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Sediment Monitoring Plan for the Auckland Region

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Sediment Monitoring Plan for the Auckland Region

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1. Executive summary

Fine sediment discharge from streams to coastal waters is a significant environmental issue for the Auckland region. Managing this to ensure sustainable development requires a robust monitoring plan to improve understanding of the sediment sources, quantify the amount of sediment coming off the land at the catchment and regional scale, and assess the effectiveness of erosion mitigation policies. This report develops a draft design for such a stream sediment monitoring programme.

The study approach was to:

- Review the various needs for sediment information.
- Develop a monitoring strategy that aligns the monitoring approach and site slection to the type of information needed.
- Determine the most suitable GIS-based model to provide a region-wide reporting tool for State of Environment reporting.

Information on stream sediment loads in the Auckland region is needed to meet the following objectives:

- State of Environment reporting (as required by section 35 (2) (a) of the Resource Management Act, 1991) that provides a regional overview as well as accurate data on sediment loads into key receiving waters, and also identifies any trends in sediment yields stemming from catchment management or climate change.
- To contribute to community outcome monitoring (as required by the Local Government Act, 2002).
- To help inform on the efficiency and effectiveness of ARC's policy initiatives and strategies for sediment management.
- To provide baseline, regionally representative data from which impacts of individual activities can be measured through compliance monitoring.
- To ensure that developments meet consent conditions or to trigger mitigation responses during runoff events carrying high sediment loads.

The general strategy for meeting these information needs is to use a spatially-distributed sediment yield model to report on a region-wide basis, and to monitor at specific sites to calibrate and validate the model predictions or to provide robust data on sediment yields where it is most important.

The information needs can be met by operating four general types of sediment monitoring sites:

- Calibration/ Baseline sites are focused on relatively small, uniform catchments and aim to provide calibration data for the regional sediment yield model and/or baseline data for catchments. Individual sites may service both functions.

- Validation sites are focused towards the downstream ends of catchments that are currently experiencing development/landuse change issues, have sediment management initiatives in operation, and/or deliver sediment to sensitive coastal environments. Their results are used to validate the sediment yield model and/or to validate the effectiveness of sediment management policies.
- Reference sites are located in relatively small, uniform, pristine, and stable catchments where the sediment yield should be sensitive only to climate and inter-annual weather variability.
- Compliance sites are those set up explictly to meet Resource Consent monitoring conditions.

Considering existing sediment data coverage and gaps, the locations of existing flow recordings sites, and existing/developing sediment yield issues around the region, a draft list of seven, high-priority sites is recommended: two Calibration/ Baseline sites, four Validation sites, and one Reference site.

The recommended model type to provide region-wide information on sediment yields for state-of-the-environment reporting, and for assimilating the results of monitoring at calibration and validation sites, is a physically-based sediment generation and routing model that is operated off spatially distributed rainfall records at a daily or finer time-step and is responsive to catchment landuse and erosion treatment measures. The GLEAMS model appears to be a reasonable candidate; however, model selection and application to the Auckland region should be the subject of further work.

2 Introduction

2.1. Background

Fine sediment derived from land erosion is a major contaminant in receiving estuaries and coastal waters in the Auckland region and thus is of concern for the Auckland Regional Council (ARC). Existing knowledge indicates various landuse activities and urban development as potential sources of high sediment generation, thus a key issue for the region is to manage the effects of development on the natural environment. This includes balancing the needs for sustainable environmental management with the community's social, economic and cultural well being. Specific objectives include managing and minimising the adverse effects of present and future urban and rural development, growth, and landuse intensification across the region.

Meeting these goals requires a robust monitoring strategy that improves understanding of the sediment sources and quantifies its supply and transfer through the region's waterways. Since it is not practical to monitor sediment loads continuously in all streams around the region, a key task is to design a sampling program at a selection of sites and to upscale the results across the region. Several recent studies have made progress on this task.

M. Hicks (NIWA memo 24 November 2008) provided to ARC an outline of a possible strategy to monitor sediment at a regional level. The basis would be a spatially-distributed sediment yield model that would be responsive to rainfall, landuse and erosion treatment measures. Monitoring would be undertaken to calibrate this model and validate its predictions.

Hicks et al. (2009) reported on event sediment loads and mean annual loads (or yields)[1] for nine basins with various landuses under Waitemata Formation terrane. Their analysis showed a relationship between sediment yield and catchment rainfall, mean slope and landuse, but they recommended more monitoring to provide results for other lithologies within the region.

A recent review by N Holwerda (internal unpublished ARC document) also contains information for selecting suitable sites for sediment monitoring and provides information on the current sites monitored for stream hydrology.

[1] For this report, the term "load" generally refers to the mass discharge of sediment over time periods or events spanning less than a year (e.g. kg/s, t/day, t/event) while the term "yield" refers to the annual average sediment load (t/yr). "Specific yield" is the sediment yield per unit catchment area (t/km^2/yr).

2.2. Purpose and objectives

The purpose of the current project is to develop a design for stream sediment monitoring in the Auckland region. The main objectives are to:

- Review needs for sediment information.
- Develop a monitoring strategy that aligns the monitoring approach and site slection to the type of information needed.
- Determine the most suitable GIS based model to provide a region wide reporting tool for State of Environment (SoE) reporting. Such a model would predict spatially-distributed sediment yield that would be responsive to rainfall, land use and erosion treatment measures.
- Review existing sediment monitoring and existing recommendations for future monitoring.
- Develop a ranked site list and determine data collection objectives and sampling specifications.

2.3. Approach

The study proceeded in two stages:

- A one day workshop to review recent relevant studies, discuss needs and outcomes for sediment monitoring, discuss approaches for modelling sediment yields, and to advance on establishing a draft list of sites for monitoring. The workshop was held over one day at NIWA, Hamilton, on 23 July 2009. It was attended by M. Hicks, S. Elliott, M. Green, and A. Swales from NIWA and by A. Taylor and P. White from Auckland Regional Council.
- Preparing this report, which summarises the findings of the workshop.

3 Needs for stream sediment data

In overview, the needs by ARC for sediment information in the Auckland region may be classified as follows:

- State of Environment (SoE) reporting
- Sediment management policy, including
  - Baseline information
  - Policy development
  - Policy effectiveness
- Compliance monitoring

3.1. State of Environment reporting

ARC has obligations for State of Environment monitoring and reporting as required by section 35 (2) (a) of the Resource Management Act (1991). SoE reporting needs to present overview/summary information at the regional level, such as:

- Point data on mean annual (t/yr) and/or sediment loads on a year by year basis to estuaries/harbours/the open coast on a sub-region/ harbour/ catchment basis, e.g., figures at stream/river mouths, tables for the region, and so on.
- Spatially-distributed data on mean annual ($t/km^2/yr$) or annual (t/km^2) sediment specific yield, e.g. maps locating high sediment generation areas, tables listing yields by landuse by catchment or harbour, and so on.
- Changes in the above since the last reporting date.
- Trends in the above over multiple reporting periods.

With trend monitoring, it is required to distinguish climate-driven change in sediment yield from that associated with landuse activities. This requires information from reference catchments that retain a stable landuse.

As well as providing the regional overview SoE reporting helps focus attention on areas with particular issues, such as a catchment undergoing landuse conversion that is supplying a lot of sediment to a coastal receiving waters. It also helps identify large scale or cumulative impacts of contaminants and disturbance associated with varying landuses where further research and monitoring may be required.

3.2. Sediment management policy

Management of land-based activities to limit sediment delivery to the stream network is an important ARC policy. The current policy is detailed in the Sediment Management Plan (ARC, 2001), which is currently being reviewed. Key aspects of the policy involve regulation of urban development and consent conditions requiring mitigation of increased sediment loads. Sediment information is utilised both in the development and operation of the sediment management policy, and is also needed to assess the effectiveness of the policy.

3.3. Baseline information

Information on how much sediment is produced from various landuse related actvities (and catchment physical characteristics) is also required for understanding baselines and for assessing policy effectiveness. Of particular value is regionally representaive information on the sediment yield expected from stable landuses (e.g., established native forest, mature urban) and also the sediment yield associated with various types of landuse change (e.g., urbanisation). Stable landuses invariably deliver less sediment than those that are in the process of being converted. For example, the aerial proportion of a pasture catchment undergoing urbanisation during any one period may be constrained in order to keep the sediment yield at the catchment outlet below a given level. Setting the area limit requires data on the specific sediment yield (i.e., t/km^2'yr) expected from a pasture landuse, a mature urban landuse, and an area undergoing urbanisation. Alternatively, or as well, sediment management targets may require that the sediment yield from the urbanising portion of the catchment does not exceed a given multiple of the yield expected under the former pasture landuse. It is desirable to have information from catchments with uniform and stable landuse to provide baseline data, which generally requires that they be low-order catchments. However, information from a larger, mixed-landuse catchment may also be useful if that provides a baseline from which to assess the efficacy of policy initiatives applied to that particular catchment.

3.4. Policy development

Policy development requires regional-scale and generic information, including:

- How much sediment is coming from where
- What trends may be occurring
- On a unit area basis, how much sediment is produced from various landuse related actvities (notably earthworks, sub-divisions, market-gardening, pastoral farming, and forestry)

- The efficiency and effectiveness of mitigation measures (such as riparian planting, sediment retention ponds).

The first three of these needs are much the same as those for SoE reporting.

3.5. Policy effectiveness

Sediment information is also needed to inform on the efficiency and effectiveness of sediment management policies, rules or other methods and to demonstrate that the expenditure of ratepayer funds on the policy implementation is warranted.

As well as the formal regional policy, there are also other methods used such as community projects that aim to reduce stream sediment loads and that are subsidised with ratepayer funds (e.g., the riparian management project currently underway in the Mahurangi catchment).

It appears that in practice the sediment management policy is applied on a selective basis around the region, targeting areas proposed for landuse change and/or with existing sediment problems in receiving waters. Areas undergoing landuse change identified during the workshop include Whangateau, Wairoa-Clevedon, Whiford, Henderson, and Silverdale. These areas could be used to determine policy effectiveness in the coming decade.

The assessment of policy effectiveness is fundamentally required at the fresh/salt-water interface – thus the prime need is for sediment load information at the downstream ends of catchments.

3.6. Compliance monitoring

Compliance monitoring involves monitoring to demonstrate that developments comply with consent conditions. For example, the efficiency of sediment retention ponds in zero-order channels may need to be demonstrated, or their sediment discharge may need to meet baseline targets. Such monitoring is funded by the consent holder, is typically undertaken by consultants, and the information collected is reported to ARC (the consenting authority).

Since this monitoring is already funded on a distributed-user basis, it lies outside the scope of this report (i.e., for ARC-funded monitoring). However, and ideally, if such compliance information could be collated on a regional basis and analysed, then the results could be fed back into a policy effectiveness monitoring programme.

4 Monitoring strategy: matching data collection to information need

4.1. Overview of strategy

In this section we develop a monitoring strategy to service the sediment information needs of the ARC. The basic approach is to classify the type of monitoring and site characteristics required to meet each information need. First, however, it is necessary to develop an approach to provide region-wide information, because this creates additional needs for site-specific monitoring.

From the previous section, it is clear that two general types of sediment yield information are required:

(i) information specific to individual streams or receiving waters and

(ii) sediment yields distributed across the region.

For the latter case, which is required primarily for SoE reporting but which is also important for policy development, it is impossible to measure sediment loads everywhere around the region, therefore a method needs to be employed that essentially enables spatial interpolation of site-specific information.

We propose that this regional overview problem be managed by use of a spatially-distributed, regional-scale sediment yield model. The model should generate sediment from hillslopes into watercourses, route it downstream, and deliver it to coastal water bodies. The model outputs on sediment production and delivery could then easily be mapped, tabulated, broken down by landuse, and totalled by catchment, harbour, and over the whole region. It should be sensitive to landuse and rainfall and should ideally also incorporate sediment management measures within its modules for sediment generation and routing.

We discuss options for such a model in Appendix 1, but its selection and application are beyond the brief of this present study. Here, we simply recognise that such a model requires two types of site-specific sediment information:

- Calibration data, to relate sediment yields to the main combinations of landuse and catchment lithology found in the Auckland region – this requires data from catchments that are relatively uniform in landuse and lithology, which essentially limits the choices to relatively small catchments (of the order of several km^2 in area).

- Validation data, to verify that the sediment yield predicted by the models is acceptably close to that actually measured[2] – this is most important to demonstrate at the delivery points to coastal receiving waters, hence the need to monitor towards the downstream end of relatively large catchments (order 10's to 100's of km^2).

4.2. Types of sediment monitoring site

From the foregoing, we recognise six types of sediment monitoring sites, as summarised in Table 1. These are listed in order of increasing catchment size. Small catchments will generally be needed for the *Model calibration* and *Baseline* information: this is forced by the need for uniform landuse. Similarly, the *Reference* sites will likely need to have relatively small catchments simply because there are few, if any, large catchments that remain pristine. *Compliance monitoring* sites will typically also have small catchments since consents are usually issued for areas where a particular activity is focused (e.g., an urban subdivision); however, consents may occasionally require monitoring sediment yields from large catchments. *Model validation* is best done for catchments that contain a variety of landuses and at sites close to the estuaries or the coast, thus larger catchments are expected. Similarly, *Policy* validation is expected generally over relatively large areas and for catchments connecting with sensitive coastal waters.

[2] Appropriate validation standards will need to be defined at the stage when a model has been setup and run – see Appendix 1.

Site type	Information need serviced	Catchment requirements	Term of monitoring	Type of data needed
Model calibration	Regional sediment yield model calibration – for SoE reporting & policy development	Catchments that are uniform and stable in land use and lithology (typically relatively small & closer to headwaters); site network needs to cover main land uses and lithologies in region; main gaps are in greywacke, Northland Allocthon, volcanic, and alluvium lithologies; focus on pasture land use	Short-term, sufficient to define calibration coefficients	Event sediment loads, ideally by size fraction Time-series data through events Mean annual yields via rating relations
Baseline information	Land use-specific baseline information	As above, plus uniform catchments undergoing land use change and/or with mitigation measures in place	Short-term, sufficient to define mean annual yield or response coefficient	Event sediment loads, ideally by size fraction Time-series data through events Mean annual yields
Compliance monitoring	Compliance on consent conditions Policy development (efficiency of policy development and implementation)	Catchments, typically small, subject to development or activity requiring a resource consent, often with mitigation measures in place (such as sediment retention ponds); sometimes representative of or indexing larger catchments	Determined by consent conditions	Determined by consent conditions, but typically event loads; sometimes time-series of SSC or load during events
Reference	SoE reporting on climate-driven trends Reference dataset on annual yield variability due only to rainfall variability Regional model calibration and	Catchments that are relatively pristine and are expected to remain so for the foreseeable future, with no significant development or land use change planned – sites in reserves or in water-supply catchments are ideal. It would also be advantageous if these have uniform lithology and land cover. Ideally these would be large	Ongoing	Mean annual yield[3] Annual yield

[3] Mean annual yield is the average yield over multiple years; annual yield refers to the year by year yield.

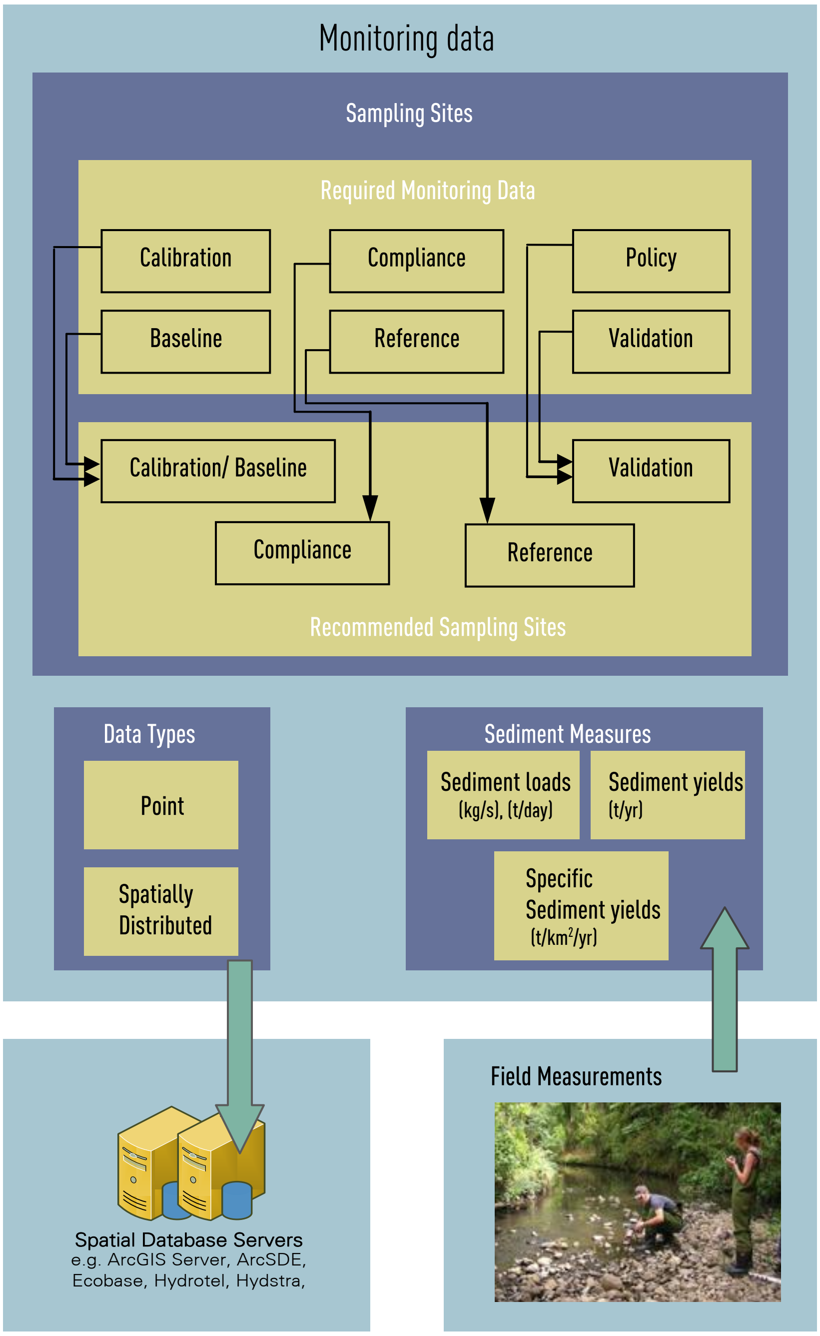
	validation	catchments, but, practically, the lack of large pristine catchments may force the use of smaller ones.		
Policy validation	Policy effectiveness monitoring. Baseline data pre-development or pre-application of policy initiatives	Typically large catchments upstream from receiving waters with existing sediment issues, or planned development / intervention, or widespread sediment management initiatives, or scientific or political interest, or a combination of these.	Medium-term, at least until development or issue matures; may also include a pre-development/ pre-intervention control period	Annual and mean annual yield
Model validation	Validation of regional sediment yield model – for SoE reporting	Typically large catchments upstream from receiving waters with existing sediment issues, planned development/intervention, widespread sediment management initiatives, scientific and/or policy or political interest	Medium-term, at least until development/ issue matures	Annual and mean annual yield

Table 1: Types of sediment monitoring sites , catchment characteristics, expected term of monitoring, and information needs serviced.

4.3. Rationalisation

By considering areas of overlap in sediment information needs and catchment characteristics, the above six site types can reasonably be merged into four as shown in Figure 1.

Figure 1 Four types of sites are recommended to enable the six types of required monitoring data.



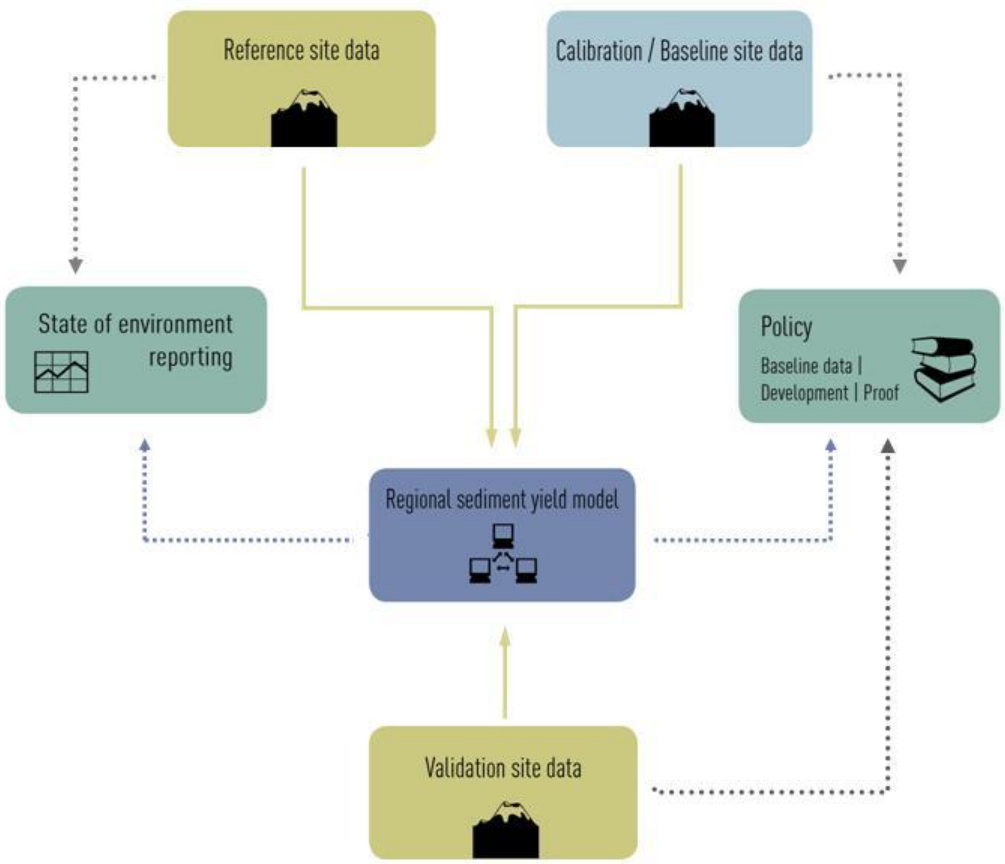
For example, sites required for model calibration and for understanding baselines have essentially the same requirements (e.g., uniform catchment and landuse characteristics, which are typically only found in smaller catchments). Also, Policy and Model validation sites are both typified by large catchments with typically mixed characteristics upstream from important waterways.

On this basis, we propose the following pragmatic list of site types:

- Calibration/ Baseline (meeting needs for model calibration and baseline data)
- Validation (meeting needs for model and policy validation)
- Reference (tracking trends due only to climate change)
- Compliance (to demonstrate compliance with consent conditions)

We focus on these four broad types (and use this site-type nomenclature) from here on. Figure 2 illustrates the relationship between the various site types, the regional sediment model and the outputs from the sites and model for the purposes of reporting.

Figure 2. Diagramatic representation of the site types and realtionship with the model.



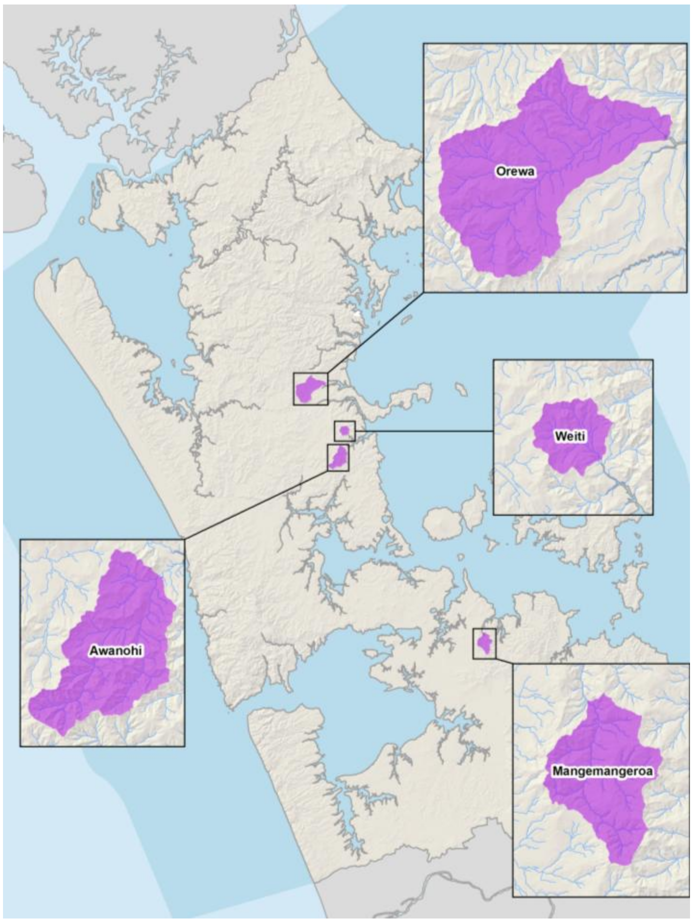
5. Existing sediment monitoring and existing recommendations for future monitoring

5.1. Existing sediment monitoring

Currently, ARC monitor (or are in the process of beginning monitoring) stream sediment loads at four sites as seen in Figure 3:

- Orewa
- Mangemangeroa
- Awanohi
- Weiti

Figure 3 Existing sediment monitoring sites



At the Orewa and Mangemangeroa sites the objective is to provide information on storm and mean annual yields to the estuary downstream. Both catchments have mixed landuse with ongoing development, so in terms of the site types described above these two are best classified as Validation sites.

Awanohi and Weiti are monitored primarily for assessing policy effectiveness (Megan Stewart-Carbines, ARC, pers. comm.), so they too, are best classified as Validation sites. The aim of the monitoring is to see whether having vegetation removal as a permitted activity in a sensitive catchment is an effective policy. The main concern is the impact of mud deposition from storm runoff on shellfish beds on intertidal flats in the receiving Okura Estuary. Real-time records of flow and turbidity (from an optical backscatter [OBS] sensor calibrated to suspended sediment concentration) enable a running accumulation of sediment load during runoff events. An alert is initiated when the accumulated event load passes a threshold, and ARC staff then carry out ecological monitoring in the estuary to see what effect the sediment delivery may have on the ecology. A secondary, compliance component is that if an alert is triggered, ARC compliance officers may check the forestry operations to make sure they are compliant with the Auckland Regional Sediment Control Plan.

Auto-samplers are installed (or planned) at all four sites. The current sampling strategy at all sites is discrete sampling during storm runoff events, with the auto-samplers activated above a given stage threshold. At Weiti, the auto-sampled suspended sediment concentration (SSC) is used to calibrate the OBS record.

5.2. Holwerda report

N Holwerda (internal unpublished ARC document, 2009) recently made recommendations for sediment monitoring at existing flow recording sites in the Auckland region.

His analysis initially looked at the catchment characeristics of the existing *flow* recording sites, using data on lithology, landuse, source-of-runoff, climate type, and average gradient extracted from the River Environment Classification (REC). The objective in doing this was to establish how well the spatial variability across the region was sampled by the runoff sites. He weighted each characteristic by the length of stream channel (upstream from the monitoring site) in each class. He found that:

- Most of the streams with flow recorders have a warm-wet climate, are low gradient and lowland fed, are in soft sedimentary lithology and pasture landuse.
- Most sites are on lowland, medium-high order channels; there are relatively few on steep/headwater channels.

- There is generally good representative cover over the main landuse and lithology groups, but coverage is lacking in volcanic and alluvium terranes and in forest (both exotic and indigenous) and scrub landcovers.
- There is no room for movement in the flow recording network, with all the existing flow-recording sites needed.

He then rated the potential value of sediment information from each flow recording site by plotting each site into *sediment yield* vs *level of risk* space. He estimated specific sediment yield (t/km^2/yr) off NIWA's WRENZ website (http://wrenz.niwa.co.nz/webmodel). He rated risk in terms of the risk level of downstream coastal receiving environments, as discussed with ARC marine scientists. This risk level was set as either Low, Medium, or High. His sediment monitoring recommendations were based on the following ranking rules:

1. Any sites monitoring flows that enter High risk coastal habitats
2. Take the furtherest downstream site where there is more than one site in a catchment.
3. Sites that monitor flows into Medium / Low risk coastal habitats, with a specific sediment yield above 150 t/km^2/yr
4. If a catchment has a portion of high sediment yield land even if Low risk and specific sediment yield is below 150 t/km^2/yr.

By this process, Holwerda recommended seven existing flow recording sites for future sediment monitoring (Table 2). His ranking procedure also confirmed that Weiti (7505) and Awanohi (7502), which are currently already being monitored as part of the Okura estuary monitoring, were both worthy of continued monitoring.

As well, using the same criteria, Holwerda also recommended sediment monitoring at eight new sites, where flow monitoring would have to be started (Table 3).

It is of note that our workshop discussion identified a signficant amount of uncertainty in the information underpinning Holwerda's ranking system. This uncertainty included the use of the WRENZ model to estimate sediment yields. The WRENZ sediment model is a national-scale modelled calibrated with data from over 200 river sites; however, few of those sites were in the Auckland region, thus the WRENZ sediment model is not well calibrated there. Also, the 150 t/km^2/yr threshold for specific sediment yield appears high. For example, seven out of the nine sites investigated by Hicks et al (2009) had mean annual specific yields less than 100 t/km^2/yr.

Existing sites in monitoring priority order	Current uses
1: Tamahunga at Quintals Falls (6501)	MGT site, used as a water balance site for the Omaha aquifer, WQ, FWM site in adjacent catchment, saline site D/S, high risk coastal receiving environment
2: Mahurangi at College (6806)	LTB, WQ, FWM, saline, 9 sites for downstream marine ecology
3: Kaukapakapa at Taylors (45415)	MGT, FWM, Saline
4: Kaipara at Waimauku (45311)	WQ, FWM, Saline, Flood flow investigation, MGT and LTB
5:Mangemangeroa (8304)	Monitor development in catchment. Marine ecology, sediment deposition.
6: Wairoa at Tourist Rd Br (8516)	LTB, MGT, WQ, flood monitoring site.
7:Hoteo at Gubbs (45703)	LTB, WQ, FWM, Saline

Table 2. Holwerda's recommendations for sediment monitoring at existing flow recording sites (from Table 10 of Holwerda, 2009). Abbreviations: MGT – Management Monitoring; WQ – Water Quality; FWM – Fresh Water Macro; LTB – Long Term Baseline (see Appendix 6.6 of Holwerda, 2009, for further detail).

New sites in monitoring priority order	Current Uses	% of catchment sediment potentially monitored	Receiving Environment risk
1: Matakana	WQ, low flow gauging, FWM	56	High
2: Puhoi	FWM, 10 L defect sites UNI services	71.4	High
3: Waiwera	WQ, low flow gauging, FWM, prior record	90	High
4:Whangapoua	None	30	High
5: Turanga	None	90.2	Medium
6: Makarau	Current NIWA site, rain gauge in catchment	93.3	Medium
7: Waireia	None	35.8	Low
8: Waihoihoi/ Slippery Creek	Sediment Chemistry, Marine Ecology, Sentinel Shellfish, FWM, WQ	34	Medium

Table 3. Holwerda's recommendations for new sediment and flow monitoring sites (from Table 11 of Holwerda, 2009). Abbreviations as in Table 2.

5.3. Hicks et al. report

Hicks et al. (2009) analysed mean annual suspended sediment yields from nine catchments in the Auckland region that had existing data on sediment loads. They found that the variation in specific sediment yield was due mainly to catchment rainfall, mean slope, and landuse. A regression model indicated that for a given rainfall x slope product, the specific yields from forested areas were 2/3 those from pasture areas, while the specific yields from urbanised areas were 1/4 of those from pasture areas.

They recommended more sediment monitoring to improve/validate this relationship. Also, since the dataset analysed was limited to catchments in Waitemata Sandstone terrane, they recommended that sediment sampling be extended to cover catchments in other lithologies, notably in the Onerahi Chaos (Northland Allochton) terrane in the northern part of the region and the greywacke terrain in the southeast.

All but one of these nine sites had small catchments (0.6 – 5.3 km^2) and most had one dominant landuse (i.e., either pasture, exotic forest, urban, or native forest). Thus, they fall generally into the Calibration/ Baseline site-type, and their results are suitable for helping calibrate the regional sediment yield model discussed in section 4.1. Mahurangi at College (48 km^2) is a larger and more mixed catchment and has areas under sediment control treatment, thus it is better regarded as a Validation site.

6. Draft list for sediment monitoring sites

From earlier discussions and discussion during the workshop, a working set of sediment monitoring sites was drawn up for each of the site-types defined in Section 4.2. The selection process was pragmatic rather than sophisticated and objective (e.g., statistics based). It was recognised that there will likely be limited funding available, which will likely restrict the number of sites to six-nine active at any one time. This number could be increased with co-funding (e.g., with neighbouring authorities where sites lie on the region's borders). Also, since each sediment monitoring site requires a flow record, in the first instance the search for sites was focused on existing flow recording sites (Holwerda, 2009). Some additional site locations without existing recorders were suggested to fill specific gaps.

A draft priority ranking was assigned within each site type based on a subjective set of rules for example – is there exisitng flow recording equipment installed, where sites meet more than one site type they were given greater priority. No attempt has been made here to assign priorities among site types. We assume that will be decided by ARC. The results of this exercise are summarised in Table 4 and site locations are displayed in Figure 4.

6.1. Calibration/ Baseline sites

The Calibration/ Baseline sites aim to fill the gaps in lithological variation around the region, focussing on sites with mainly pasture landuses. The lithologies[4] targeted (in priority order) were the Northland Allochthon terrane (Kaukapakapa @ Taylors), volcanic terrane (Waitangi @ SH Bridge), and the Hunua Greywacke. For the latter, a new site on a small forested catchment in the Hunuas would meet the requirements of both a Calibration site and a Reference site.

6.2. Reference sites

Reference sites were selected to represent northern and southern sections of the East Coast. Sites on reserve land or in water-supply catchments were sought to ensure stability of land cover[5]. The options with existing flow recording sites are limited, thus it will probably be necessary to invest in new flow monitoring sites for this purpose. General areas for new sites are

[4] Lithologies based on GNS (2001).

[5] Reference sites in exotic forest would not be ideal, since the hydrological behaviour and sediment yield from these will evolve as the forest matures and their usefulness will expire on harvesting (and the investment in the time-series will be lost).

suggested in the Hunuas (possibly a Wairoa tributary) and in the north eastern part of the region. Since these sites are essentially to detect climate-change effects that might reasonably be expected to be similar in style across the region, then only a small number of sites should be required. We recommend two.

6.3. Validation sites

Most of the existing flow recording sites fall into the Validation type by virtue of their mixed and changing landuses, sediment management treatments, and proximity to sensitive receiving waters. The approach was to organise potential sites discussed at the workshop in terms of the major harbours that they drain into, then for each harbour to assign a ranking based on a subjective assessment of the characteristics and issues associated with each site. For example, for the Kaipara Harbour sites the highest priority site would appear to be the Hoteo @ Gubbs, by virtue of the combined weight of it having a large catchment with a mix of landuses and it being relatively close to the harbour. Similarly, for the Waitemata Harbour, at least one of the Henderson Stream branches (Oratia or Opunuku) is recommended based on the extent of intervention associated with the "Project Twin Streams" initiative. On the East coast, both the Mahurangi and Wairoa sites appear good candidates based on their relatively large size, existing/ongoing development and intervention, and existing issues in the receiving waters. On the other hand, Orewa, Mangemangeroa, Weiti, and Awanohi sites might be considered as alternatives since sediment monitoring is already underway at these four sites. The Papakura site appeared to be the only qualifying site draining into the Manukau.

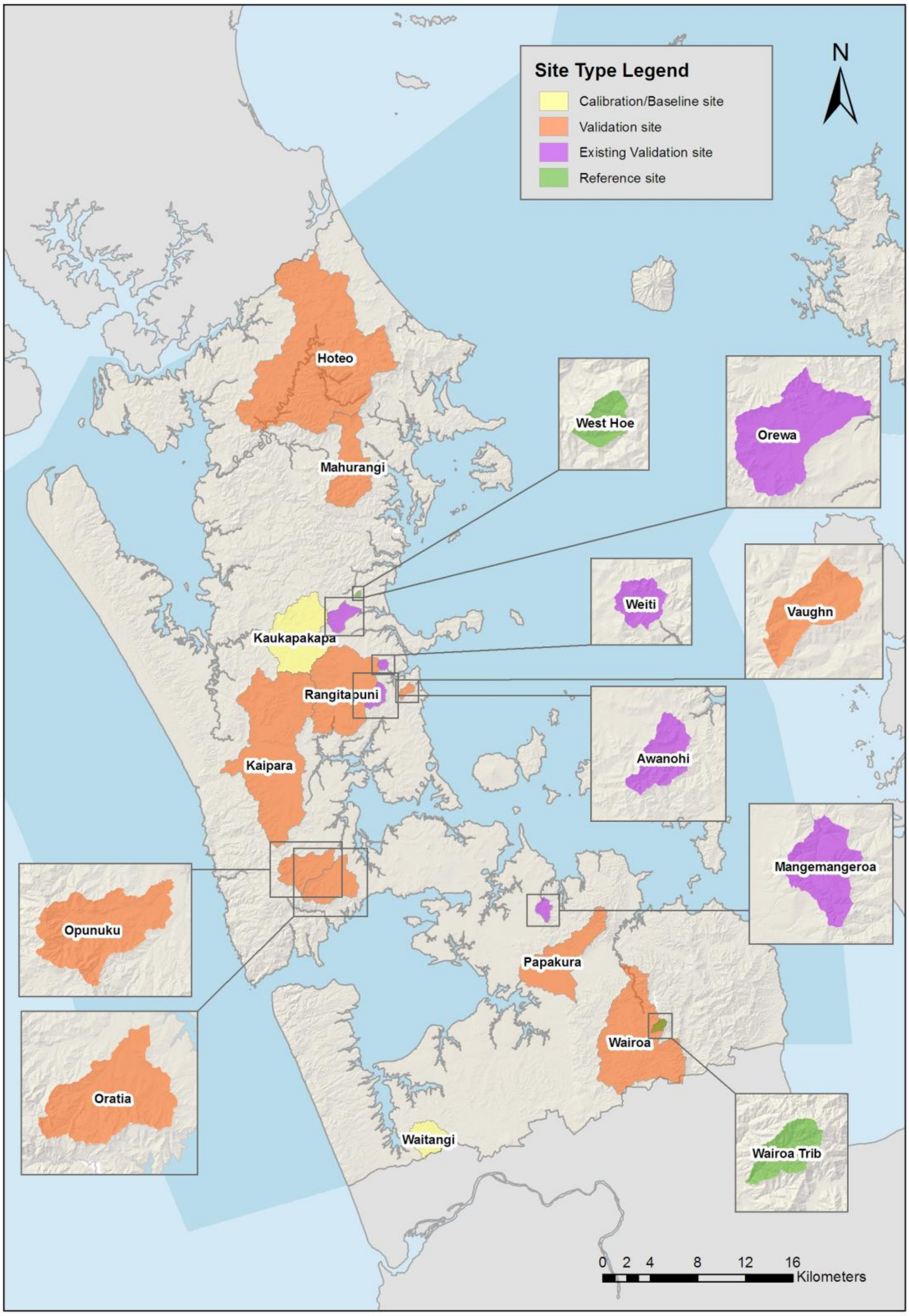
6.4. Compliance sites

We have made no atempt to select other sites of this type as this is a matter to be dealt with by individual consents. Nor have we assigned priorities to Compliance sites, since the need for these is set by consent decisions, and the sites will generally be funded by those requesting the consent. Information can be gathered from consents and may be used in the model.

6.5. Summary

In summary from Table 4, our draft priority ranking suggests that sediment monitoring be undertaken in the first instance at two Calibration/ Baseline sites, four Validation sites, and one Reference site.

Figure 4 Recommended site locations for sediment monitoring.



Site type (refer 4.3 for details)	Receiving coastal water	Site	Area (km^2)	Justification	Main Lithology	Comments	Priority (by type)
Calibration / Baseline	Kaipara Harbour	Kaukapakapa @ Taylors	61.6	Large catchment; mainly pasture but mixed land use	Mainly Northland Allochthon, some Waitemata Group		1
	Manukau Harbour	Waitangi @ SH Bridge	17.6	Need another site in Pukekohe market-gardening area	Bombay Hills volcanics		1
Validation	Kaipara Harbour	Hoteo @ Gubbs	268	Large catchment; good mix of land uses, no data yet from Kaipara Harbour tributaries.	Waitemata Group & Northland Allochthon	Possible site for research	1
	Kaipara Harbour	Kaipara @ Waimauku	162	Large catchment, good mix of land uses, of interest to iwi	Waitemata Group, Plio-Pleistocene Alluvium		2
	Waitemata Harbour	Rangitapuni @ Walkers	82.7	Near estuary, ongoing development	Mainly Waitemata Group, Plio-Pleistocene Alluvium		2
	Waitemata Harbour	Opunuku at Vintage Reserve	24.4	Project Twin Streams initiative, major sediment source, lots of intervention	Mainly Waitemata Group, Plio-Pleistocene Alluvium		3
	Waitemata Harbour	Oratia at Millbrook Road	27.7	Project Twin Streams initiative, major sediment source, lots of intervention	Mainly Waitemata Group, Plio-Pleistocene Alluvium		3
	Manukau Harbour	Papakura @ Great South road Bridge	53.2	Large, near harbour; mixed lithologies, land use	Mainly Pleistocene Alluvium, with Waitemata Group and Hunua Greywacke		1
	East Coast south (Tamaki Strait)	Wairoa @ Tourist Road	114	Large, high sediment yield, mixed land use, development planned	Mainly Hunua Greywacke, with Plio-Pleistocene Alluvium		1

	East coast north (Long Bay)	Vaughn @ Weir	2.3	Small, early in urban development stage,	Waitemata Group	Mixed land use, mainly pastoral, but urbanising	2
	East Coast north (Mahurangi Harbour)	Mahurangi @ College	46.5	Large, near estuary, lots of intervention, aquaculture issues, existing and planned development	Mainly Waitemata Group, with Northland Allochthon	Mixed land use	1
Existing Validation	East Coast north (Orewa Estuary)	Orewa @ Kowhai Avenue	9.6	Mixed land use with ongoing development, downstream estuary issues	Mainly Northland Allochthon, with Waitemata Group	Existing sediment monitoring site	
	East coast south (Tamaki Strait)	Mangemangeroa @ Recorder	4.4	Mixed land use, ongoing development, downstream estuary issues	Waitemata Group	Existing sediment monitoring site	
	East Coast north (Okura Estuary)	Weiti Forest	1.7	Forest harvesting underway; monitoring to assess if this is impacting estuary ecology and hence to assess effectiveness of forest harvesting policy	Northland Allocthon & Waitemata Group	Existing site Serves also to check on compliance with forestry best-practice	
	East Coast north (Okura Estuary)	Okura @Awanohi Rd	5.5	Monitoring to assess if forest harvesting policy is impacting estuary ecology	Waitemata Group	Existing site	

Reference	East Coast north	West Hoe	0.53	Native forest	Waitemata Group	Existing flow recorder site, also serves as Calibration site	1
	East Coast south	Wairoa Tributory	2.16	Native forest	Hunua Greywacke	Need new flow recorder site Also serves as Calibration site	2

Table 4: Draft list of sediment monitoring sites, classified by site type then by location of receiving water. 1 is highest priority. Existing validation sites excluded as already part of an existing programme and will be funded.

7. Monitoring objectives and methods

7.1. Calibration / Baseline sites

As detailed in Table 1, the Calibration / Baseline sites require information on sediment loads and size grading at the event scale, which can then be used to estimate mean annual yields.

We suggest that the sediment load data is best acquired using auto-samplers programmed to sample during storm runoff events on a flow-proportional compositing basis. While not delivering instantaneous sediment concentration data, the compositing approach (by virtue of increasing the potential number of samples by a factor of six-eight, e.g. from, say, 24 to 192) enables a more reliable integration of the sediment load through events. This also enables all events to be sampled rather than just a sampling of events[6].

The alternative approach for compiling a continuous record of sediment load is to use a turbidity / optical-backscatter sensor that has been calibrated with sediment sampled from the site. Fouling and sensor drift often mean that these records require considerable editing, particularly if a record is maintained during base flows. The calibration is sensitive to particle size and organic content, thus, ideally, it is best to have some knowedge of the dynamics of the partcle size and organic component of the suspended solids load during events at the site in question. The advantages of a turbidity sensor are that:

(i) it provides a higher resolution time series and

(ii) with telemetry it can provide real-time data that can be used to trigger compliance events and enable quick detection of malfunction.

If funding permits, it would be wise to use both a turbidty sensor and auto-sampler, with one instrument providing a back-up for the other. Time-savings on editing and calibration of the turbidity record could be made by only calibrating and editing "on the fly" when the turbidity record is required.

The mean annual yield can be determined either by direct integration of the sediment load record or by using a sediment rating approach (which may be event-load or SSC based).

The duration of monitoring for calibration purposes was discussed but not finalised at the workshop. The aim should be to define a sediment load rating relationship (e.g., an event-load rating) to a suitable standard, which should

[6] Experience has shown that when using auto-samplers to collect discrete samples, because an auto-sampler has only 24-28 bottles available it often turns out that too few samples are collected over an event – either because the sampler has run out of bottles or simply due to inflexibility in the sampling schedule. Thus what tends to happen is that some events are well sampled while others are not. While such data enables event yields to be sampled, e.g. to build event yield rating relations, it typically does not enable a continuous record of the sediment load.

only require around two years of record providing an adequate number and range of storms are sampled. One option could be to monitor until the uncertainty in the long-term average yield estimated from an event-load rating relation (e.g., using the boot-strapping approach used by Hicks et al., 2009) fell below a certain limit. Based on the degree of variability in annual sediment yields reported by Hicks et al. (2009), chasing a stable mean annual yield through continuous sampling may require 5-10 years of monitoring. With a shorter, rating-focused sampling approach, samplers could be circulated around more sites and the regional model could be calibrated sooner.

Particle size is best sampled with depth-integrated samplers, collecting samples at multiple verticals so that cross-channel variability can be averaged out. Cross-channel variability may turn out not to be important, e.g. at a turbulent, well-mixed site or where the load is dominantly clay grade. However, the ideal is to confirm this by measurement rather than simply assume it is so. The suggested approach to deal with change in size grade through events is to sample and analyse grainsize through at least one event. The data collected can then be used to calulate an overall size grading for the total event sediment load. This grading may then be assumed to be representative of other events. The alternative approach – if the site is suitable – is to deploy an in-situ device that will continuously monitor size grade at a point during one-several events. Such a device could be moved from site to site. One such device is the LISST[7], although it is not particularly robust and NIWA's experience is mixed with regard to its capability to measure the larger particles in suspension.

7.2. Validation sites

As detailed in Table 1, the Validation sites require information on sediment loads and size grading at the event scale, which can then be used to estimate annual yields and mean annual yields. The same compositing auto-sampling approach as for Calibration/ Baseline sites is recommended.

Validation (and calibration) of model output is most likely achieved by comparing cumulative-mass curves of measured and predicted event loads over one-several years. This avoids having to chase the inevitable variability in loads experienced on an event-by-event basis.

The duration of monitoring policy effectiveness would depend on the time-span of the treatment effort. Ideally, these sites could be established several years before any intervention begins, in order to provide a period of baseline data.

[7] The LISST is a device made by Sequoia Scientific Inc. (http://www.sequoiasci.com/products/Particle.aspx) that uses low-angle laser scattering (or laser diffraction) to measure the size grade of suspended material, classifying it into 32 size bins. It comes in various forms, including a submersible version for *in situ* deployments.

7.3. Reference sites

As detailed in Table 1, Reference sites need to demonstrate trends driven only by climate change and to capture inter-annual variability in sediment yield due only to weather variability. They provide a reference for isolating weather/climate driven variability in sediment yield from human effects. This can be done directly off a long record of continuously sampled sediment load (e.g. with compositing auto-sampling, which would require a substantial effort), or by looking at changes with time in rating relations (less effort, but samples would still need to be collected sufficiently often to resolve the sampling error due to interannual variability, i.e., during at least some events every year). The longer such sites can be maintained the more valuable their data will become. At present, there are no river/stream sites in New Zealand with continuous sediment load records lasting longer than 10 years.

7.4. Compliance sites

The data needs – and hence the sampling approach – for Compliance sites will depend on the site, issues, and consent conditions (see for example, Section 5.1). As illustrated by the existing Awanohi and Weiti sites (Section 5.1), real-time turbidity monitoring provides the opportunity for triggering compliance inspections.

8 Conclusions

The main conclusions of this study are as follows:

Information on stream sediment loads in the Auckland region is required for three general purposes:

- State of Environment reporting that provides a regional overview as well as accurate data on sediment loads into key receiving waters.
- Developing and assessing sediment management policy, and understanding baseline sediment-yield.
- Compliance monitoring – to ensure that developments meet consent conditions.

The strategy for meeting these information needs is to use a spatially-distributed sediment yield model to report on a region-wide basis. Specific sites will be monitored to calibrate and validate the model predictions or to provide "hard" reliable sediment yield numbers where they are most important.

The information needs can be met by operating four general types of sediment monitoring site:

- Calibration/ Baseline sites are focused on relatively small, uniform catchments and aim to provide calibration data for the regional sediment yield model and baseline data for setting policy compliance targets.
- Validation sites are focused towards the downstream ends of catchments that are currently experiencing development / landuse change issues, have sediment management initiatives in operation, and deliver sediment to sensitive coastal waters. Their results are used to validate the sediment yield model and/or to validate the effectiveness of sediment management policies.
- Reference sites are located in relatively small, uniform, pristine, and stable catchments where the sediment yield should be sensitive only to inter-annual weather variability and longer-term climate variability.
- Compliance sites are those set up explictly to meet Resource Consent monitoring conditions.

Considering existing sediment data coverage and gaps, the locations of existing flow recording sites, and existing/developing sediment yield issues around the region, a draft list of seven, high-priority sites is recommended: two Calibration/ Baseline sites, four Validation sites, and one Reference site.

The recommended model type to provide region-wide information on sediment yields for state-of-the-environment reporting, and for assimilating the results of monitoring at calibration and validation sites, is a physically-based sediment generation and routing model that is driven by spatially distributed rainfall records at a daily or finer time-step. A possible candidate is the GLEAMS model (Appendix 1), but final selection of a model and its application to the Auckland region should be the subject of further work.

9. References

Auckland Regional Council, 2001: Regional Plan: Sediment Control.

GNS 2001. 1:250,000 Geological Map 3: Auckland. Institute of Geological & Nuclear Sciences, Lower Hutt.

Hicks, D.M.; Hoyle, J.; Roulston, H. 2009. Analysis of sediment yields within Auckland Region. NIWA Client Report CH2009-041 prepared for Auckland Regional council. May 2009. 82 p.

Holwerda, N. 2009. Hydrology spatial representation, relative to the River Environment Classification, significant coastal habitats and sediment yield. Unpublished report to Auckland Regional Council. 56 p.

Appendix 1: Regional scale sediment yield model

A.1 Requirements of a regional scale sediment yield model

A spatially-distributed, regional-scale sediment yield model has been recommended as a way to meet the need for State-of-the-Environment (SoE) information covering the whole of the Auckland region (since monitoring every stream, or even every major stream is prohibitive). While the model will only produce predictions or hindcasts of sediment yield (i.e. not actual measurements), such results can nonetheless be validated from monitoring at a manageable number of key sites.

The essential requirements of such a model are:

- The sediment generation should be senistive to rainfall and landuse and/or landcover, including landuse or landcover based sediment management practices.
- It should be capable of incorporating sediment management structures (such as retention ponds) and riparian management areas within its water and sediment routing network.
- The model outputs on potential sediment production and delivery can be mapped and tablulated across the region, with sediment yields broken down in various ways such as landuse-at-source, total by catchment, total by harbour, and so on.
- The model needs to deliver results at the event scale (with a time step of one day at a maximum, ideally several hours), so that:
    - (i) the effect of rainfall variation on sediment yield can be demonstrated,
    - (ii) annual yields (for given years) and mean annual yields (for given time periods such as the five year SoE reporting cycle) can be totalled, and
    - (iii) the model's performance can be validated over these time bases. It may also be desirable to output "synoptic" results on sediment loads from individual events.
- This requires input data on spatially distributed daily rainfall (which may well be possible from rain-radar monitoring). It would also need regular – at five yearly or even annual intervals – updating of the landuse/land

cover GIS layers, as well as updates on sediment management treatments.

A.2 Models considered

Several potential GIS-based sediment yield models were discussed during the workshop. These fell into three general types:

- Empirically-calibrated mean annual yield predictors (e.g. Sparrow model, CLUES). These are driven by rainfall, landuse, slope, and soil/lithology layers, but provide results only on long-term average sediment delivery from catchments. Thus they would only be useful when applied say over a 5-year SoE reporting period. They have the facility to include treatment of sediment production (given appropriate calibration data), but have very limited scope for incoporating in-channel sediment mangement.
- Statistically-based event load models (e.g. CESIT). This type is similar to the above except that rainfall magnitude-frequency relations are used to generate event sediment load series on a random basis. The record of event sediment loads so generated should reproduce the correct long-term yield statistics when applied on a 'boot-strapping' basis (e.g. mean annual yield and interannual variability), but it cannot predict what would actually have ocurred in any event, year, or 5-year period.
- Physically-based sediment generation and routing models (e.g. GLEAMS). These generate runoff and sediment from hillsope elements and route the water and sediment downstream through channel networks. As above, the water and sediment runoff is modulated by static layers of catchment characteristics (slope, soils, lithology) and occasionally-changing layers (e.g. landuse, landcover), while actual space-time delivery rate is driven by spatially-distributed rainfall time-series data.

Only the latter type has the requirements outlined in A.1 so that is what is ideally preferrred. Of that type, it seemed that the GLEAMS model offers the best poential, so we focus on that.

A.3 Recommended model - GLEAMS

The GLEAMS model is based on a US Dept of Agriculture model. It operates on a 1-day time scale (thus daily rainfall produces a daily slug of sediment into the drainage network). Routines developed by NIWA allow this material to be routed to the catchment outlet on a daily basis. It is reasonably popular, and has been applied by NIWA Hamilton staff at the catchment scale in several areas of the North island, including in the Auckland region. Discussion points regarding its application over the Auckland region included:

- It is able to use occasionally-updated landuse/landcover layers (but these would need to be generated regularly by ARC as part of the SoE reporting).
- While it would be a challenge applying it over the whole Auckland region, it would not be impossible (it has already been applied successfully to small parts of the region).
- Daily rainfall layers could be interpolated from the regional rain-recorder network; alternatively, the rain radar could be used.
- Once set up and calibrated, ARC staff could be trained to use the model on a production and maintenance basis. In this regard, a custom user interface would be useful (if the source code is accessable).
- Short-term effects on landcover (e.g. re-vegetation) would need to be 'parameterised' (i.e., calibration parameters would need to be applied locally).
- At present, it can only handle treatments such as riparian planting in relatively crude fashion.
- It can handle off-channel sediment retention ponds, but it would need to be modified to handle in-channel ponds/reservoirs.
- It can't handle stream-bank erosion[8].
- With regard to the above process limitations, the model could be viewed as a framework for focussing process-based research studies, with research results being assimilated into the model during, say, 5-yearly reviews. An example might be that a NIWA study of stream-bank erosion resulted in the incorporation of a stream-bank erosion module into the GLEAMS model by 2015.
- Once set-up, the GLEAMS model could also be run in predictive mode, for example to predict the effects on sediment delivery of a climate-change induced change in rainstorm characteristics (as could a model such as CESIT).
- An ultimate vision would be to forecast daily sediment loads. This would benefit from collaborating with rainfall–runoff forecasters.
- Setting-up, improving, and maintaining such a model will require a siginficant investment.

A.4 Scope of model application

A major point of discussion centred on the scope of the model application. It was acknowledged that, technically, applying a model such as GLEAMS over the whole region would be a challenge, but achievable nonetheless. However,

[8] Incorporating retention ponds and bank erosion would require further model code development.

key considerations were the setup cost, including what might be required to improve the user interface so that ARC staff could input data and run the model on an operational basis.

One option discussed was to restrict the model application to sub-regions (e.g., the catchments of selected estuaries/harbours). In that case there could be scope to focus the calibration and validation monitoring down to fewer sites (depending on the sub-regions selected), and one could expect that the data input/output effort would scale with the area of the model domain. However, there would be little saving in the costs to develop user interfaces and train staff.

A possible way forward would be to set up and prove the model in a consulting study for a pilot area before investing in development of a refined interface and training. Such a staged implementation, however, would not deliver region-wide information in the short term. To achieve this would require the interim use of one of the simpler types of model (i.e., an empirical mean annual yield model or event-load statistical model as covered in Section A.2), but this would compromise the outputs achievable and would not enable any model validation on a year-by-year basis (since this type of model only delivers results at the mean-annual time-base).

A.5 Model validation

Some discussion also concerned how best to validate the model outputs, using data from the Validation sites, and what would be acceptable performance standards. It was concluded that decisions on these questions should best be left until a model had been chosen and run.

A.6 Conclusion and recommendation

We conclude that the GLEAMS model, or one similar, offers the best opportunity to realise the capability to produce region-wide, state-of-the-environment type information on sediment production and its change with time and management policy. However, setting-up, improving, and maintaining such a model will require a siginficant investment.

We therefore recommend that the final selection and implementation of such a model (including how best to phase its setup, development of a user interface, training, and defining validation criteria) be advanced in a further study that can proceed in parallel with setting up the monitoring sites proposed in the body of this report.