Review of Turbidity and Suspended Sediment Monitoring at Horizons Regional Council

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Prepared for Horizons Regional Council

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1. Executive summary

This report provides a peer review of procedures used in Horizons Regional Council's turbidity and suspended sediment monitoring network, which is currently being expanded and upgraded with state-of-the-art instrumentation. The review is to help ensure that the network is operated to best-practice standards and delivers information useful for answering management questions relating to river water quality, sediment loads, and initiatives to mitigate catchment erosion.

In scope, the review covers the protocols and methodologies for future measurement and processing of continuous turbidity time series data, for deriving suspended sediment concentration series data from the turbidity record, and for processing existing data.

The review results are given in terms of comments on existing practice, recommendations for improvements, and an outline of the next steps.

Overall, the current Horizons field and data-processing approaches are thorough and reflect the experience gained and the investment made over the past decade.

The main issues requiring improvement relate to the documentation of data editing procedures, quantification of uncertainty in synthetic/derived data records, laboratory procedures for analysing suspended sediment concentration, and field sampling strategies for collecting data to calibrate relations between turbidity and suspended sediment concentration (SSC).

Specific recommendations are:

- To replace the Total Suspended Solids (TSS) laboratory analysis method for SSC analysis with one that analyses the full sample retrieved from the field. The TSS method can substantially under-represent the coarser fractions of the suspended load.
- To use event sampling to ensure the relation between turbidity and SSC is adequately sampled across the range of SSC that delivers the bulk of the river sediment load. Regularly-scheduled sampling programs that typically intersect base-flows (such as SOE water quality monitoring) are inefficient for this purpose.
- To better document and illustrate procedures for editing turbidity data, filling record gaps with turbidity proxy data, and deriving calibration relations. As well as providing clear instruction, this will archive the rich reservoir of experience that Horizons has accumulated over the past decade.
- To use existing datasets to evaluate the hypotheses underpinning the methods to remove turbidity record noise.
- To complete data reviews/audits with summary statistics classifying the record duration (or derived results such as sediment load) by QC code.
- To quantify and include in record Comments the uncertainty in the functions used to patch/adjust turbidity records from proxy signals and to convert

turbidity through into cross-section SSC. These error statistics should be related to QC codes associated with the edited series data so that errors can be estimated on derived results such as annual and mean annual sediment load.

As well as acting on these recommendations, a priority for Horizons should be to more clearly specify the sampling strategy and standards/expectations required of the monitoring network so that it delivers results useful to the various intended purposes. For example, for the purpose of validating maps of predicted mean annual sediment yield and expectations of erosion control measures, it will be necessary to set minimum monitoring periods and accuracy requirements for mean annual sediment load. Options for SS particle size analysis also need to be investigated.

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Reviewed by

Jeremy Walsh

Approved for release by

Charles Pearson

2. Introduction

2.1 Background

Turbidity monitoring is an integral, multi-use component of Horizons Regional Council's water quality monitoring network (Roygard et al., 2010). Low range turbidity, typical during normal flows, relates to values such as the suitability for swimming and river clarity, while high range turbidity during floods and freshes provides a proxy for suspended sediment concentration and so enables determination of sediment load.

The water quality monitoring network has several purposes including state of environment (SOE) monitoring, identifying causes of observed degraded water quality, and monitoring effectiveness of regulatory and non-regulatory initiatives. In the latter case, the key programme benefiting from turbidity and sediment monitoring is Horizons' Sustainable Land Use Initiative, which is addressing sediment loss from highly erodible land.

Over the past decade, Horizons has invested in moving from the more typical discrete sampling techniques for turbidity and sediment monitoring to continuous, sensor-based monitoring. Over this period, the number of sites being monitored has increased, instrumentation has improved in capability and reliability, and valuable experience has been gained in field operations and in data processing. Now, their current network is in the midst of a major upgrade that will, by June 2011, have state-of-the-art 0-4000 Formazin Neph던olometric Unit (FNU) sensors established at 16 hydrometric/water quality sites across the region to measure turbidity every 5 minutes. As a part of this upgrade, nine sites are also being fitted with automatic samplers to assist in full coverage of both turbidity and sediment sampling, while manual sediment gaugings and particle size analysis will provide further information.

At this turning point (which can be viewed as the transition from the 'learning curve' to mature monitoring with established protocols), Horizons have sought a peer review of their current procedures in order to ensure best practice underpins their turbidity and suspended sediment data. This report provides that review.

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2.2 Aim and objectives

The review aims to provide initial feedback on the turbidity and sediment monitoring programme, past and future, by:

1. Reviewing the protocols and methodologies for future measurement and processing of continuous turbidity time series data and derivation of suspended sediment series.

2. Reviewing the protocols and methodologies employed to process existing data from Horizons monitoring of continuous turbidity time series data and derivation of suspended sediment series.

3. Recommending any improvements to measurement techniques and quality assurance protocols and identify the next steps to ensure best practice is followed.

2.3 Work program and report outline

The bulk of the work involved a visit to the Horizons office to interview Horizons technical staff regarding field and office methodologies, instrumentation limitations, and lessons learnt over the past decade. This report proceeds by reviewing what has been and is being done, with comment and recommendations for change inserted where appropriate. Turbidity monitoring is considered first, followed by suspended sediment monitoring, then comments are given on the field sites visited. The recommendations and the next steps are then summarised. While the comments are directed largely towards current/future procedures, they typically apply also to the re-processing of existing data.

3. Preliminary note on turbidity instruments and standards

It is useful to begin with a brief overview on turbidity instruments, units, and standards. This is necessary because while in general turbidity is a measure of the amount of light scattering from a solution, the response of a given instrument over a given range of variously turbid reference solutions is dependent on the instrument design, notably the angle between the light source and detector (e.g. whether attenuation, side-scatter or back-scatter) and the wavelength and bandwidth of the incident light (e.g., near infrared monochrome or broad-spectrum white light). Thus, different instruments measure different things and produce numbers that may not be equivalent or even inter-converted. For this reason, standards are adopted for instruments with a limited range of specifications. Also, whereas previously the same units (e.g., Nephelometric Turbidity Units or NTU) were often assigned to a range of instruments, in recent years it has become conventional to associate standards with unique units. While this proliferates the number of turbidity units, it at least avoids false assumptions about instrument and data equivalence. A commonly used standard has been EPA 180.1, which was established by the US Environmental Protection Agency in 1993. Measurements complying with this standard are reported in Nephelometric Turbidity Units (NTU). An alternative standard, favoured in Europe, is ISO 7027. This specifies a different light source and detector geometry, and measurements are reported in Formazin Nephelometric Units (FNUs).

Problems can arise when different types of instrument are used to compile a turbidity record. For example: (i) a portable hand-held instrument, calibrated in the laboratory, is used to check for drift in a field instrument of different type; (ii) different instrument types are used to measure high and low turbidity ranges; (iii) the instrument type is changed during an upgrade; (iv) a relationship between suspended sediment concentration (SSC) and turbidity is established off samples taken to a laboratory instrument but is then applied to a turbidity record from a different type of field instrument.

For these reasons, it is essential to record instrument type and standard in metadata documents and it is best practice to adopt and sustain a given standard. In the case of existing records from non-standard instruments, tables such as provided in USGS (2004) may assist with assigning appropriate units.

4. Turbidity monitoring program

4.1 Instrumentation and standards

Horizon's turbidity monitoring program commenced in 1999 using in-situ Analite sensors in King Country mudstone catchments such as the Ohura. While meeting the EPA 180.1 standard (and so delivering turbidity readings in formal NTU), these instruments were found to be unreliable.

In 2005, the sensors were upgraded to Greenspan sensors (TS100, TS1200). While the more recent (post 2008) Greenspan sensors now meet the EPA 180.1 standard, it was later appreciated that the earlier vintage Greenspan sensors did not and so provided turbidity information that was inconsistent with laboratory instruments.

In 2010, the ISO 7027 standard was adopted by Horizons and WTW sensors (meeting this standard) were installed as the primary in-situ sensors at 6 sites. The WTW sensors have dual ranges (0-40 and 0-4000 FNU), outputting a dual record, and have sapphire-glass lenses and built-in ultrasonic vibration to inhibit lens bio-fouling.

As well as these in-situ sensors, various sites currently have secondary, in-line sensors that measure turbidity in a water circuit continuously pumped from the river. Also, some sites have secondary in-situ sensors of various types. These secondary sensors are typically used to provide a back-up record for times when the primary sensor fails.

4.2 Data editing

4.2.1 Why it is needed

Data records from permanently deployed in-situ turbidity sensors are invariably patchy in quality and usually require considerable editing. Typical problems include calibration drift, over-ranging, lens bio-fouling, light-beam obstruction, and occasional instrument failure.

For turbidity monitoring, calibration drift (in instrument gain and/or offset) needs to be checked on a regular basis – either by checking the sensor with standard solutions, by comparing the sensor reading against check measurements made in situ with portable sensors, or by analysing water samples with lab instruments. In the latter cases, it is important that the checks follow the same standard.

Over-ranging occurs when the water is more turbid than can be detected by the sensors, and is an issue particularly when the turbidity record is intended as a proxy for SSC. This was a common problem during floods and freshes with early vintage sensors with relatively low ranges. Depending on the sensor, over-range conditions can result in an error value, flat-lining at the peak-of-range, or apparent reduced turbidity (due to scattering being reduced through attenuation). The latter case may be hard to distinguish in a time-series from a real reduction in turbidity.

Lens bio-fouling, due to algal growth on the lens (often compounded by silt embedding in the biofilm), is the most common cause of poor turbidity data. It is typically manifest as an increasingly noisy record that eventually begins to ramp upwards, but disappears when the lens is cleaned. Ways to inhibit bio-fouling include wipers, micro-water jets, special lens-coatings, and ultrasonic vibration.

Beam obstruction occurs when light is reflected off plant debris that collects around the sensor and/or its housing, but may also be caused by living stream biota (e.g. fish, macrophytes).

Segments of record affected by these problems need to be identified and either corrected or else deleted and the gap replaced with synthetic data.

Comment

While Horizons staff report that the new WTW sensors have superior capability to avoid bio-fouling, it should not be assumed that the sensors are perfect. Thus, procedures are still required to check for the onset of fouling during data collection. With telemetry, this can be checked by regular visual inspection of the record, which may need to be done every few days through the vulnerable summer period. If significant fouling is identified, it is better to manually clean the sensor than to rely on data editing.

4.2.2 Turbidity data editing up to 2005

Prior to 2005, data editing at Horizons followed a set of staged procedures to clean bio-fouled turbidity records. For fouling on turbidity recession trends, the noisy record was simply smoothed, but for upward-ramping trends the record was deleted until such time as the sensor was cleaned and the gap was bridged by linear interpolation. No attempt was made to convert informal NTU records (from non-standard sensors) to formal records.

Comment

These editing steps are prone to over-representing the correct turbidity, thus I agree with the decision to discard data editing using such methods and to re-process the data using the current editing protocols.

4.3 Turbidity data editing since 2005

Since 2005, improved turbidity data editing procedures have been developed. These provide the foundation for the current/future editing protocols (documented in Horizons 2010), and are also now being used to re-edit the pre 2005 data. A key feature is that the data editing proceeds to completion in yearly batches. This is a good approach because it enables the person editing the data to remain familiar with the events over the year under analysis. The main steps are as follows.

4.3.1 Drift-checking

Sensor drift is checked by comparing sensor turbidity (FNU for the modern fleet of WTW instruments) with the lab-measured FTU of the monthly water-quality samples. Agreement within 10% is considered acceptable.

Comment

This 10% agreement is pragmatic as in situ measurements will not always agree exactly with the turbidity of samples collected nearby, due to in-river mixing and lab sub-sampling effects.

4.3.2 Data Cleaning

Data cleaning is undertaken by a multi-stage process:

- Spikes (single-point high values) are removed with a numerical filter.
- If fouling/noise is apparent, 1-hour, 3-hour, 6-hour, and if necessary 12-hour averaging filters are used to remove noise peaks, with values replaced typically by the minimum observed over the averaging period. An operator based decision is made before the averaging period is increased, and a diagnostic quality code is assigned to each edited data value.
- The filtered turbidity record is compared visually with concurrent hydraulic/hydrologic records and/or the records of secondary sensors (e.g. in-line sensors or in-situ sediment sensors), auto-samples or manual samples. A decision is made as to whether the turbidity record being examined is real (i.e., hydrologically driven) or should be deleted and a gap inserted. Upward-ramping fouled records are generally deleted.
- Event records are inspected for signs of sensor over-ranging (e.g., see 5.2.1). Suspect spans of record are deleted and commented.

Comment

This stage is a key one for data quality and depends substantially on operator judgement, which draws on all available information for the period of record being considered. I agree that this the best way to do this, but it requires the editor to be highly skilled, experienced, and diligent. Thus, some certified (at least in-house) training program would be appropriate. It is also important that methods are applied consistently, thus it is important to have these well documented and illustrated with examples. I note that the editing procedures have been documented (Horizons, 2010), but these are not illustrated graphically (with case example data) and more flow charts (like the existing one for data cleaning) would be helpful. There is possibly too much reliance at present on the knowledge of one key staff member (Senior data delivery coordinator, Brent Watson).

The use of minimum-value filters to clean-out bio-fouling noise is based on the assumption that the noise ‘troughs’ are for times when the measurement is not fouled by algal fronds. I recommend that this be tested by running an experiment with two WTW sensors side by side, with the ultrasonic vibration turned off on one and the other kept clean either with the ultrasonic vibration or manual cleaning if necessary.

4.3.3 Merging sensor records

With multiple sensors suited to different turbidity ranges or with the modern WTW dual range sensors, it is necessary to merge or “bolt together” the multiple records into one. Cross-over to the higher range record(s) is made at an appropriate threshold turbidity, and the higher ranged record needs to be merged with the lower range. For several reasons (e.g., different sensor types, different physical locations on the bank with associated differences in SSC and mixing, differential sensor drift), the two signals may not overlie, thus it is necessary to merge the two.

Comment

The documented procedure is vague on how this should be done, although Brent noted that what is usually done is simply a vertical shift of the high range record to align it at the cross-over turbidity. Generally, the low range sensor should be taken as the reference record, so it is the high-range record that should be shifted. It is also important that when relating SSC from auto- or manual samples to in-situ turbidity (i) this relation is made to the merged turbidity record and (ii) the samples should be collected as physically close as possible to the reference sensor (usually the low range sensor).

With the new WTW dual-range sensors, differential drift between the two ranges should not be an issue. However, the low range is preferred for the standard since this has higher resolution and will actually be used for most of the time.

4.3.4 Patching gaps

Horizons patch gaps (i.e., replace deleted/missing turbidity record with synthetic data), particularly during events with either no data or with over-ranged sensors, using an expedient proxy record with which turbidity correlates. Options available at various Horizons sites include suspended sediment sensors (essentially, these tend to be short-path attenuation-type sensors that output a voltage or current that is empirically correlated with SSC), secondary (e.g., in-line) turbidity sensors, auto-samples providing lab-based turbidity measures, and hydraulic variables based on the rated stage record.

With all of these, it is necessary to establish relations (ratings) between the proxy record and the reference turbidity record from periods of concurrent record. Which is preferred will depend on what is available, their record quality, and their measurement interval, but a general rule would be to choose sediment/turbidity sensors over hydraulic proxies. While turbidity-SSC and turbidity-turbidity relationships are sensitive to sediment character and size-grade, they tend to show less variance than do turbidity-discharge relations, which are strongly influenced also by sediment supply.

The above dependencies on suspended sediment size grade and supply mean that the ratings of any sort can shift within floods and freshes (e.g., between rising and falling stages) and between events. For these reasons, it is preferred to look for separate rising/falling stage relations and to develop, if possible, relations “on-the-fly” from data close to the period being patched rather than use a long-term average relation. All of this benefits from accumulated knowledge of the site characteristics.

The patched records and their origin are flagged with an appropriate QC code.

Comment

While “filling missing record” is mentioned briefly in Horizons data editing procedures documentation (Horizons, 2010), my observation was that the procedures and protocols for this were still “work in progress”. Thus, this is an area that would benefit from more attention. Example protocols to develop would be the order of preference for the various proxies available at each site and when use of separate rising-/falling-stage relations were justified.

Consideration could be given to parameterising turbidity recessions (e.g., by defining the constant in an exponential decay function, such as $T/T_p = e^{-kt}$ where T_p is peak turbidity, t is time since turbidity peak, and k is an empirically determined characteristic of the site).

With regard to using hydraulic data as a turbidity proxy, I have two comments. First, while a preference was stated for using velocity rather than discharge for a hydraulic proxy (because velocity often tends to asymptote to a maximum while discharge increases), in reality there should be little significant difference unless the site also has a direct velocity record (e.g., from a side-looking acoustic-doppler instrument). Without a direct velocity record, a velocity record has to be generated from the discharge record anyway via a hydraulic geometry relation based on discharge gaugings. Second, I would be cautious about using hydraulic data as a proxy for filling anything but short gaps – such as bridging bio-fouled episodes or over-ranged segments of high turbidity events – and even then only when adequate calibration data were available. This is because, in my experience, turbidity responds substantially to fine sediment supply factors (affecting both SSC and size grade) that relate only indirectly to the local hydraulic variables. There comes a point when it might be best to leave the gap, rather than fill it with the delusion of something meaningful.

From the perspective of using the turbidity record as a proxy for SSC and (thence to compute suspended sediment load), an alternative approach to patching the turbidity record with SSC data would be to leave at least some gaps in the turbidity records unfilled and to fill the gaps in the SSC time-series at the stage when this was generated off the turbidity series. In practice, there would be no difference in the derived SSC record so long as the same relations were used to convert synthetic turbidity back to SSC in cases where actual SSC data were used to patch the turbidity record. Perhaps the decision to follow this approach could be based on whether or not the gap in the turbidity record extended into flood flows (which carry the bulk of the sediment load) – if it did, and if SSC data were available, then the gap over the flood event could be left to be patched within the SSC record.

The QC tagging of all turbidity data values is, therefore, an essential procedure, particularly if the aim is to have – after data editing – a gapless record. This will also enable easy summaries of data quality and help estimates of uncertainty in derived results (e.g., suspended sediment loads). A tabulation of % record by QC code should complete the editing or auditing process.

4.3.5 Quality assurance

Internal (i.e., within Horizons) auditing of edited turbidity data is done by visually overlaying and comparing annual plots of the raw and edited data.

Comment

It is important that the auditing is done by a person familiar with the editing process and experienced with processing turbidity data – this is because the editing process is far from trivial, integrates threads of data and information from multiple sources, and – to some degree – requires subjective judgement. The auditing procedure should be documented, and a flow chart summarising the auditing pathway and decision points would be helpful.

5. Suspended sediment monitoring program

Horizons' general strategy is to use turbidity time series data as a proxy for SSC, which can then be combined with water discharge to derive suspended sediment load (SSL). The rationale is that (i) the variance in the SSC-turbidity relationship is less than that in the traditional SSC-discharge relationship and (ii) an instrument based record captures greater temporal detail more efficiently than does auto- or manual sampling. Key components of this strategy are the relationships between (i) SSC and turbidity at the point of turbidity measurement and (ii) between this point SSC and the cross-section mean SSC, which is required to compute the suspended sediment load. With sediment load as the sampling purpose, it is important that these relations are well established for the high flow range since typically this transports the bulk of the long-term average sediment load. Hicks et al. (2004) show that typically in New Zealand rivers flows less than the mean flow transport only a few % of the long-term average suspended sediment yield.

5.1 SS sampling for turbidity vs SSC calibration at-a-point

5.1.1 Field Sampling

To date, Horizons have collected SS samples in three ways: using auto-samplers during floods and freshes, bankside dip samples during regular State-of-the-Environment (SOE) water quality sampling runs, and using depth-integrating samplers at gauging cable-ways and bridges during floods and freshes. The bulk of the samples collected are associated with the SOE runs, with ~ 95% of these having been collected at base flows. While these may have been collected at the same general location as Horizons in-situ turbidity sensors, they have often not been collected directly beside the sensors. A basic assumption has been that suspended sediment is uniformly mixed at the monitoring sites over all discharges.

To date, auto-samplers are located at only a few sites and are generally triggered at fixed time intervals above a stage-threshold.

<u>Comment</u>

It is recommended that SS sampling at all sites being operated for sediment objectives includes auto-sampling during high-flow events. This sampling should be scheduled to provide an adequate distribution of samples across the expected/encountered range of turbidity as well as to inform on the dynamics of the turbidity-SSC relationship during events (the latter depends primarily on changes in the size grading of the suspended load passing the turbidity sensor, which depends both on sediment supply dynamics and mixing).

For this purpose, auto-sampling is better triggered on a flow-proportional basis (using a data-logger to accumulate flow past the monitoring site) or at fixed intervals of turbidity change. Sampling simulations with existing stage or turbidity series data can be used to optimise sampling thresholds and intervals (my understanding is that Horizons already have this simulation capability).

If at all possible, the auto-sampler intake point should be located beside the in-situ turbidity sensor (since, at least from perspective of sediment load determination, the main purpose of auto-sampling is to collect data to relate measured turbidity to SSC). This intake-siting requirement is not so important for SOE sampling for dissolved constituents, since these are well mixed through the flow. Thus, Horizons should be wary about the compromises involved when using auto-samplers or hand samples for both SOE and sediment load purposes.

5.1.2 Lab analysis

SSC has been analysed in the laboratory in recent years using the Total Suspended Solids (TSS) method. In brief, this involves pipetting or pouring a sub-sample from the (shaken) original sample and then passing the sub-sample through a glass-fibre filter.

Comment

While the TSS method's sub-sampling allows parallel analysis of multiple constituents in the original sample and so has become a standard for water quality analyses, it under-catches the coarser fractions of the suspended load, particularly those in the sand grades, thus it variously underestimates the true SSC of the full sample depending on the sediment size grade (Guo, 2006). Since the sand component of suspended sediment loads from western North Island rivers draining Tertiary sedimentary and Mesozoic greywacke terrain is typically about 25-30% and can dominate the suspended load from tephra catchments (Hicks et al., 2004), the TSS method can reasonably be assumed to be providing an underestimate of the true SSC for samples from Horizons' region. On that basis, I recommend that SSC analyses to service Horizons SS program be confined to whole-sample analyses (as per ASTM, 2002). Also, Comments should be added to records and turbidity-SSC ratings to capture the method used in SSC analysis and to flag the associated uncertainty in load estimates.

5.1.3 Turbidity vs SSC relations

Current Horizons procedures are to hand-draw turbidity-SSC relations. These are then entered into the Hilltop Ratings software package as rating tables, which are then used to convert turbidity to SSC (in the same way as stage-discharge ratings are used to convert stage series data to discharge series). As with stage-discharge ratings, the turbidity-SSC ratings are time-stamped and updated ratings can be merged with old ones over a transition period if there is an observed shift in the relationship. This is a good system, because the rating data provides an audit trail and can be updated easily.

Horizons current practice also examines the turbidity-SSC rating data for rising/falling stage separation. If this is identified, separate functions may be defined for rising and falling stages; alternatively, a "happy average" line is drawn.

Since much if the existing calibration data are derived from SOE sampling, the turbidity-SSC relations to date are typically data-poor (or lack any data) at the high turbidity end and often require extrapolation.

Comment:

As discussed in 5.1.1, it is important that the overall monitoring programme includes SS sampling that is focussed on developing and then maintaining turbidity-SSC relations. The investment being made is too large to rely on compromise samples such as collected from the SOE program.

The present rating-fitting approach tends to be subjective and could be improved through the use of statistics. Key information to record on a running basis are the standard error of the rating fit, any trend in the magnitude of the residuals as turbidity increases (which shows whether the error is linear, factorial, or a more complex function of turbidity), and the turbidity range over which the calibration has been established. Such information will assist in decisions to change ratings (e.g., by testing if the most recent data plot a statistically significant “distance” from the current rating), to use multiple ratings (e.g., by testing if an improved standard-error results from a time-stratified or dQ/dt-stratified dataset), and finally in helping estimate the error on sediment yield calculations.

Generally, the fitted turbidity-SSC rating and also its quality-of-fit (i.e., calibration range and standard error of fit) will change simply as more data is added. However, as with stage-discharge ratings, it is quite possible (indeed, is to be expected) that the turbidity-SSC relations will shift with time. This can arise, for example, when an extreme erosion event activates large new sources of sediment that changes the typical size grading of the suspended sediment. Such effects can persist anywhere from several months to years. Staff should be alert for such shifts (particularly after large floods) and will need to decide if a new turbidity-SSC rating needs to be established. When a turbidity-SSC rating is “retired”, its final accuracy statistics should be filed in Comments.

While the ratings are fitted within Hilltop Ratings, it may be expedient to export the rating data to other software packages in order to extract these statistics (a tailored VB macro in Excel would suffice). It would be useful to summarise the accuracy statistics in annual audit reports.

As mentioned previously (section , where the turbidity record has been patched from SSC data, the conversion back to SSC should be made with the inverse function. Alternatively, it may be better that the derived SSC record is simply patched with the original SSC data.

It will be important to carry through the quality codes (QC) on the edited turbidity series data to the generated SSC data. For example, to capture the SSC estimates proxied originally from discharge records.

I recommend that whenever SS loads are calculated that the load total over the period of interest is broken down by quality code. Ideally, each QC could have an uncertainty level associated with it which could be propagated through into the uncertainty of the total load.

5.2 Calibration to cross-section mean SSC

The final step before determining the SS load from turbidity is to relate the point SSC beside the turbidity sensor to the discharge-weighted cross-section mean SSC (which is not the same as the spatially-averaged SSC). This is best done by doing a full suspended sediment gauging, using depth-integrating samplers at multiple verticals, and taking concurrent point samples (e.g., with an auto-sampler). The relation will depend on the degree of mixing, which depends on the turbulence and the size grading of the suspended load.

To date, Horizons appear to have generally assumed perfect mixing and have not applied any adjustment.

Comment

It is my understanding that Horizons now intend that a point to section-mean SSC relation be established for all sites in the network (past and future) that are to be used for SS load information. The suggested approach is to collect depth-integrated samples during a single event over a range of discharge and define the mixing ratio (i.e., the ratio of section-mean to point SSC) as a function of discharge. This function can be included in Hilltop TIDEDA as another rating to be applied during the process of converting edited turbidity to SS load. As with the turbidity-SSC relations, it is recommended that this mixing rating be filed with comments that quantify its uncertainty (e.g. standard error, relationship of error to discharge).

Fortunately, since at least the turbulence characteristics of a site are unlikely to change much over time, (i) present and future point to section-mean SSC relations may reasonably be applied to past records, and (ii) once established for a site there is little reason to continue monitoring the relation unless there is evidence that the size grading of the suspended load has changed.

During manual sediment gaugings, it is recommended that depth-integrated samples are also collected for particle-size grading because (i) this informs about the expected degree of mixing, (ii) informs about the expected relationship between turbidity and SSC (for a given SSC, a higher turbidity results from a smaller grainsize), and (iii) provides a basis for estimating the size-grading of suspended sediment load over events or on a mean annual basis.

Further work is required to settle on procedures for sampling for particle size analysis. One option to consider is whether full size gradings are required or whether a sand/mud split would be adequate. Full size gradings are required if particular grainsize statistics (such as the mean or median size and sorting) are required – such as for use in sediment transport/dispersion calculations or modelling. The mud fraction (i.e., silt and clay grades finer than 0.063 mm) is typically well-mixed in river flows and has a dominant influence on turbidity (since the back-scattering of light is greatest from particles sized similarly to the light wavelength), thus it is of particular interest for water clarity issues. It also tends to dominate floodplain deposition. The sand fraction (0.063 – 2 mm) tends to be less well mixed and concentrates near the channel bed. It is of greater interest to issues such as riverbed aggradation (i.e., rising bed levels) and coastal stability (since river sands nourish beaches adjacent to river mouths). A mud/sand spilt can be achieved by pouring the sample through a small-diameter 0.063 mm mesh sieve, then back-washing the sand off the sieve.

6. Site inspections

Four sites were inspected: Mangahao at Ballance, Mangatainoka at Pahiatua Town Bridge, Manawatu at Hopelands, and Manawatu at Teachers College. The latter three sites have mains-powered pumped circuits with in-line turbidity sensors as well as in-situ turbidity sensors and auto-samplers. Site-specific notes follow.

Mangahao at Balance: Some concern that Greenspan sensor is too close to bed and driftwood ‘nest’.

Mangatainoka at Pahiatua Town Bridge: Good site, with stable bank and good mixing at location of in-situ monitoring and pump-sampling.

Manawatu at Hopelands: Has in-line turbidity sensor, plus five in-situ sensors, including WTW dual-range sensor. These could be rationalised. Thought could be given to using data on-hand for this site to cross-calibrate sensors (for the purpose of gap-filling) if this has not already been done; also, the multiple records could be used to investigate the hypotheses underpinning the editing of bio-fouled signals. Powered slackline system looks excellent for depth-integrated sampling, but the bankside vegetation needs clearing first. This would be a good site for bedload monitoring/sampling if this was ever entertained.

Manawatu at Teachers College: Well instrumented site, with sampling and in-situ sensing at a stable, rip-rapped bank with good mixing characteristics. Daily manual sampling program, begun in June 2010, will continue at least until July 2011, possibly a further two years. This should provide an excellent dataset to develop turbidity-SSC calibration relations, to validate derived SSC time-series records, and to derive error statistics for SS load determination.

7. Recommendations for improving practice

The key recommendations from this review are to:

1. *Analyse SSC using full samples*

   It is strongly recommended that the TSS laboratory analysis method be discarded for SSC analysis and replaced with one that analyses the full sample retrieved from the field (e.g., ASTM, 2002). The TSS method is a compromise one that might be suitable for WQ analyses of well mixed constituents, but if suspended sediment flux is one of the monitoring purposes then it should not be used.

2. *Focus SS sampling particularly across the high flow range*

   Suspended sediment loads are carried mainly during high flow events, thus proxy records like turbidity need to be calibrated to SSC across the full range of SSC encountered. This requires event-sampling with a schedule that provides a good distribution of points across the calibrated range. Regularly-scheduled sampling programs that typically intersect base-flows (such as SOE monitoring) are inefficient for this purpose.

3. *Better document turbidity data-editing and turbidity-SSC calibration procedures*

   These need to be robustly documented. The reality is that at present these procedures remain a 'black art', and (from a broader perspective than Horizons operations) what is done depends very much on the experience of those editing the data and the level of resources provided to get the job done. In this context, while Horizons have a relatively rich reservoir of experience, this is vulnerable to being lost until it is well documented. While a start has been made on this, this existing documentation needs to contain greater detail and be illustrated with examples.

4. *Use existing datasets to test hypotheses underpinning the cleaning of bio-fouled sensor data*

   A key hypothesis underpinning the method to remove turbidity record noise due to bio-fouling is that a minimum-value filter is appropriate. This can be tested with existing datasets from parallel sensors.

5. *Include summary QC statistics with data audits*

   Data reviews/audits should include summary statistics classifying the record duration (or derived results such as sediment load) by QC code.

6. *Error/reliability statistics should be determined and filed with calibration relations*

   This should be done both for the functions used to patch/adjust turbidity records from proxy signals and for those used to convert turbidity through into cross-section SSC. The error statistics should be related to QC codes associated with the edited series data so that errors can be estimated on derived results such as annual and mean annual sediment load.

8. Next Steps

The recommended next steps would be to:

1. Act on the above recommendations (in the priority order given above).
2. More clearly specify the sampling strategy and standards/expectations required of the monitoring network so that it delivers results useful to the purpose. For example, for the Sustainable Landuse Initiative, Horizons' strategy is to use the SEDNET model to map potential mean annual sediment yield in order to focus soil conservation efforts and predict their effectiveness. The expectation is that the sediment monitoring network will assist this by validating the spatial distribution of sediment yield and the effectiveness of land-treatment measures. For this to succeed, the monitoring duration will need to be adequate to enable comparison of actual and expected mean annual yield. Alternatively, consideration could be given to validating off event yields – providing SEDNET can be operated at the event scale.
3. Further explore the options for SS particle size analysis, including in-situ sensors and in-line systems.

9. Conclusions

Overall, the current Horizons field and data-processing approaches for continuous turbidity data are thorough and reflect the experience gained and the investment made over the past decade.

The adoption of well recognised standards for instrumentation is a key factor in turbidity monitoring generally and underpins the existing and future Horizons turbidity monitoring network.

The new generation of in-situ sensors being deployed meet the strict ISO 7027 standard and go some distance towards mitigating operational issues such as bio-fouling and over-ranging. However, their performance is unlikely to be perfect and so the monitoring program will still need care and attention and a substantial investment in data editing and auditing.

It is appropriate that past records of turbidity data are reprocessed using current methods, although this may mean that some of these data are unrecoverable.

Deriving continuous series data on suspended sediment concentration from turbidity records requires adoption of field, laboratory, and analysis procedures designed specifically for suspended sediment sampling, rather than compromising by using procedures developed for analysis of well-mixed water quality constituents.

Key recommendations for improvement are to:

- analyse SSC using full sample, rather than using the TSS method
- focus SS sampling particularly across the high flow range
- better document turbidity data editing and turbidity-SSC calibration procedures
- use existing datasets to test/improve hypotheses underpinning data cleaning procedures
- include summary QC statistics with data audits
- determine and file error/reliability statistics.

The next steps should be to apply these recommendations, to more clearly specify the sampling strategy and standards/expectations required of the monitoring network so that it delivers results useful to the various purpose, and to investigate options for SS particle size analysis.

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