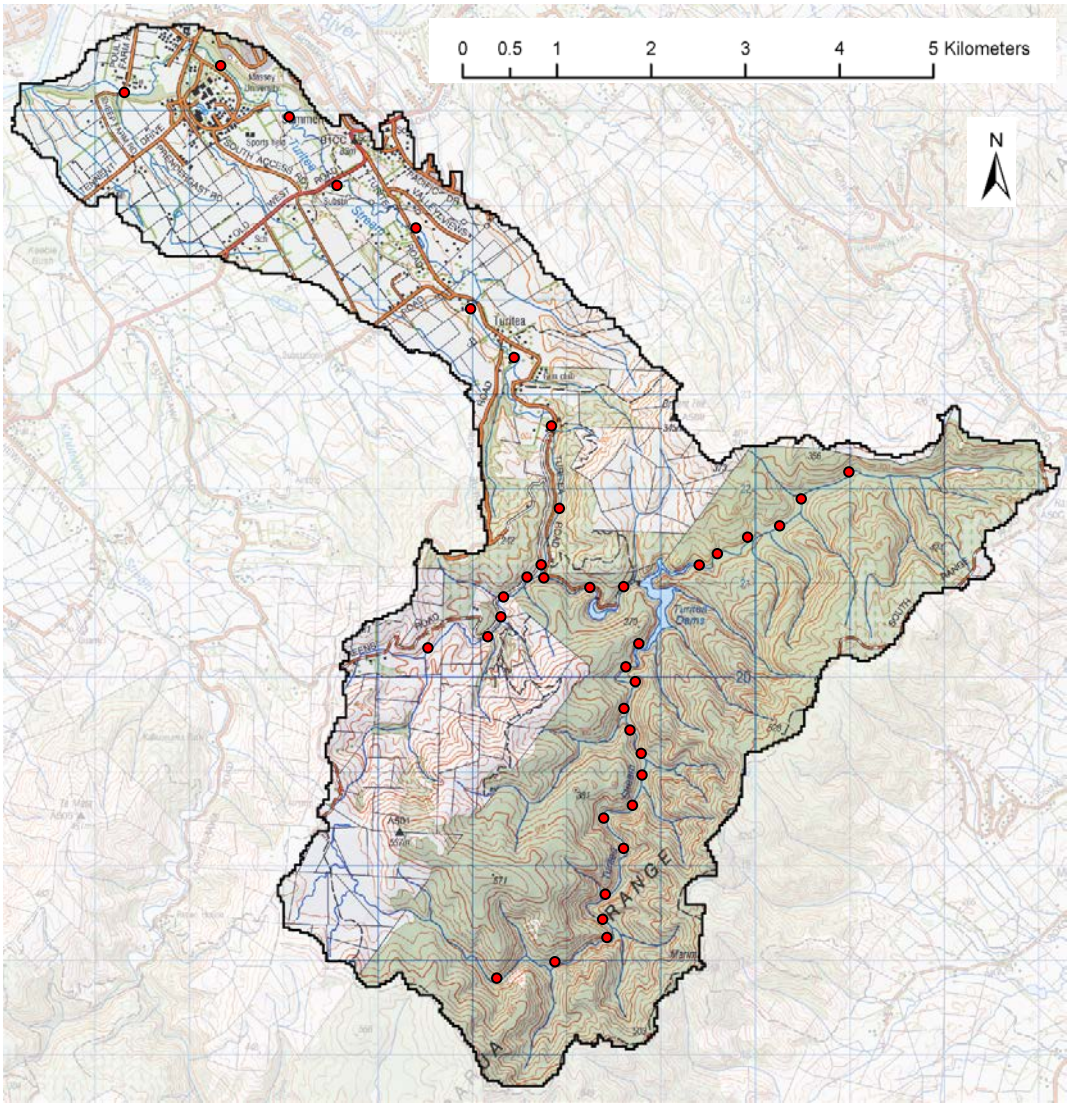

Figure 2. Suggested sample locations for surface grain size characterisation.

Cumulative frequency curves should be plotted at each site (cf. Figure 3), from which a D_{50} can be derived, together with any sorting coefficients if desired. These plots can serve as baseline for future reference to detect any change in surface sediment character in the system. The D_{50} at each site can then be plotted against distance downstream and the extent to which the sediment characteristics at and downstream from the dam sites differs from the expected norm from upstream trends can be inferred.

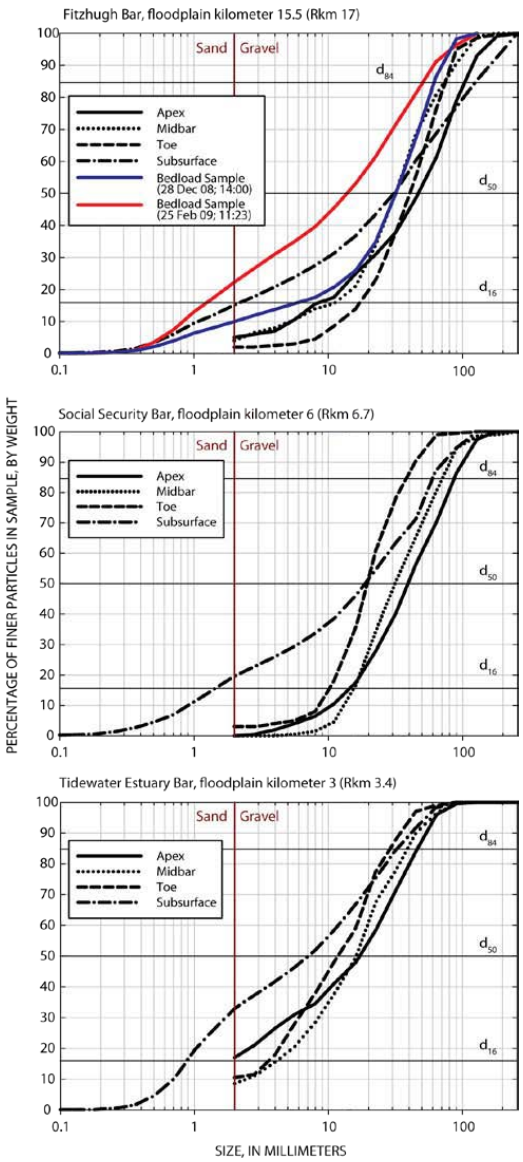

Figure 3. Grain size distribution curves (from Wallick *et al*., 2009).

3.3.2 Subsurface grain size

Subsurface sediment should be measured so that the extent of armour development (armour ratio) can be assessed. This will entail bulk core sampling (cf. Kondolf *et al*., 2003), whereby a cylindrical core sampler is driven into the bed and material removed by hand. This need be nothing more sophisticated than an open-ended bin (cookie-cutter) being pushed into the river bed, the surface fraction is then removed and measured as per 3.3.1, followed by removal of the underlying substrate in bulk. This material can be measured by wet sieving on site if the site access permits, alternatively the material should be bagged, dried and sieved in the laboratory.

An adequate sample size is difficult to determine and Kondolf *et al*. (2003) discuss this at some length. There are 'ideal' and 'practical' sample sizes, which are scaled according to the maximum grain size in the sample: Wentworth (1926) suggested that in coarse material, i.e. maximum grain size 64-128 mm, while an ideal minimum sample size is 256 kg, he recommended a practical sample size of 32 kg. For a 50 mm gravel, the BSI standard sample size is 35 kg. Mosley and Tinsdale (1985) concluded that accurate determination of mean grain size of a 16 mm gravel (D_{50}) required 100 kg, but suggested that if the largest stone is less than 5% of the total weight of the sample, estimation of median grain size is unbiased. Since their study was New Zealand based, it would be a legitimate rule

of thumb to apply in this study (i.e. suited to the nature of NZ rivers), although Wallick *et al*. (2009) sampled c.32-39 kg of material, with due acknowledgement that the distribution of clasts >68 mm was probably not adequately characterised.

To sample a sufficient quantity of subsurface material will require several 'cookie cuts' being made in the stream bed within a discrete location, as recommended by Kondolf *et al*. (2003). Logistically this is more taxing and time consuming than measurement of surface sediment and realistically is going to be more limited in terms of where this can be achieved in the catchment, although inevitably, the more data collected, the more robust the dataset, but a statistically significant sample size probably is not achievable, so a targeted sampling at strategic locations above and below the dams would suffice (Figure 4). It would also be valuable to assess the impact of the 'Greens Road' tributary on bed substrate in the mainstem of the Turitea, so in addition to sites in the immediate vicinity of the dam samples upstream and downstream of this confluence would be useful. Sites farther downstream would allow some assessment of the extent of armouring of the bed in a presumably replenished condition (cf. Figure 4).

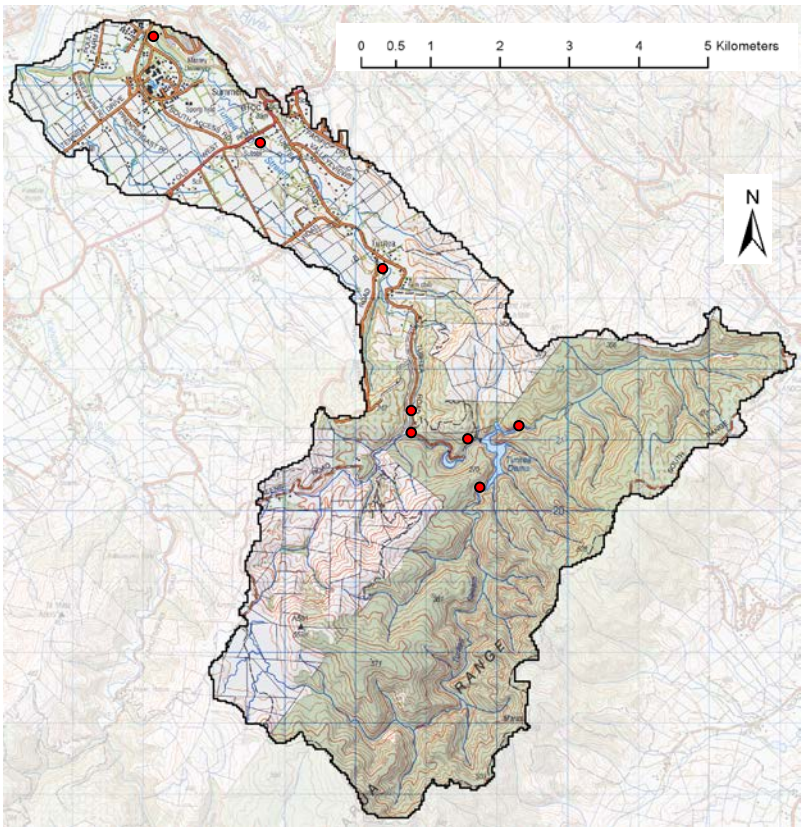

Figure 4. Suggested locations for subsurface sampling.

3.3.3 Hydraulic properties

Reach averaged shear stress (τ_c) can be measure using the DuBoys equation, based on a measured channel cross section mapped by levelling or more sophisticated ground survey:

$$\tau_c = \rho g R S \qquad (1)$$

Where: ρ = fluid density (1000 kg m^{-3}), g = gravitational acceleration (9.81 m s^{-1}), R = hydraulic radius (A/P) (m), S = slope (m/m)

Pohl (2004) notes that equation 1 assumes a steady uniform streamflow and a regular channel cross-section shape with a width at least 10 times greater than depth. This may or may not be applicable. In wide, shallow channels, Pohl (2004) suggests R can be approximated by mean depth. Thus, as mean depth of flow or channel gradient increase, the average boundary shear stress on the channel bed becomes greater.

The τ_c can be quantified for a range of flows, preferably by direct measurement, but if not feasible this can be obtained by deriving speed of flow for a given wetted channel cross-section using Manning's equation:

$$V = \frac{R^{2/3} S^{1/2}}{n} \qquad (2)$$

where: *R* = hydraulic radius (A/P), *S* = friction slope, *n* = flow resistance

Discharge can then be computed from the continuity equation:

$$Q = VA \qquad (3)$$

Reach averaged shear stress is a generalised assessment of shear stress in a reach and is not a precise quantification of the traction force applied at the bed (which is difficult to determine in any case), but it will give an approximation of shear stress at a site (cf. Pohl, 2004).

Sediment movement on the bed will only begin once critical shear stress is exceeded. Critical shear stress for entrainment of a given grain size is derived using the Shield's equation for poorly sorted beds:

$$\tau_{cr} = 0.047(\rho_s - \rho_w)gD \qquad (4)$$

Where: τ_{cr} = critical shear stress, ρ_s = density of the sediment (typically 2650 kg m^{-3}), ρ_w = density of water (1000 kg m^{-3}), *g* = acceleration due to gravity (9.81 ms^{-1}), *D* = grain size.

It should be noted that equation 4 does not take into account grain packing or shape and must therefore be recognised as an approximation of the critical shear stress for mobilisation of bed sediment. Grain size data derived from surface sampling (3.3.1) can be inserted into equation 4 to establish the critical shear stresses required to mobilise the given grain size. This in turn can then be compared with the reach average shear stress (1) at a given flow (3) to ascertain the potential mobility of the bed at key sites above and below the dams. This follows an approach set out by Pohl (2004), who suggests that if the average boundary shear stress exceeds the D_{50} critical shear stress, entrainment and transport of the median grain size can occur. Since turbulence and sediment packing is not taken into account, this should only be used as an approximation.

Bed mobility is best assessed for high flow events, since it is these that are likely to result in sediment transport. A ratio of τ_c: τ_{cr} will indicate whether entrainment is likely. A ratio exceeding 1 indicates entrainment is possible, conditional upon bed structure. Bed structure could be assessed using a penetrometer to record depth of penetration of a cone into the bed for a given number of blows from a hammer dropped from a consistent height onto the rod supporting the cone. A compaction index (number of blows / depth) can be used to infer packing, where a tightly packed, underloose bed will have a higher index of compaction than a loosely packed, overloose bed. This would provide additional information on the nature of the bed structure if required.

Hydraulic properties can be assessed for a number of sites as appropriate along the length of the Turitea to assess the extent to which bed mobility changes as bedload is replenished along the length of the stream away from the dams. Furthermore, this will provide a baseline for future work to examine any changes in bed mobility over time at a site and along the stream length (Figure 5).

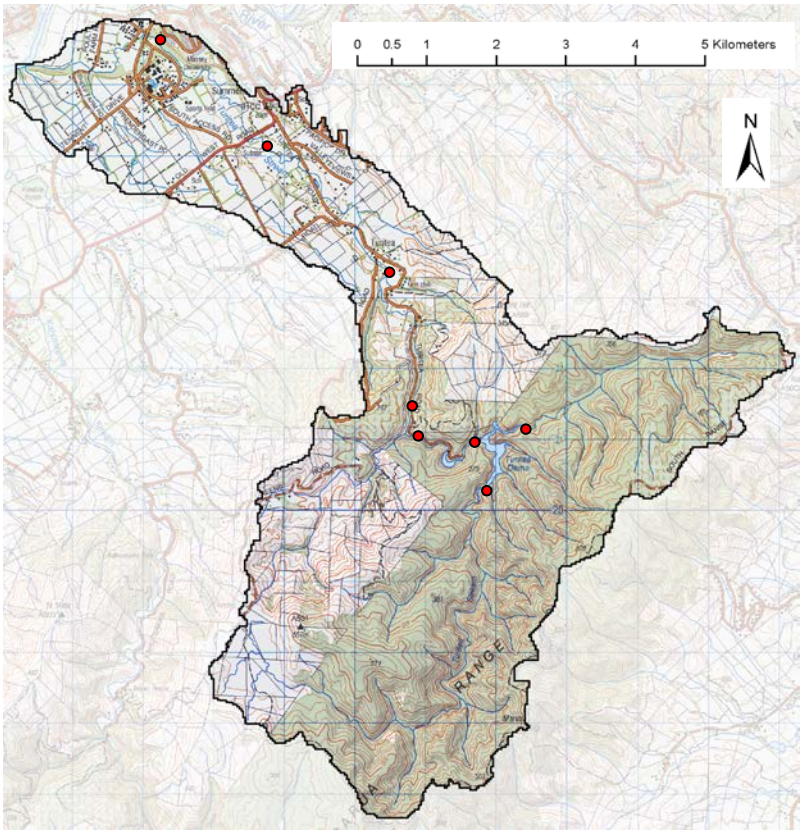

Figure 5. Suggested sites for assessment of hydraulic properties.

4. Conclusion

The recommendations in this report outline an approach that will potentially generate a comprehensive dataset on the nature of the Turitea bed sediment character. This will allow as full as possible appreciation of the impacts of the dams on sediment characteristics and quantify the spatial extent and intensity of sediment starvation in the system below the dams. Furthermore, this work will establish a baseline from which to monitor any ongoing impacts. Inevitably if done thoroughly, the recommended methods will require considerable investment of time, but aspects of the approach may also be suited to student project work in the future, which might enable some deferment of cost. An appropriate series of sampling sites will need to be considered carefully to maximise data generation within the available budget and to this end I recommend a thorough field reconnaissance in the first place. To some extent the recommended sampling locations in Figures 2, 4 and 5 are based on a visit to the catchment on 27 November 2012 and take into account site access and strategic locations as discussed above.

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