Monitoring of riverbed stability and morphology by regional councils in New Zealand: application to gravel extraction management

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Summary

Project and Client

Tasman District Council requested Landcare Research to review the range of techniques used by regional councils for monitoring changes in riverbed levels, river stability and morphology, and to help manage gravel extraction with a view to determining future data collection needs.

Objectives

The objectives agreed to by TDC and Landcare Research were to review the following:

- the techniques used for bed level monitoring and subsequent analysis
- the frequency of monitoring, and whether it accounts for both long-term trends and short-term fluctuations in bed level
- if the method(s) and frequency of monitoring are considered optimal by Regional Councils
- if cross section survey techniques are used, what range of river types are monitored and what are typical cross section distances
- what other methods have been used, or are being considered, to optimise riverbed stability monitoring
- approaches to assessing gravel supply and sustainable gravel extraction rates

Methods

Information was obtained by:

- accessing published information on regional council Web sites.
- sending a direct request to council staff at Hawke's Bay Regional Council, Gisborne District Council, Marlborough District Council, Environment Bay of Plenty, Horizons MW.
- some information for Otago Regional Council and Greater Wellington Regional Council was derived from an Environment Canterbury review of gravel extraction policies.

Results

- River cross-section surveys are the primary tool used by regional councils to monitor riverbed levels and calculate gravel volume changes. These are used in combination with gravel extraction volumes derived from contractor's returns to calculate gravel load on a conservation of volume basis. The trends in bed levels, gravel volumes and gravel extraction volumes are used to set gravel extraction limits.
- Aerial photos and site inspections are used by many councils to supplement the information from cross sections and provide an indication of river behaviour between the cross sections.
- The river cross-section survey networks have usually been established for flood risk management and the design is not considered ideal by many councils for gravel management purposes (particularly in terms of cross section location and spacing, and frequency of measurement).
- River cross section surveys are used both on gravel-bed and silt-bed rivers.
- The frequency of surveys has been highly variable in the past, ranging from 1 to 30 years, mostly focusing on monitoring long-term trends in bed level. With increasing demands

on gravel resources, and the need to have better knowledge of gravel supply rates, many councils are increasing the frequency of surveys. For rivers with high extraction pressure, surveys are now typically carried out every 1 to 3 years.

- Cross-section spacing is highly variable, ranging from 100 to 1400 m and is primarily dependent on river size. There does not appear to have been a clear rationale for cross section spacing but it is clearly related to river width. In many larger rivers cross sections were initially spaced at ½ mile (0.8 km).
- Councils have used 3 different software packages for analysing the bed level data (RICODA, XSECT and Hilltop Software) and generally use the end area method for calculating mean bed levels and gravel volumes.
- Many councils acknowledge that current bed level monitoring is not ideal for managing gravel extraction and have initiated major reviews of their cross-section networks, reporting of gravel extraction volumes, data analysis and interpretation.
- A number of councils have completed LIDAR surveys of some rivers, primarily intended for flood modeling and management purposes. LIDAR is regarded as too expensive for routine application to gravel management at present, but will be a useful tool as the cost decreases in the future and combined terrestrial and bathymetric LIDAR becomes available.
- Setting appropriate gravel extraction volumes requires information on the gravel load of rivers. Three approaches have been used to estimate gravel load in New Zealand and assist setting gravel extraction limits: a morphological method based on conservation of volume (derived from gravel volume changes (from cross sections surveys, or more recently using GPS, LIDAR, or digital photogrammetry) and gravel extraction rates), as a proportion of suspended sediment yield, and calculation of load from bedload transport formulae.

Conclusions

- River cross-section surveys remain the primary tool used by regional councils to monitor riverbed levels, on both gravel-bed and silt-bed rivers. They are often supplemented by aerial photo analysis and site inspections to provide an indication of river behaviour between cross sections.
- Because the river cross-section survey networks have usually been established for flood risk management the design (cross section location and spacing, and frequency of measurement) is not considered ideal by many councils for gravel management.
- In the past the focus has mostly been on long-term trends in bed level with relatively low frequency of surveys (often >5 years). But with increasing demands on gravel resources, and the need to have better knowledge of gravel supply rates, many councils are increasing the frequency of surveys to 1 to 3 years for rivers with high extraction pressure.
- Cross-section spacing is dependent on river size but there does not appear to have been a clear rationale for cross section spacing (in terms of river width or morphology).
- Councils have generally used the end area method for calculating mean bed levels and gravel volumes implemented in 3 different software packages (RICODA, XSECT and Hilltop Software).
- LIDAR surveys have been completed for some rivers but are primarily intended for flood modeling and management purposes and the LIDAR technology is currently regarded as too expensive for routine application to gravel management. It will be a useful tool as the

cost decreases in the future and combined terrestrial and bathymetric LIDAR becomes available.
- Three approaches have been used to estimate gravel load in New Zealand and assist setting gravel extraction limits: a morphological method based on conservation of volume (derived from gravel volume changes [from cross-sections surveys, or more recently using GPS, LIDAR, or digital photogrammetry] and gravel extraction rates); as a proportion of suspended sediment yield; and application of bedload transport formulae.

Recommendations
- The effective regulation and monitoring of gravel excavation rates requires the systematic collection of measurements of the trends in bed levels, gravel deposition and excavation rate data over time. This data can be used to set and adjust extraction levels according to gravel supply.
- In the rivers of Tasman District that typically do not have large natural deposition zones there is a need to assess the proportion of gravel supply that can be sustainably harvested without having significant in-stream and downstream effects.
- There is a need to better establish gravel transport rates through short-term investigations involving a combination of field measurement and modelling of gravel transport.
- To calculate gravel volume changes and transport rates more accurately, three dimensional surveys of riverbeds are desirable. Presently digital photogrammetry or GPS are the most cost-effective options for obtaining such data. There is a clear need to consider LIDAR in the future as the cost decreases and combined terrestrial and bathymetric LIDAR becomes available.
- TDC should comprehensively review methods of determining sustainable extraction rates being applied by other councils who have recently reviewed their gravel extraction policies.

1. Introduction

Extraction of gravel from riverbeds is used both to source aggregate for roading and construction, and to improve the flood carrying capacity of rivers by reducing the build up of gravel within the flood channel. River cross-section surveys are the primary tool used by most regional councils, including Tasman District Council (TDC), to monitor river bed levels and to help set gravel extraction limits. Knowing the gravel transport rate is fundamental to setting gravel extraction limits, whether it is applied to estimating aggradation rates in natural long-term deposition zones or assessing the proportion of gravel transport rate that can be sustainably harvested without causing significant downstream effects. While river cross-section surveys provide direct data on trends in mean bed levels, they do have limitations for calculating changes in gravel storage in the river and gravel transport rate. Calculation of gravel storage changes from cross section data typically only gives a minimum estimate of the gravel transport rate, particularly when derived from relatively infrequent cross section surveys (Fuller et al. 2003).

TDC requested Landcare Research to review the range of techniques used by other regional councils to monitor changes in riverbed levels, river stability and morphology, and to help manage gravel extraction with a view to determining future data collection needs.

2. Background

Over-extraction of gravel can destabilise channels and banks, and/or affect the ecologic functioning of rivers particularly if undertaken at the wrong time, or in the wrong place, or in a way that damages the river bed or margins. For these reasons regional councils exercise controls on the amounts, and the process of extraction, to avoid or reduce adverse effects.

The potential impacts of gravel (over)extraction are well known (e.g., Kelly et al. 2005; Rinaldi et al. 2005) and include:

- bed degradation and consequent effects on channel and bank stability,
- increased sediment loads, decreased water clarity and sedimentation,
- changes in channel morphology and disturbance of ecologically important roughness elements in the river bed,
- ecological effects on bird nesting, fish migration, angling, etc.,
- modification of the riparian zone including bank erosion,
- direct destruction from heavy equipment operation,
- discharges from equipment and refuelling,
- reduction in groundwater elevations,
- impacts on structures and access,
- bio security and pest risks,
- impacts on coastal processes.

Effective regulation and monitoring of gravel excavation rates require the systematic collection of measurements of the trends in bed levels, gravel deposition and excavation rate data over time (EBOP 2003). These data can be used to set and adjust extraction levels according to gravel supply. Setting appropriate gravel extraction volumes requires information on the gravel supply. Directly measuring the gravel load is difficult so indirect techniques are commonly used to estimate gravel load. The three most common approaches used to estimate gravel load in New Zealand have been a morphological method based on repetitive measurements of river bed topography, application of bedload transport formulae, and estimates as a proportion of suspended sediment yield. The morphological method is the most widely used and has mostly been based on cross section surveys (e.g., Griffiths 1979; Noell 1992; Sriboonlue & Basher 2003), or more recently on digital photogrammetry, LIDAR and GPS (e.g., Lane et al. 2003).

Cross-section surveys provide a good long-term understanding of bed level trends, but have limitations for estimating gravel transport rates (relating to the spatial variation in river bed topography, temporal fluctuations in bed material transport and frequency of surveys).The method requires long-term data sets to give reliable time-averaged transport rates, and typically only give minimum estimates of transport rates particularly when derived from relatively infrequent cross section surveys (Fuller et al. 2003).

Many councils take advantage of natural accumulation zones to harvest gravel that is not being transported to the coast (e.g., on the Waimakariri and Wairau rivers). Where there are no natural accumulation zones there is a need to assess the proportion of gravel transport rate that can be sustainably harvested without having significant downstream effects. Some councils recognise gravel transport is episodic, with the largest volumes transported in major floods, and specific site excavation rates are reviewed after significant flood events.

TDC use river cross-section surveys as the primary tool to monitor river bed levels and to help set gravel extraction limits, but there is considerable public and political debate about the interpretation of the results of cross section surveys. TDC are currently reviewing gravel extraction policy and as part of this review are assessing alternatives to river cross-section surveys.

3. Objectives

The specific objectives agreed to by TDC and Landcare Research was to review the approach of other regional councils to the following:

- the techniques used for bed-level monitoring and subsequent analysis,
- the frequency of monitoring, and whether it accounts for both long-term trends and short-term fluctuations in bed level,
- if the method(s) and frequency of monitoring are considered optimal by regional councils and if not, what would be considered a good balance between cost and data usefulness,
- if cross-section survey techniques are used, what range of river types (width, gradient, nature of bed sediments, etc.) and consequently what typical distances are they spread apart (either in terms of a multiple of the cross section length, and/or active channel bank-to-bank distance),

- what other methods are employed or being considered to optimise riverbed stability monitoring,
- approaches to assessing gravel supply and sustainable gravel extraction rates.

4. Methods

Information was obtained by
- accessing published information on regional council Web sites (Environment Canterbury and Environment Bay of Plenty, Marlborough District Council);
- sending a direct request to council staff at Hawke's Bay Regional Council, Gisborne District Council, Marlborough District Council, Environment Bay of Plenty, Horizons MW. Horizons MW did not respond;
- some information for Otago Regional Council and Greater Wellington Regional Council was summarised from an Environment Canterbury review of gravel extraction policies (Environment Canterbury 2006).

5. Results

5.1 Environment Bay of Plenty

Environment Bay of Plenty (EBOP) uses a number of different methods to monitor gravel transport and the effects of gravel excavation. These include cross-section measurements, analysis of records of gravel extraction, aerial photography, LIDAR and use of bedload transport formulae (EBOP 2001, 2003; Pak 2003; Balley 2006). They suggest the effective regulation and monitoring of gravel excavation activities requires systematic collection of measurements of the trends in bed levels, gravel deposition and excavation rate data over time to allow setting of maximum and minimum excavation rates.

Cross-sections are the primary means of monitoring gravel dynamics in the Bay of Plenty. The specific objectives of the monitoring programme are:
- to provide EBOP with reliable data to identify a) the quantity of gravel available for extraction, and b) present extraction rates,
- to provide a basis for setting maximum annual gravel extraction rates.

EBOP has established a comprehensive system of cross-sections and these are surveyed at 1 to 5 year intervals (Table 1). The survey frequency varies to meet the need to survey rivers after significant floods. For example the rivers most affected by the major floods in July 1998 were resurveyed ahead of the programmed date. There is no uniform approach to the spacing of cross-sections: on some rivers they are 100 metres apart while on others they are 1 kilometre apart.

Table 1 EBOP cross-section survey programme as at July 2002 (Pak 2003; EBOP 2003)

River Name	No. of Cross-Sections	Cross-Section Spacing	Suggested Frequency of Survey	Extraction Pressure
Otara	37	300–800 m	2–5 year	Low
Waioeka	20	300–800 m	2–5 year	Med
Waimana *	35	400–1200 m	1–2 year	Med
Whakatane (below Pekatahi Bridge)	35	300–750 m	2–5 year	Med
Whakatane* (above Pekatahi Bridge)	34	500–1200 m	1–2 year	Med
Rangitaiki (Lower)	67	300–700 m	3–5 year	Low
Rangitaiki (Waiohau)	12	900–1200 m	5 year	Low
Rangitaiki (above Aniwhenua)	28	800–1300 m	5 year	High
Whirinaki *	7	500–1000 m	1–2 year	Med
Tarawera	18	700–1500 m	5 year	Low
Ohutu *	6	400–600 m	1–2 year	Med
Mangamate *	7	350–550 m	1–2 year	Med
Ruarepuae *	7	100 m	1–2 year	Med
Horomanga *	14	300–800 m	1–2 year	Med
Kopuriki *	3	250 m	1–2 year	Med
Kaituna (below Te Matai)	26	500–600 m	3-5 year	Low
Kaituna (above Te Matai)	17	400–800 m	3–5 year	Low
Mangorewa	3	500 m	3–5 year	Low
Waiotahi	7			Med
Waikokopu *			2 year	Med

* More frequent surveys may be appropriate to match excavation activities.

EBOP assesses what distance is appropriate to monitor each river system effectively. In general, this depends on the size of the river, ensuring data collection is tailored to the level of detail and accuracy of monitoring required for each river. The main emphasis is on long-term monitoring, with EBOP aiming to compare new data with as long a record as possible, so that long-term trends are identified.

Gravel volumes are determined from the cross-section data using RICODA to calculate mean bed levels and gravel volumes. The end area method is generally used to calculate gravel volumes, although there is also a more complicated algorithm that takes orientation of the cross sections into account.

Resource consents have a requirement for submission of returns to EBOP of the volume of gravel extracted. Currently, operators' records show gravel volumes after it has been screened and processed or sold. For river management purposes and for determining the amount of

material available for excavation, the relevant measure is the total quantity removed from the river, not just the commercial components of the gravel removed.
The results of these surveys are checked against gravel excavation records to develop an understanding of the movement and management of gravel in the river systems of the Bay of Plenty region. Estimates of gravel yield are derived from these records of gravel extraction operators, and from using the information from the cross-section surveys or other survey methods. The quantity of gravel transported by the river is derived from "gravel balance" calculations as the difference between net change in river storage (estimated from inter-survey bed level differences), and gravel excavated (estimated from gravel excavation returns over the period between cross-section surveys). Gravel supply rates for the main rivers are given in EBOP (2003) and Pak (2003).

Aerial photography is regularly undertaken on rivers throughout the Bay of Plenty, and this enables visual evaluations of gravel accumulations to be made. Aerial photography enables EBOP to identify and direct gravel excavation to these areas.

Environment Bay of Plenty have recently commissioned a trial LIDAR survey of the Otara, Waioeka, Waimana and Whakatane rivers to determine a three-dimensional model of these riverbeds. The survey will be repeated in around 3 to 5 years time and will improve the precision of assessing the gravel dynamics. EBOP regards the method as costly.

EBOP's main aim is to manage excavation levels to avoid both over- and under-excavation. The amount of gravel required to be excavated from a particular river reach for river management purposes, or the maximum amount available for commercial excavation, depends on the amount being transported by the river and deposited in that reach. In some years no gravel at all will be deposited in a particular reach, while in others there may be a significant amount. Gravel transport is to a large degree episodic, with significant proportions transported in the major floods. Specific site excavation rates are reviewed after significant flood events.

- To encourage stable channels, the following factors are promoted:
- maintaining bed levels and grades within a desirable range,
- maintaining good river alignments,
- keeping gravel extraction roughly in balance with natural supply rates,
- maintaining compatibility with existing flood protection structures and utility assets.

In addition to the cross-section-based estimates of gravel transport rates, Balley (2006) used empirical bedload transport formulae(Meyer-Peter and Muller, Engelund and Hansen and Einstein and Brown formulae) to calculate gravel transport in two Bay of Plenty rivers (Whakatane and Whirinaki). The aim was to obtain an understanding of the fluvial geomorphology of the rivers, assess their natural conditions and responses, and obtain design information. This approach requires information on the depth, width, and gradient of the channel, sediment characteristics, energy slope, roughness, Mannings n, and water velocity. Sediment transport rate were calculated for each cross section. The three formulae used gave quite different results at different flows. The estimated annual bedload transport rates were compared with annual supply rates given in EBOP (2003) and Pak (2003) derived from annual bed volume changes based on cross-section surveys. It is not clear if these transport rates have been used to help set gravel extraction limits.

5.2 Environment Canterbury

Environment Canterbury (Ecan) monitors riverbed levels by periodic cross-section surveys of a network that covers many Canterbury rivers, with data extending back as far as the 1930s (Table 2; Ecan 2006). While it is a large network, there are a number of rivers with little or no bed level monitoring. The rationale for most cross section survey networks is based on flood risk management objectives such as setting design bed levels and river widths. Recently Ecan has carried out a major review of its approach to gravel management, including assessment of gravel supply in all its rivers (Ecan 2006).

The frequency of cross-section survey records varies considerably between rivers (between 3 and 30 years), with few rivers being surveyed more frequently than every 5 years. In some rivers no cross-section surveys have been undertaken at all. The programme of monitoring is founded on the basis of historic survey rotations; however. this is then refined through a prioritisation process due to the limitations imposed by resource constraints. This process identifies priority rivers, or sections of rivers, for surveying based on topical issues and points of concern. On most rivers cross-sections are spaced quite widely (>500 m).

Ecan uses XSECT as a tool for analysis of bed level monitoring data. However, ECan undertakes very little interpretation of the data. Analysis has generally been limited to flood modelling and/or river engineering design purposes. The recent review (Ecan 2006) recommended that existing data analysis is improved and extended to include interpretation relevant to gravel resource management, and to include mechanisms that ensure feedback to appropriate gravel management objectives.

The cross section information is considered alongside annual gravel extraction data, existing gravel consents, and sustainable gravel supply estimates for respective rivers (see Ecan 2006 for a summary of supply rates) to identify key rivers of concern where bed level monitoring is currently inadequate. This also provides a useful tool for prioritising improvements to specific river monitoring regimes. Ecan (2006) identifies rivers that require urgent development of monitoring programmes (Rangitata, Makikihi, Te Moana, Waipara, Clarence) and rivers that require improvement (e.g., increased frequency and/or more cross-sections) to the current cross-section monitoring (Rakaia, Selwyn, Kowai, Pareora, Hinds, Temuka).

Although the current bed level monitoring programme is adequate for river management purposes, it has a number of limitations for gravel resource management (Ecan 2006). These include:

- drivers behind existing monitoring come primarily from flood-risk management and do not sufficiently incorporate gravel resource management purposes,
- data sets are incomplete and for some rivers non-existent,
- the extent of data is inconsistent across the region,
- there does not appear to be a particularly cohesive systematic approach to riverbed monitoring,
- surveys are not always exactly replicated,
- the design of the existing monitoring programme in relation to particular rivers does not sufficiently take account of relevant factors that affect gravel management.

Table 2 Ecan cross-section survey network (Ecan 2006)

River	Duration of surveys	No. of surveys	Average survey frequency (yrs)	No. of cross-sections	Average no. of cross-sections surveyed	Average distance between cross-sections (m)
Ashburton						
- Main	1937–2002	10	7	28	15	750
- North Br	1948–2002	17	3	53	24	757
- South Br	1937–2002	8	9	26	17	913
Pareora	1949–1999	4	17	27	26	588
Opihi	1953–2004	10	6	40	25	650
- Upper	1952–1998	5	12	14	8	1418
Orari	1949–1995	7	8	64	45	732
Waihi	1962–2004	8	5	48	24	493
Waimakariri	1960–2004	8	6	63	60	913
Ashley	1960–2001	7	10	25	13	840
Temuka	1953–2001	6	10	15	11	438
Hinds - Main	1937–2001	6	13	32	24	932
- Upper	1967–2003	5	9	15	13	790
- South	1969–2002	4	11	5	5	820
Otaio	1984–2002	2	18	32	32	730
Waihao	1966–2001	6	7	35	21	404
Kowhai	1987–2002	3	8	25	25	436
Rangitata						
Makikihi						
Te Moana						
Waipara						
Pahau						
Kowai	1977		30	7		
Selwyn	1999		10	10		
Rakaia	1988		40	25		
Kakahu						
Clarence						
Conway						
Waiau						
Hurunui	1989		30			
Waitaki						
Hakataramea						
Twizel						
Oaro						
Waianiwaniwa						
Kurow Creek						
Otiake						
Otekaieke						
Maerewhenua						
Penticotico						
Elephant Hill Strm						

Central to the limitations of the existing programme is the underlying purpose of the monitoring primarily being flood risk management. The drivers of the programme have not specifically incorporated gravel resource management needs, which might result in differences in the frequency and extent of surveys and cross section spacing.

Consideration of the existing data indicates records are erratic and there does not appear to have been a systematic approach to undertaking the cross-section surveys. Surveys have generally been undertaken infrequently; and there is significant variation between rivers in the frequency of surveys (ranging roughly between 5 and 35 years) and the reasoning behind this is not clear. There is inconsistency in the number of cross-sections surveyed on each monitoring occasion; and there appears to have been minimal analysis and interpretation of the resulting data.

Ecan (2006) identify a number of organisational issues affecting effective use of cross section survey to set gravel extraction limits. The bed-level survey programme is currently managed by Land and Coastal Resources section, although decisions about survey priorities are mostly made by River and Hazards section. However, the data collected are not used by Land and Coastal Resources section and do not in practice relate directly to the core work of this section. The rationale for this situation is historical, and may no longer be appropriate. It has led to a fragmented approach to management of the cross section survey programme.

Ecan (2006) recommended changes to ensure bed-level monitoring provides information that is relevant and appropriate to gravel resource management. Central to this is the development of specific objectives and policies for gravel resource management that will provide the purpose and drivers for the monitoring programme. However, it also recognised that it is important that an integrated approach is taken to the review and development of this programme. It needs to recognise and take account of the interrelationship between gravel resource management, river ecology, river engineering and flood risk management, and the relative importance of each of those factors in a particular river or river reach. Ecan (2006) recommended that a region-wide framework for assessing the bed-level monitoring requirements of rivers is developed. This framework needs to establish all the factors to be taken into account in determining the monitoring regime for a particular river, as this will differ from river to river. This assessment will then give direction to the frequency of surveys; the number of cross sections to be surveyed; the required accuracy and precision of the measurements; and the underlying design bed levels (which may vary within and between rivers depending on the sensitivity of infrastructure present, and the capacity of flood control works).

The following were recommended as key assessment criteria to determine the necessary monitoring regime for a particular river or section of river:

- Sensitivity of the reach, taking account of trends in riverbed changes shown by existing bed-level monitoring data and/or completed assessments of natural sediment supply. A sensitive reach is one where bed levels and volumes appear to be degrading rapidly or falling below design levels, or where a lack of aggradation is evident. This may be due to natural processes or potential over extraction.
- Extraction pressure takes account of past, present and projected rates of gravel extraction. Close attention should be paid to reaches where large volumes of material have or are being extracted, or where demand is increasing rapidly.

- Flood risk takes account of the level of flood risk posed within the reach, giving consideration to whether design bed levels can be changed due to changes in flood risk rating.
- Presence of sensitive infrastructure such as bridges, water intakes, pylons. etc.
- Bed and bank stability takes account of existing problems associated with bed and/or bank stability, and potential problems that may arise through flow path changes consequent upon extraction activities.
- Ecological sensitivity, such as native fish or salmonid spawning sites; bird nesting areas; significant indigenous fauna and habitat.

There must be sufficient flexibility within the system to allow review of these regimes in response to information obtained through improved monitoring, in response to improved understanding of particular river systems, in response to changes in management objectives within particular rivers, and following unforeseen events such as floods. The particular aspects of the monitoring regime established for a particular river can then be carried through to gravel extraction consents granted within that particular river system, and where necessary, conditions implemented that are directly relevant to those monitoring parameters.

Ecan (2006) determine gravel supply rates as follows:

- For rivers where bed level monitoring has been undertaken and gravel extraction volumes are known, gravel load is calculated on a conservation of volume basis over the surveyed river reach. Gravel entering the reach either leaves or remains in the reach. So for a given reach:

$$\frac{\Delta V_g}{\Delta t} = Q_{gravelinput} - Q_{gravelout} - Q_{gravelextraction}$$

where: ΔVg = change in volume of gravel (m^3) calculated from riverbed surveys

Δt = years between surveys

$Q_{gravel\ input}$ = volume of gravel entering the reach from upstream (m3/yr); often only able to be estimated from catchment erosion rates

$Q_{gravel\ extraction}$ = volume of gravel extracted from the river reach (m^3/yr); derived from gravel extraction returns

$Q_{gravel\ out}$ = export of gravel out of the river reach by downstream transport (m^3/yr); this is the unknown in the equation and can be solved for.

This approach provides a minimum estimate of gravel load, with the accuracy of the estimate depending on the frequency of cross-section surveys and the spacing of cross-sections. It also requires an estimate of gravel entering the reach which is often only poorly known. Bed level surveys do, however, provide reliable data on trends in bed level. Ecan (2006) provide a logic diagram (Fig. 1) for calculating sustainable gravel supply using this method.

For rivers without bed-level monitoring, estimates of the sustainable gravel yield were made using the suspended yield of similar rivers (based on location, underlying geology and catchment similarities) derived from Hicks and Shankar (2003). The sustainable gravel yield of the similar river was then modified to reflect differences in catchment area, river channel slope and relative suspended sediment yield. The proportion of the suspended sediment yield assumed to be bedload (gravel) ranged from 10 to 20% in different rivers (Ecan 2006).

Most consent issued by Ecan for the extraction of gravel from riverbeds contain a condition requiring extractors to maintain a record of the volume of gravel extracted under the consent, and to provide quarterly gravel returns to ECan indicating the volume extracted over the preceding quarter. Gravel excavation return records provide an indication of the total volume of gravel being extracted from each river catchment each year, although given the limitations of the returns process, Ecan (2006) suggest this may not be an accurate indication. The key

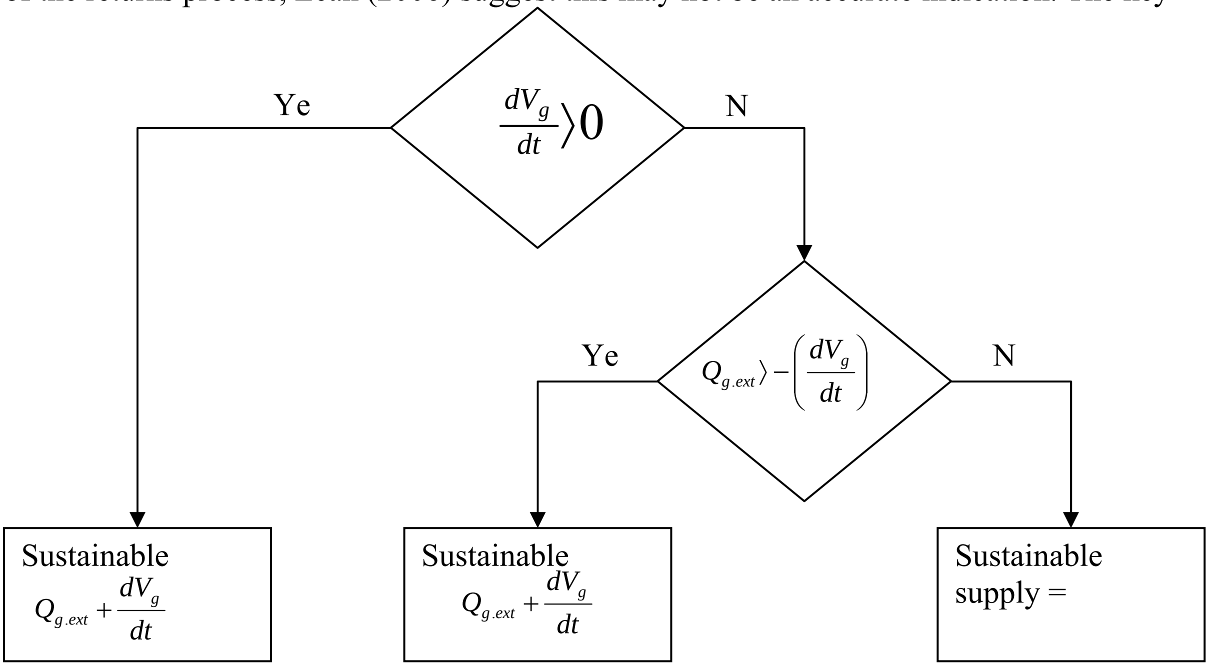

Fig. 1 Logic diagram for calculating sustainable gravel supply (Ecan 2006)
Where $Q_{g.ext}$ = volume of gravel extraction
dV_g = change in gravel volume in river bed,
t = time interval

limitation of the existing gravel returns system is that it is dependent on the accuracy and honesty of the records provided by consent holders. It is very difficult to audit these records, and on-the-ground monitoring to provide a cross-check requires considerable resources. This means that although the gravel returns records can provide a general estimate of the volume of material extracted from particular catchments, the accuracy of these records will always be inherently uncertain, and therefore so will the impacts of extraction. There are also inherent limitations in the gravel returns data due to a lack of a consistent requirement regarding the basis upon which extractors calculate their returns. At present, returns could be based on a range of factors, including truck tallies, loader buckets, or post-processing sales.

Although there are inherent limitations in the existing gravel extraction returns system, Ecan (2006) suggest there are limited alternative methods for monitoring volumes of gravel extracted that will not require a significant increase in the scale and intensity of monitoring. Similar systems are used by other regional councils, and Canterbury gravel extractors have indicated they consider the existing system of quarterly returns to be an efficient and suitable level of requirement.
However, for effective and sustainable management of the gravel resource, Ecan (2006) suggest a greater level of accuracy is required since the amount of extraction is key

information in the gravel resource equation. It is impossible to manage a resource effectively without a good understanding of what is there and what is being removed and the impacts of doing so. Standard consent conditions presently require extractors to measure material extracted to within 10% accuracy. Although the more accurate the better, this level of accuracy is probably appropriate. However, it is very difficult to determine whether or not this is being achieved.

There are a number of potential improvements to the gravel extraction returns process that may improve the effectiveness of the system and the accuracy of the resulting records. Ecan (2006) recommend that the existing system of monitoring extracted volumes be reviewed, and some or all of the following improvements incorporated:

- Gravel allocation be based on previous years' returns. This would provide a disincentive for extractors to under-report quantities in their returns, as a lesser volume will carry through to subsequent years' allocation. The alternative might be that extractors over-report their returns where actual extraction volumes are less than consented volumes, to ensure the same or similar allocation in following years. However, a system of charging for each cubic metre extracted would counteract this potential over-reporting.
- The conditions of consents should specify the measure for expressing the quantity of gravel. The key factor to be measured for sustainable gravel management purposes is the quantity of all material actually removed from the river. Measurements of volumes post-processing, or based on sales will not necessarily capture the total volume of material removed.
- There should be consistency in the requirement for submission of returns and consent holders should maintain a record of monthly volumes of gravel extracted.
- Wherever practicable, extractors should be directed to extract at separate sites so that on-the-ground compliance monitoring may provide a better cross-check to gravel returns.
- Before and after photographs provide information useful for assessing the general environmental state of a particular site both before and after extraction.

Implementation of on-site methods of monitoring extraction volumes is another method by which the accuracy of gravel returns can be audited. An example of such a method is proposed by Otago Regional Council, which is proposing to implement a truck movement monitor system. This process consists of a seismic monitor that is installed at specific gravel extraction access points. The monitor is able to distinguish between large and small vehicle movements, and thus record the number of trucks. Generally the size of trucks used by a particular operator will be known, and therefore the monitored truck movements can in turn be used to estimate the quantity of gravel extracted. The ORC requires extractors to advise them before exercising their resource consent, and the council usually has a good idea of how long extraction will take, so are able to readily install the monitor for the period of extraction. Clearly the monitor is most effective where access to an extraction site is only used by the extractor being monitored.

Ecan (2006) recommend the following be incorporated into an improved monitoring regime:

- Regular aerial photographs of all major rivers and rivers with high extraction rates. These provide a very useful illustrative overview of a particular river system, and can give valuable supplementary information about the riverbed between cross-sections.

Aerial photographs are a useful support tool to other monitoring data, and help to remind users that a particular reach is part of a working system.

- Increased on-the-ground site monitoring to 'ground truth' trends identified by monitoring data and to encourage accurate reporting of extraction volumes.
- Increased input to the specific locations for extraction before the exercise of consents. This enables a greater level of refinement in determining the specific location of extraction, which is particularly important in rivers and reaches where extraction pressure is increasing and/or in rivers where degradation is occurring or infrastructure needs protecting. The dynamic nature of river environments means unpredictable changes can occur in short timeframes. If significant changes have occurred since the granting of the consent, input immediately before extraction beginning ensures extraction occurs from the locations most appropriate at the time of extraction, rather than slavish compliance with originally submitted plans when this may have become inappropriate. At present, ECan has a reasonable level of input where river schemes are in place; however, in other areas this input is limited, and is exacerbated by extractors not always notifying ECan before exercising their consents.
- Monitoring of effects on aquatic ecosystems.

Ecan (2006) describe improvements in the technology available for measuring changes in river bed gravel volumes and transportation rates. NIWA has been experimenting with remote-sensing technologies for estimating gravel transport rates in large braided rivers using the "morphological method" (Lane et al. 2003). Repeat topographic surveys are carried out at relevant times, such as before and after a flood and a comparison of the topography allows an estimate of the volume of material that has been eroded and deposited. The storage volume changes are combined with the average distance that the bed load moves (the "step length") to calculate transport rate. The method depends on very accurate surveys of the riverbed to construct high resolution digital elevation models (DEMs) of the riverbed from which annual bedload transport can be estimated. Several alternative methods are available for undertaking the measurements required to create the DEMs, including digital photogrammetry (digitising high-resolution aerial photographs), aerial laser scanning (LIDAR), RTK GPS surveys, echo-sounders and RTK GPS within channels containing water, and GPS and/or calibration of water colour on aerial photos with actual water depth measurements.

LIDAR surveys produce a three-dimensional model of the riverbed and can improve the precision of assessing gravel dynamics. ECan have used LIDAR surveys to help flood plain modelling of the Waimakariri and Ashley flood plains, and coastal erosion surveys, particularly in areas where cliffs pre-dominate the coastline, making traditional surveys difficult. Currently, the cost of LIDAR surveys mean that for gravel and river management purposes, they are likely to be feasible only for very large rivers such as the Waimakariri. LIDAR surveys are also less practical for smaller or more entrenched rivers, where a significant proportion of the riverbed is under water, as the survey does not penetrate water. Where the bed is under water, the survey needs to be supplemented by depth surveys taken from a boat. Bathymetric LIDAR is available but very expensive.

Costs for LIDAR survey can range from around \$150/km^2 to \$600/km^2, depending on the area surveyed – the larger the area surveyed, the lower the per km^2 cost (Ecan 2006). LIDAR surveys provide useful information for a wide range of management purposes and therefore additional cost efficiencies can be achieved in areas where there are multiple agencies with an interest in the information obtained, as the cost of the survey can be shared. LIDAR surveys are not as accurate as traditional GPS cross section surveys, which achieve accuracy of about

+/-50 mm. The LIDAR specification usually states an accuracy of ±150 mm, although over clear open ground LIDAR can achieve accuracy of about ±70 mm (Ecan 2006). However, the key benefit of LIDAR surveys is the significant volume of additional information that is provided. Traditional cross-section surveys only provide data for the specific cross-sections surveyed. Information between cross-sections has to be interpolated from the survey data. Although this can provide general trend information, it can not always provide accurate information about specific sections of the riverbed, particularly in rivers where cross-sections are a considerable distance apart. LIDAR surveys provide data for every 2–3 m, so a much more detailed picture is given. This would be particularly useful for identifying specific sections of rivers that are aggrading and degrading, in order to better direct localised gravel extraction.

5.3 Hawke's Bay

Hawke's Bay Regional Council (HBRC) uses river cross section surveys as the main basis for assessment of gravel availability (Michael Adye, pers.comm., May 2006). Gravel extraction is an essential part of the river management regime particularly for maintenance of design flood capacity.

Reaches of rivers from which gravel is extracted are surveyed every 3 years, with other sections of rivers being surveyed every 6 years. In many rivers the record goes back to the 1970s, but the current frequency of surveys has been carried out for over 10 years. River types include single thread gravel rivers and silt bed rivers. Cross-sections are at approximately 0.5 km intervals. HBRC uses XSECT for analysis of bed level monitoring data.

Gravel allocation is currently done annually on the basis of specific quantities from identified river beaches. Visual inspections are carried out before allocation as cross-sections do not always provide an accurate picture of gravel availability. The total volume of gravel extracted from rivers in the Hawke's Bay region is on average approximately 500 000 m^3, with over 700 000 m^3 extracted in 2005. Gravel extraction returns are required on a monthly basis. On-site monitoring is carried out. For less reliable contractors and newcomers this can be weekly, but is less frequent for reliable contractors.

Aerial photos are taken on an annual basis and help set annual allocations. HBRC believe LIDAR may be an alternative to river cross-section surveying but have yet to evaluate it for gravel extraction management. HBRC have extensive areas of the region LIDAR surveyed for flood management purposes.

The current gravel allocation process is now coming under some scrutiny because of the pressure on the gravel resource and HBRC are planning a major review. The key issues are:
Larger extractors are seeking longer term consents,
A need to improve equity to all extractors as some have long haul distances (it is easier to push larger extractors to more distant sites for some of their allocation),
Coastal erosion is an issue, and it is unclear if present river management practices and gravel extraction reduce sediment supply to the coast and impact on coastal processes and erosion.

5.4 Otago Regional Council

Ecan (2006) provide brief details of the gravel management approach used by Otago Regional Council (ORC). Until 2 years ago very little monitoring had been undertaken and there was little information on the volume of gravel available in different rivers. However, monitoring has now increased and ORC produce 3 or 4 river reports each year that summarise gravel inputs and outputs, indicate sustainable extraction rates, and recommend future extraction levels. The reports take a broad geomorphological approach, looking at how gravel gets into rivers, land use and land-use change, hydrology, historical extraction, engineering works and structures, and how all these impact on the gravel resource.

Cross-section surveys are undertaken every 5 years but it is not clear on which rivers. The data are analysed using XSECT to determine whether rivers are aggrading, degrading or remaining stable. Aerial photos are available for every river but are flown infrequently (>5 yrs) and it is not clear if they are used to help set gravel extraction levels.

5.5 Greater Wellington Regional Council

Greater Wellington Regional Council (GWRC) have cross-section networks on all their major rivers and use them as the primary tool for monitoring bed levels and setting gravel extraction limits (Ecan 2006). The frequency of surveys is variable. A meeting is held between Consents Management and Operations (river engineers) each year to determine which rivers to survey based on:

- the extent of gravel extraction (if large volumes are being extracted then surveys would be undertaken every year),
- the sensitivity of the reach (if bed levels are degrading then surveys would be undertaken every year),
- the presence of sensitive infrastructure (e.g., bridges, water intakes).
- On other lower priority rivers, a revolving programme results in surveys every 2 to 8 years.

RICODA is used to analyse the cross-section data. Changes in bed levels and gravel volume are used to set sustainable extraction volumes.

Gravel extraction is monitored from operators returns. Consented volumes are generally based on previous years' use.

5.6 Marlborough District Council

Marlborough District Council (MDC) have a network of cross sections on the Wairau River from Tuamarina to the Waihopai confluence (Christenson 2001). The lower part of the Wairau is a natural depositional zone that has aggraded over time. Data from the cross-sections are used for both calculating flood capacity and managing gravel extraction to maintain flood capacity. MDC believes such data provide a reasonably accurate account of aggradation volumes in the lower reaches of the Wairau River (B. Williman, pers. comm., June 2006).

There are 29 cross-sections spaced at c. 800 m intervals. They have been surveyed at irregular intervals ranging from 4 to 15 years (1969, 1984, 1991, 1996, 2001, 2004/05). MDC now aims for a frequency of about every 3 to 5 years. Data were initially analysed using

RICODA to calculate mean bed levels and estimate changes in gravel volume storage, but are now analysed in Hilltop Software. Results are summarised in Christenson (2001), along with an error analysis on the calculations of bed level and gravel volume changes. MDC also use aerial photographs and on-site inspections to provide additional information on how the riverbed is behaving between the cross sections. Christenson (2001) suggests a full topographic survey of the riverbed would be useful once the technology for implementing this (e.g. LIDAR) becomes more affordable.

An analysis of the sediment supply to the Wairau River is included in a review of Wairau River gravel extraction policy (MDC 2005). The long-term sediment supply is estimated from the volume of gravel deposited in the Wairau fan over the last 14 000 years (70 000 m^3/year). This is compared with variation in gravel supply since 1953 estimated from cross-sections in the aggrading zone of the river (-25 000 to +140 000 m^3/year). The data provide a clear indication of the variation in gravel supply through time. Gravel supply has tended to reduce through time as a result of trapping of sediment in the Benhopai dam, gravel extraction in upstream reaches of the Wairau, and soil conservation works in the upper catchment.

Gravel extraction is monitored from operators returns and is compared with bed-level trends to set recommended extraction rates. In recent years gravel extraction rates have exceeded deposition rates and necessitated a major review of extraction management (MDC 2005).

5.7 Gisborne District Council

Gisborne District Council (GDC) monitor bed levels in about 20 rivers ranging from big (Waipaoa, Waiapu) to small (D. Peacock pers. comm., May 2006). The monitoring is primarily directed at flood capacity rather than gravel extraction. Cross-sections are generally monitored every 3 years (going back in some rivers to 1948). The cross-sections are about 0.8 km apart, and the surveyed active channel width ranges from 60 to 100 m. The data are used to define mean bed level for calculating flood capacity and tracking changes in flood capacity over time.

GDC have obtained LIDAR coverage for the whole of the Gisborne floodplain at a cost of c. $4/ha. It is mainly used for hydraulic modelling of flood flows.

5.8 Gravel supply rates

Setting appropriate gravel extraction volumes requires information on the gravel load of rivers. Measurement of bedload transport in gravel bed streams is notoriously difficult and expensive, and has been undertaken in very few rivers. The approaches used include (after Hicks & Gomez 2003):

- bedload sampling. Because bedload transport rates are highly variable spatially and temporally, it is very difficult and time-consuming to use direct sampling to get an unbiased estimate of time-averaged transport rate.
- bedload traps. These provide reliable data on bedload yield, but are difficult and expensive to install, particularly in larger rivers.
- bedload tracers. These can provide reliable data so long as the tracer can be recovered, and the relationship between transport rate, entrainment and displacement length, and the velocity of the sediment is known.

- bedload transport formulae. These are relatively difficult to apply, requiring information on the depth, width, and gradient of the channel, and on sediment characteristics, and are best suited for time-averaged transport rates. There are a range of approaches that relate bedload transport rate to water discharge, shear stress, or stream power.
- morphological methods based on bed level cross section surveys, photogrammetry, GPS and LIDAR surveys. Morphological methods have mostly been based on cross section surveys (e.g., Griffiths 1979; Noell 1992, Sriboonlue & Basher 2003), or more recently on digital photogrammetry and LIDAR (Lane et al. 2003). These methods require long-term data sets to give reliable time-averaged transport rates, and typically only give minimum estimates of transport rates particularly when derived from relatively infrequent cross section surveys (Fuller et al. 2003).
- as a proportion of suspended sediment yield (e.g., Environment Canterbury 2006).

In addition estimates of long-term gravel supply have been made for some rivers (e.g., Wairau and Motueka) by calculating the volume of gravel deposited in fans during the Holocene (Marlborough District Council 2005; Peterson 1997).

There have been few direct measurements of bedload transport rates in New Zealand. The three approaches commonly used to estimate gravel load in New Zealand and help set gravel extraction limits are: the morphological method based on conservation of volume; application of bedload transport formulae; and as a proportion of suspended sediment yield. For rivers where bed-level monitoring has been undertaken and gravel extraction volumes are known, gravel load can be calculated on a conservation of volume basis over the surveyed river reach (for details see section 5.2). This morphological method is the most widely used and has mostly been based on cross section surveys (e.g., Griffiths 1979; Noell 1992; Sriboonlue & Basher 2003), or more recently on digital photogrammetry, LIDAR and GPS (e.g., Lane et al. 2003). The cross-section surveys provide a good long-term understanding of bed-level trends, but have limitations for estimating gravel transport rates (relating to the spatial variation in river bed topography, temporal fluctuations in bed material transport and frequency of surveys). The method requires long-term data sets to give reliable time-averaged transport rates, and typically only gives minimum estimates of transport rates, particularly when derived from relatively infrequent cross-section surveys (Fuller et al. 2003).

By default gravel supply rates are often estimated as a proportion of suspended sediment yield (SSY), as the cheapest and most practical option (e.g., Ecan 2006). Recent analysis of New Zealand-wide information on SSY (Hicks et al. 1996, Hicks & Shankar 2003a, b) has provided reliable estimates of SSY throughout New Zealand. Gravel supply rates can be calculated from published estimates of SSY (e.g.,Hicks & Griffiths 1992;Hicks & Shankar 2003; Hicks et al. 2004), from similar rivers (based on characteristics such as location, area, underlying geology, rainfall, channel slope, flow regime), or from a national coverage of spatially distributed SSY. This national GIS coverage enables reconnaissance-scale estimates of SSY from New Zealand's rivers and streams. It was developed by NIWA in collaboration with Landcare Research using a model relating sediment yield per unit area to mean annual rainfall and to an 'erosion terrain' classification (broadening the Hicks et al. 1996 analysis to a national scale). The erosion terrains were defined on the basis of slope, rock type, soils, dominant erosion processes, and expert knowledge. The resulting map of sediment delivery to rivers and streams has been adjusted over gauged catchments so that the sediment yield predicted by the empirical model matches the gauged yields measured at over 200 river stations. Catchment SSY can be derived by integrating the raster coverage of SSY over the catchment area. The layer can be used to estimate suspended-sediment delivery to rivers and streams from within any defined catchment boundary (see ftp://ftp.niwa.co.nz/ResourceManagementTools/Sedmap/). Having estimated SSY, gravel yield can be estimated as a proportion of SSY. Hicks and Griffiths (1992) suggest that in larger rivers bedload is <25% of suspended load, while Griffiths and Glasby (1985) estimate that the bedload delivered to the coast is 3–10% of suspended load. This is the approach Ecan has used to estimate gravel yield in many Canterbury rivers (Ecan 2006).

There are numerous bedload transport formulae – see Reid and Dunne (1996) and Hicks and Gomez (2003) for brief summaries of the use of bedload transport formulae. They are relatively difficult to apply, requiring information on the depth, width, and gradient of the channel, and on sediment characteristics, and are best suited for time-averaged transport rates. A range of approaches are used that relate bedload transport rate to water discharge (e.g. Shulits 1934), shear stress (e.g., Meyer-Peter & Mueller 1948), or stream power (Bagnold 1980). This approach has been applied to the Waimakariri River (Carson & Griffiths 1989; Meyer-Peter and Muller formula) and two Bay of Plenty rivers (Balley 2006; Meyer-Peter and Muller, Engelund and Hansen and Einstein and Brown formulae). Different sediment transport formulae often give quite different results across the range of flows.

6. Conclusions

River cross-section surveys are the primary tool used by regional councils to monitor riverbed levels, on both gravel-bed and silt-bed rivers. These are often supplemented by aerial photo analysis and site inspections to provide an indication of river behaviour between cross-sections. These are used in combination with gravel extraction volumes derived from returns from contractors to calculate gravel load on a conservation of volume basis. Trends in bed level, gravel volumes and gravel extraction are used to set extraction limits. Aerial photos and site inspections are used by many councils to supplement the information from cross-sections and provide an indication of river behaviour between the cross sections. The river cross-section survey networks have usually been established for flood risk management, and the design is not considered ideal by many councils for gravel-management purposes (particularly in terms of cross-section location and spacing, and frequency of measurement). River cross-sections are used both on gravel-bed rivers and silt-bed rivers.

The frequency of surveys has been highly variable in the past, ranging from 1 to 30 years. The main focus has been on monitoring long-term trends in bed level. With increasing demands on gravel resources, and the need to have better knowledge of gravel supply rates, many councils are increasing the frequency of surveys. For rivers with high extraction pressure, surveys are now typically carried out every 1 to 3 years.

Cross-section spacing is highly variable, ranging from 100 to 1400 m. Spacing is primarily dependent on river size, and generally appears to have been set in relation to use for managing flood carrying capacity of rivers rather than managing gravel extraction. There does not appear to have been a clear rationale for cross-section spacing but it is clearly related to river width. In many larger rivers cross sections were initially spaced at ½ mile (0.8 km).

Councils have used 3 different software packages to analyse the bed-level data: RICODA, XSECT, and Hilltop Software. All three use the end area method to calculate mean bed levels and gravel volumes, although some do have the option of using a more complicated algorithm that takes orientation of the cross sections into account.

Many councils acknowledge that current bed-level monitoring is not ideal for managing gravel extraction and have initiated major reviews of their cross-section networks, reporting of gravel extraction volumes, data analysis, and interpretation. Ii is increasingly recognised that to calculate gravel volume changes and transport rates more accurately, three-dimensional surveys of riverbeds are desirable. Digital photogrammetry or GPS are currently the most cost-effective options for obtaining such data. A number of councils have completed LIDAR surveys of at least some of their rivers, but this is primarily intended for flood modeling and management purposes. At present LIDAR is too expensive for routine application to gravel management but it will be a useful tool as the cost decreases in the future and combined terrestrial and bathymetric LIDAR becomes available.

- Setting appropriate gravel extraction volumes requires information on the gravel load of rivers. Three approaches have been used to estimate gravel load in New Zealand and help set gravel extraction limits: a morphological method based on conservation of volume (derived from gravel volume changes [from cross sections surveys, or more recently using GPS, LIDAR, or digital photogrammetry] and gravel extraction rates); as a proportion of suspended sediment yield; and application of bedload transport formulae. The morphological method is the most widely used and has mostly been based on cross-section surveys. While cross section surveys provide a good long-term understanding of bed-level trends, they have limitations for estimating gravel transport rates and typically only give minimum estimates of gravel transport rates.

Many councils recognise gravel transport is episodic, with the largest volumes transported in major floods, and suggest specific site excavation rates should be reviewed after significant flood events.

7. Recommendations

- The effective regulation and monitoring of gravel excavation rates requires the systematic collection of measurements of the trends in bed levels, gravel deposition and excavation rate data over time. These data can be used to set and adjust extraction levels according to gravel supply. In the rivers of Tasman District that typically do not have large natural deposition zones there is a need to assess the proportion of gravel supply that can be sustainably harvested without having significant in-stream and downstream effects.

- There is a need to better establish gravel supply rates through short-term investigations involving a combination of field measurement and modelling of gravel transport. Presently digital photogrammetry or GPS are the most cost-effective options for obtaining such data. There is a clear need to consider LIDAR in the future as the cost decreases and combined terrestrial and bathymetric LIDAR becomes available.

- TDC should comprehensively review methods of determining sustainable extraction rates being applied by other councils who have recently reviewed their gravel extraction policies.

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