Managing Sedimentation and Diffuse-Source Contaminants: a Limits-Based Approach

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Abstract

The assertion that cumulative effects of diffuse-source contaminants in estuaries will only be manageable by setting limits is explored, and some elements of a conceptual and technical framework for limits-based management of estuaries are laid out. This is achieved by analysing a simple system (sediment from three source regions in a catchment depositing in one estuary sink at the base of the catchment). The goal of the analysis is to determine the catchment sediment load limit that will deliver a target sedimentation rate in the estuary. The results show that there is not just a sediment load limit, but in fact there is an envelope of sediment load limits that will achieve the goal. Exploiting the load-limit envelope could benefit planning at the catchment scale in a number of ways, including zoning for landuse and designing spatial patterns of mitigation requirements. The case for managing for annual-average sedimentation rates is argued. This approach would deliver a range of co-benefits, is easily explained to different audiences, and is amenable to sophisticated analysis using the load-limit concept.

Introduction

The Land and Water Forum (2010) noted that

> "... without limits it is hard to manage diffuse discharges – nutrients, microbes, sediment and other contaminants that wash into water from the land – and impossible [my emphasis] to deal with the cumulative effects on water bodies of water takes on the one hand and diffuse and direct discharges to water on the other".

This is a key assertion and culminates in recommendations concerning the expression of measurable objectives at a regional level, the linking of objectives to standards and limits, and the need to employ a range of instruments to ensure that targets and limits so set are actually achieved. Here I explore how the setting of limits and the management of cumulative effects of diffuse-source contaminants are connected, and I lay out some elements of a conceptual and technical framework for limits-based management of estuaries.

Cumulative effects

Despite best-management practices on the land designed to mitigate the generation of contaminants, laudable industry initiatives such as the Clean Streams Accord, community involvement, and development of regional water quality standards, diffuse-source pollutants associated with landuse intensification and change (such as sediments, nutrients, heavy metals and pesticides) are still taking a toll on freshwater and estuarine ecosystems (Ministry for the Environment, 2007). This not only damages ecosystem integrity but also has the potential to limit economic growth through impairing the natural services and functions that ecosystems provide to society. In particular, management of the cumulative effects of contaminants is widely recognised as a remaining key challenge in estuary management. For example, “cumulative effects of activities on ecosystem structure, function and resilience” was named as a critical issue of very high strategic importance by regional councils in their 2009 Research, Science and Technology Strategy.

At the same time, there is a growing knowledge of the effects of contaminant stressors, including multiple-stressor interactions; effects along stressor gradients; and loss of ecosystem resilience in all types of ecosystems (not just estuaries). Furthermore, contaminant-generation/fate models that account for spatially distributed sources have been developed. We now need to put this knowledge to use in a framework that has the potential to manage the cumulative effects of stressors.

Definition of limits

Norton and Snelder (2010) distinguish between two types of limit. Environmental limits are intended to give effect to objectives, which in turn are statements of what is desired to be achieved in the environment. A standard (for water quality or sedimentation rate, for example) is a type of environmental limit. Limits to resource use are intended to give effect to environmental limits (catchment contaminant load limits or minimum lake water levels, for instance).

Objectives typically derive from value-based judgements concerning the balance between the use (by people) of natural resources and the protection of the environment. Limits therefore are not really set as such; it is more correct to think of the objective as being set, and the limits evaluated accordingly.

Limiting resource use

Although there are any number of management methods (for example, setting rules governing landuse, controlling activities through granting and declining resource consents and by attaching conditions to resource consents, allocating resources, offering different kinds of incentives), limiting resource use offers the best prospect for managing cumulative effects. Justice Salmon (2007) (and subsequently elaborated upon by Milne, 2008) put it succinctly when he said that the best possible framework for managing cumulative effects under the Resource Management Act will be based on identifying the resource and determining its capacity, and then limiting the resource’s use accordingly.

Limits-based management in New Zealand

In response to serious eutrophication of the Rotorua Lakes, the Bay of Plenty Regional Council promulgated Rule 11 in their Regional Water and Land Plan. Rule 11 sets limits on the amount of nitrogen and phosphorus leaching from the catchments of Lakes Rotorua, Rotoiti, Rotoehu, Okareka and Okaro. A central component of the scheme requires the establishment of nutrient benchmarks for rural properties in the affected regions, which are determined by a variety of measures and that result, in essence, in capping of nutrient runoff to the lake at 2004–05 levels. In the assessment of the benchmarks, allowance for fair and reasonable production is made, and physical characteristics of properties are also taken into account. In addition, the benchmarks were at least partly set to achieve certain water quality goals as expressed by the Trophic Lake Index. In the language I am using here, the nutrient benchmarks are the limits to resource use, and as for the consequent management method:

> A resource consent is required when a land use change or land management practice increases the average export of nitrogen or phosphorus from the property above its nutrient benchmark, and no nutrient management options are available on that property. Resource consent applicants must identify what nutrient management measures will be used to fully offset the proposed increase within the same lake catchment. (www.envbop.govt.nz/Factsheets/Lakes-090526-FactSheet8.pdf)

In this way, nutrient loss is prevented from increasing over the benchmarked level, and so the cumulative effects of nutrients on the lakes are to be managed. Rule 11 is one component of a larger package comprising regulatory and non-regulatory measures for managing lake water quality.

A type of nutrient trading is implied by Rule 11:

> The nutrient benchmark applies, but is split between the new properties. For example, the nutrient benchmark could be averaged amongst the new properties, or a higher percentage of the benchmark assigned to different properties. For example, new lifestyle blocks could have covenants requiring no stock is to be kept on the property (i.e. a low nutrient level), and the remaining benchmark allocated to other blocks. (www.envbop.govt.nz/Factsheets/Lakes-090526-FactSheet8.pdf)

The prospects for a full-blown nutrient trading scheme were explored in a paper published by MOTU (motu-www.motu.org.nz/wpapers/07_06.pdf), which discusses what such a scheme would look like, its potential benefits, and how it could be implemented on the back of Rule 11 and the existing administration infrastructure.

Facing similar water quality issues in Lake Taupo, the Waikato Regional Council developed the Waikato Region Plan Variation 5 – Lake Taupo Catchment, which requires capping of nutrient runoff from a range of landuses in order to achieve the goal of reducing nitrogen inputs to the Lake by 20%. Based on the benchmarking period 2001–05, Nitrogen Discharge Allowances (NDAs) for a range of farming activities were calculated. Every farmer in the Lake's catchment is required to develop and submit a Nitrogen Management Plan that details how their farming practices will meet their respective NDA. An allowance trading scheme has been set up which facilitates the transfer, by sale or lease, of allowances between willing parties. One potential partner in the trading scheme is the Lake Taupo Protection Trust, which may from time to time wish to purchase and thereby retire any particular allowance. In addition, Ngati Tuwharetoa hold 'nitrogen pools' on forested land which may be sold to third parties wishing to commence farming on land that was not farmed prior to the benchmarking period.

Horizons Regional Council has included load limits in their One Plan regional plan as one part of their strategy for managing the effects of point- and diffuse-source contaminant discharges to rivers in their region. For example, new dairy farms must comply with nitrogen leaching rates set out in the plan. Environment Canterbury is considering the use of catchment-based load limits to better manage the cumulative effects of nutrients, sediments and pathogens on rivers, lakes, wetlands and groundwater. A case study in the catchment of the Hurunui River is being used to investigate the feasibility of and technical hurdles to setting nutrient load limits

Management of contaminant effects in New Zealand estuaries

To my knowledge, estuary management based on limits to resource use has not been practised in New Zealand, although environmental limits are certainly among the arsenal of tools used to manage estuaries. Examples are use of the ‘2-cm rule’ to inform consenting of rural residential intensification. The rule originated from work done by NIWA at Okura estuary, north of Auckland. The study showed that fine sediment deposited in the aftermath of a rainstorm to a depth of 2 cm over an area of at least 100 m^2 that stayed in place for at least 7 days was enough to kill all the benthic macrofauna underneath, except crabs (Norkko et al., 2002). This experimental finding became something of a *de facto* environmental limit in a subsequent assessment of environmental effects of proposed catchment development at Okura. The rule was refined in later experimental work that looked at the effects of thinner layers of sediment, which are deposited more frequently (Lohrer et al., 2004). This led to refinements of the 2-cm rule, which were applied in an assessment of environmental effects at Whitford, east of Auckland.

Another example of an environmental limit is a sediment-quality-guideline threshold for heavy metal concentration. This has been employed in, for instance, the Central Waitemata Harbour Contaminant Study, which was commissioned by the Auckland Regional Council to predict the state of the harbour in the year 2100 under a variety of catchment development scenarios, which consisted of various combinations of landuse, stormwater treatment and contaminant source control. The study culminated in a complex ‘source-to-sink’ computer model that took the development scenarios as input and predicted associated contaminant (sediment and heavy metals) loads from each subcatchment that drains into the harbour, and the subsequent accumulation of those contaminants in the harbour. Predicted contaminant accumulation was compared to environmental limits – primarily zinc and copper sediment-quality-guideline threshold concentrations – to determine whether each development scenario being tested was acceptable. If the scenario at hand was deemed to be unacceptable, then other combinations of model input variables – levels of stormwater treatment, or different options for source control – were sought that would achieve or do better than the given environmental limits.

Although it is possible to think of the acceptable development scenario as being a limit to resource use, in the sense that development can be no more than that, there is nonetheless no obvious way of knowing when deviations to the acceptable development scenario – plan variations, granting consents for noncomplying activities, for instance – will add up to make the acceptable development unacceptable. This is the essence of the cumulative effects dilemma: knowing when enough is enough.

Evaluating limits to resource use

How, then, are limits to resource use to be evaluated, and what do they look like?

The objective must come first, and for this estuary example I will assume that the objective is to return recreational shellfish harvesting to 1950s levels. Furthermore, I will assume that, after some scientific investigation, it is agreed that the environmental limit that will deliver this objective is an annual-average sedimentation rate of 6 mm/year. Following our intuition, we can now assume that this is achievable by limiting sediment runoff from the catchment, and we now seek that catchment sediment load limit.

Recall at this point the source-to-sink model: it takes contaminants (sediments in this case) off the land and disperses them in the receiving waters at the base of the catchment, ultimately accumulating the contaminants over some period of time. In the case of sediments, the accumulation will be expressed in terms of a sedimentation rate. Now, if we have a certain target sedimentation rate – this is the environmental limit that we think will return the recreational shellfish harvest to 1950s levels – then we should be able to find the corresponding sediment load from the catchment that will result in that sedimentation rate by running the source-to-sink model backwards or, in other words, by inverting the model. When we do that, what we find is that there is not just one sediment load limit; in fact there is an envelope of sediment load limits.

The envelope of sediment load limits

I do not mean that we actually invert or run a source-to-sea model backwards in order to find the envelope of sediment load limits, but it does give the flavour of the method. In fact, what we need is a specific understanding of 'how the system works', from which, by applying some algebra, the sediment load-limit envelope can be derived. This specific understanding is shown in Figure 1, which depicts sizes and locations of contaminant source regions in the catchment, sizes and locations of contaminant sinks in the estuary, and connections, or transport pathways, that link the two. Both attenuation and transformation of contaminants may occur as they move along transport pathways. For example, sediments may be sequestered in tidal creeks before reaching the wider estuary, and sediment grainsize may change as a result of flocculation upon encountering saltwater. Note that the ocean may also be a sink for contaminants sourced from the land. It is worth noting that a source-to-sink model can be used to develop the information shown in Figure 1 (by running it forwards, not backwards), although that is not necessarily the only way. At the other end of the spectrum from the source-to-sink model, expert assessment could be applied in a desktop study aimed at scoping sediment load limits.

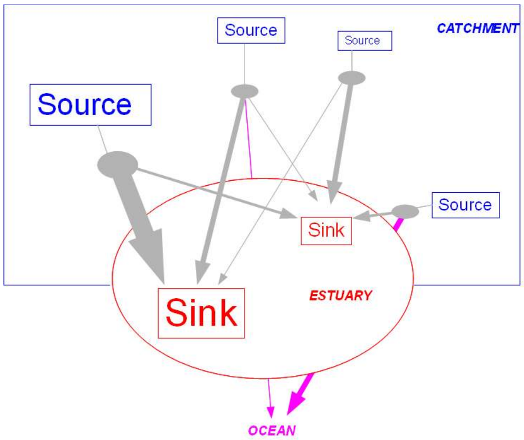

Figure 1. What is meant by 'how the system works'.

A simple example system, which comprises three sources of sediment that deposits in a single basin, is shown in Figure 2. The annual-average sedimentation rate arising from the deposition of catchment-sourced sediment is 12 mm/year. There are no other sources of sediment, for example, marine sediments washed in through the mouth of the estuary. I will use this example system now to evaluate the envelope of sediment load limits that will deliver the environmental limit of 6 mm/year sedimentation rate.

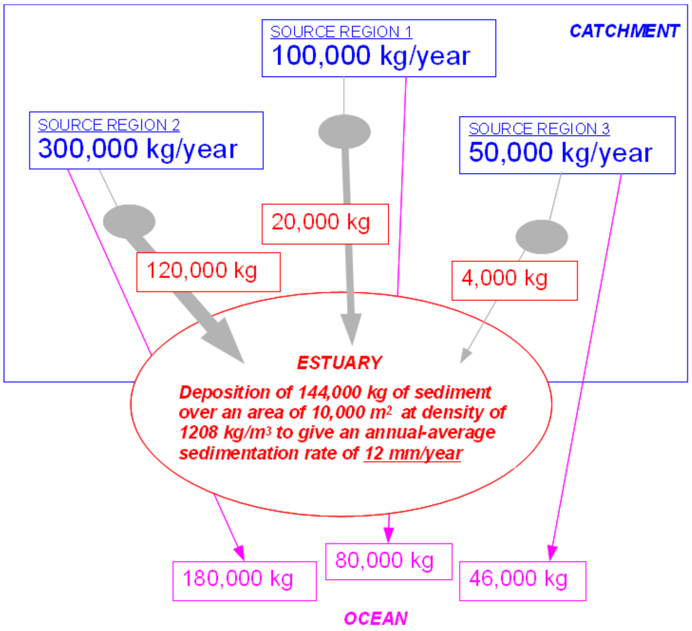

Figure 2. Example system.

The sediment load limit, by the way, is not 72,000 kg (i.e., one-half of the 144,000 kg of sediment that currently deposits in the estuary to give a sedimentation rate of 12 mm/year). If 72,000 kg were set as the catchment sediment load limit, then the sedimentation rate would be much less than 6 mm/year, since a part of the catchment sediment runoff does not actually deposit in the estuary. In effect, a large part of the resource capacity would be wasted if this mistake were made. To be completely clear, I will call 72,000 kg of sediment per year the 'target deposited mass', which is not the same as the sediment load limit. The analysis now comes down to finding the catchment sediment load limit that will result in the target deposited mass.

With the system described in Figure 2, the envelope of sediment load limits is now able to be established by reasonably straightforward algebra, which I will not give here. However, the nature of that algebra may become clear in the following explanation of the load limits.

After applying the necessary algebra, we can draw the sloping triangular plane in Figure 3, and note that every combination of source sediment loads (L_1, L_2, L_3) that lies on the surface of that plane will deliver exactly the target deposited mass of 72,000 kg/year. Here, L_1 is the annual sediment load from source region 1, and so on. For example, if we look at where the plane just touches L_3, here (L_1,L_2,L_3) = (0,0,900000). This tells us that, with the other two sources turned off (i.e., $L_1 = L_2 = 0$), L_3 needs to be 900,000 kg to deposit exactly 72,000 kg of sediment in the estuary. Referring back to Figure 2, we see that the fraction of L_3 that is deposited in the estuary on a yearly basis is 4,000 kg / 50,000 kg = 0.08. Then, 0.08×900,000 kg = 72,000 kg, which is indeed exactly the target deposited mass.

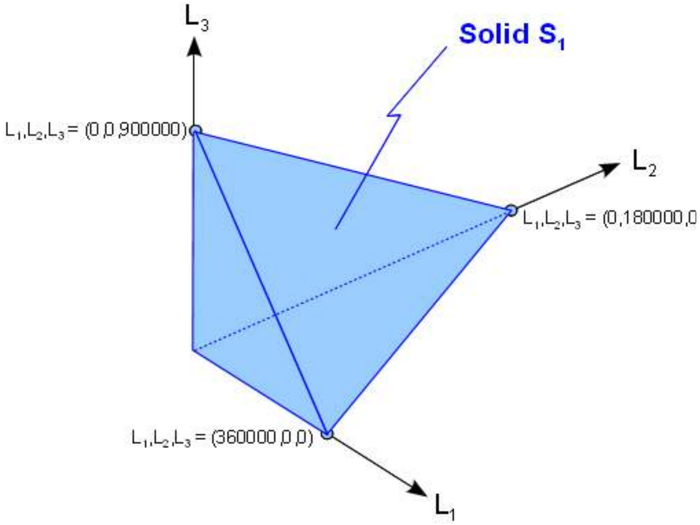

Figure 3. Every combination of loads inside the solid S_1 will deliver less than the target deposited mass.

Any combination of source loads that falls above the sloping triangular plane will result in the target deposited mass, and therefore the 6 mm/year sedimentation rate, being exceeded. On the other hand, any combination of source loads that lies below the sloping triangular plane and above zero (i.e., inside the solid S_1 in Figure 3) will result in deposition of less than the target deposited mass, which is better than (i.e., less than) the 6 mm/year sedimentation rate.

Not all of the combinations of loads inside the solid S_1 are necessarily reductions compared to present-day loads. For instance, L_1 can be as high as 360,000 kg (when L_2 and L_3 are both zero) without exceeding the target deposited mass. Referring back to Figure 2, this means that L_1 can be as much as 260,000 kg larger than the present-day load, while still achieving the target. It seems unlikely (although not necessarily out of the question) that we would want to let L_1 increase over its present-day size, and extending this logic to the other two sources, we probably would not want L_2 to exceed 300,000 kg or L_3 to exceed 50,000 kg. These restrictions are shown by the solid S_2 in Figure 4: every combination of source loads inside the solid S_2 represents a reduction compared to present-day loads.

Where S_1 and S_2 intersect we have combinations of loads that will deliver at the most the target deposited mass <u>and</u> that are reductions compared to present-day loads. This intersection is starting to look like a good candidate for finding sediment load limits. Combinations of loads inside S_1 but outside S_2 will also deliver at the most the target deposited mass, but they call for increases in at least one of L_1, L_2 or L_3, which, we can assume, will be undesirable. Combinations of loads inside S_2 but outside S_1 represent reductions in sediment runoff, but they do not deliver the target deposited mass, and so they should be discounted.

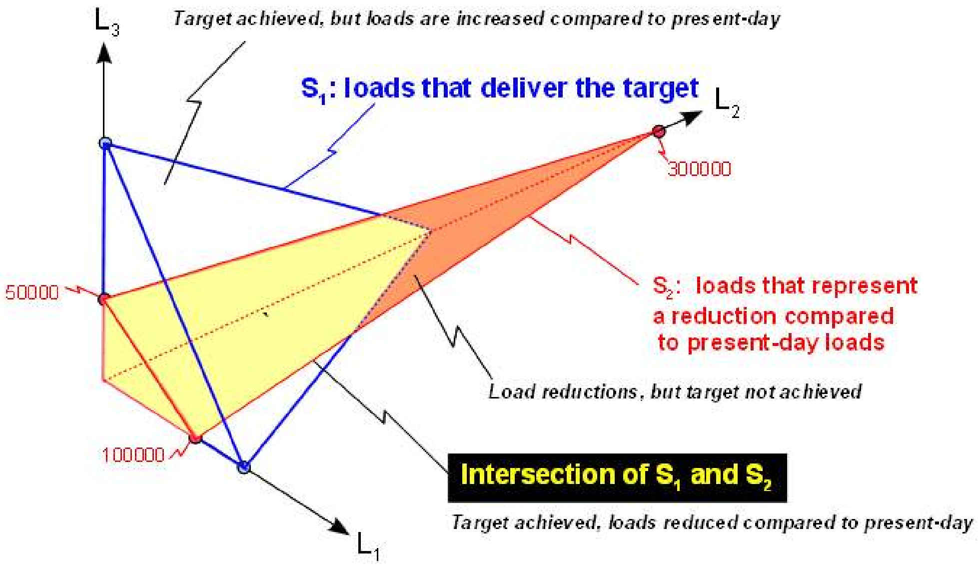

Figure 4. The solid S_2 contains all combinations of loads that represent a reduction compared to present-day loads. The intersection of S_1 and S_2 is starting to look like a good place for finding sediment load limits.

Let's assume now that the present-day source loads L_1 and L_3 can be reduced by a maximum of 20%, given a range of suitable interventions, which will reduce L_1 to 80,000 kg and L_3 to 40,000 kg. Let's also assume that it is possible to reduce L_2 by a maximum of 50%, to 150,000 kg. We can now define a third solid, S_3, which contains all of the unachievable load reductions (Figure 5), and the space that is outside S_3 but inside S_2 contains achievable load reductions. For instance, L_2 = 200,000 kg lies within S_2 but outside of S_3 which, according to our definition, makes it achievable. We can check that this is true: L_2 = 200,000 kg corresponds to a reduction of 33% of 300,000 kg, and we have specified that reductions of up to 50% are indeed possible. On the other hand, L_2 = 100,000 kg lies outside S_3, and so it is not, according to our definition, achievable. Sure enough, this represents a reduction of 67%, which is greater than the maximum possible reduction of 50%.

We have now found the envelope of sediment load limits: it lies outside of S_3 and, at the same time, inside the intersection of S_1 and S_2. Here, load combinations will deliver the target deposited mass; load combinations are reductions compared to present-day loads; and load combinations are achievable by existing mitigation methods. It is important to note that it may not always be possible to find sediment load limits that will deliver any particular objective. For example, consider the case where the maximum possible reduction in L_2 is 20%, not 50%. This means the minimum possible value of L_2 is 240,000 kg, which lies outside of S_1. This in turn means that, even if L_1 and L_3 are both zero, the target deposited mass cannot be achieved.

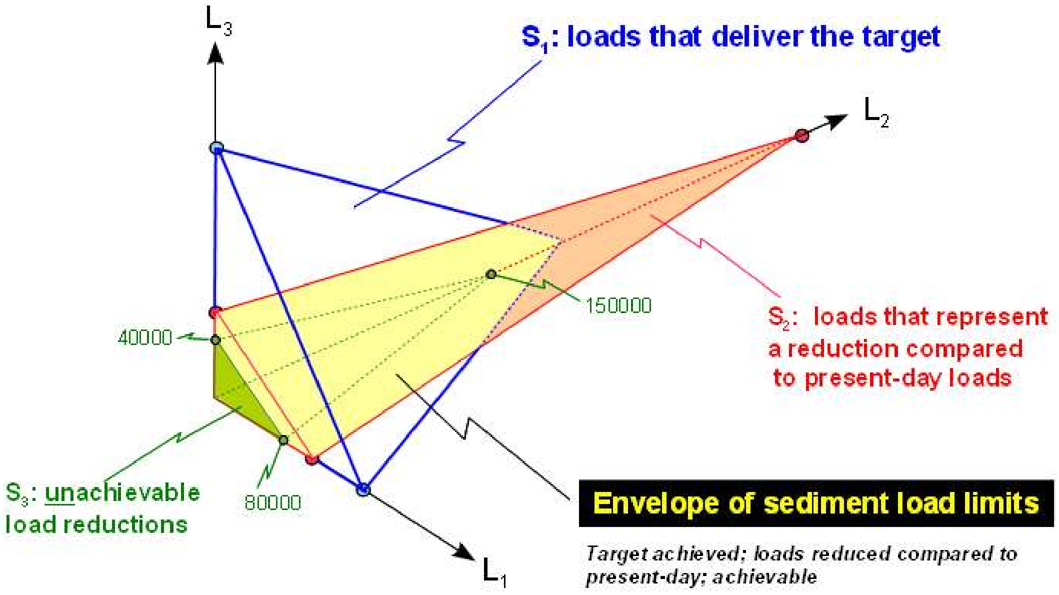

Figure 5. The space outside S_3 but inside S_2 contains all combinations of loads that are achievable by mitigation and that represent a reduction compared to present-day loads. The intersection of this space with S_1 is where we can find all sediment load combinations that deliver the target deposited mass, that are load reductions compared to present-day, and that are achievable. This is the envelope of sediment load limits.

Discussion

What does management do with the sediment load-limit envelope? Following the precedent being set in the central North Island lakes, management would focus on allocating load limits amongst all of the sediment-generating activities in the catchment, perhaps keeping some of the allocation in reserve for future planned projects (a greenfields housing development or a roading project, for instance), for the anticipated effects of climate change, and for legacy effects (for instance, sediment that is already in transit, having been eroded from the catchment but still being bound up in stream banks and beds). In this way, cumulative effects are to be kept in check.

At least two types of monitoring would be required to follow up implementation of any such scheme: firstly, monitoring of sediment runoff to confirm that allocations are not being exceeded; secondly, monitoring in the estuary to confirm that both the environmental limit (sedimentation rate) and objective (recreational shellfish harvesting) are being achieved on the back of the sediment load limits.

It is more correct to think about an envelope of sediment load limits – recognising that there is more than one way to achieve any given objective – rather than a sediment load limit. The analysis has revealed all of the ways that the objective at hand can be achieved. As we move around inside the envelope, changes in one or other source sediment loads are compensated for by changes in sediment loads from other sources such that the goal is still achieved. In other words, the envelope tells us exactly how to offset sediment loads from different source regions one against another while still achieving the desired environmental outcome.

Exploiting the load-limit envelope could greatly assist spatial planning on the land at the catchment scale. For instance, development in one part of a catchment may be offset by conservation in another part to achieve a particular outcome in the estuary at the base of the catchment, and landuse zones could be set accordingly. Or, it might be easier to achieve a higher level of mitigation in one part of a catchment compared to another, because of different opportunities or obstacles at the farm scale, for instance. Using the load-limit envelope to calculate offsets, the planner could design spatial patterns of mitigation requirements that take advantages of those opportunities and that recognise those obstacles, and that will add up as a whole to deliver desired environmental outcomes in the estuary receiving waters. This would almost certainly result in there being different rules governing mitigation in different parts of a catchment (for instance, one farmer being required to do more mitigation than his neighbour). This could result on the one hand in equity issues, and on the other hand in avoiding the inefficiency and ineffectiveness that is often associated with uniform application of rules. Either way, the principle here is to plan for the entire assemblage of activities in the catchment, taking account of the physical character of the catchment, the way the catchment is connected to the estuary receiving waters, landuse activities and mitigation opportunities.

The sediment load-limit envelope could also lay the foundation for a sediment trading scheme at the individual landowner scale of the type being used to manage nutrient issues in central North Island lakes. However, the sediment budgeting tools required to make a trading scheme workable at that small scale are some way off being available. In my view, consideration of the sediment load-limit envelope will primarily benefit planning at the catchment scale in ways that I have just touched upon.

Estuaries are typically much more complex than the simple example used above. To deal with at least one aspect of that complexity, a theory of sediment load limits has been developed that can account for any number of source regions connected by any pattern of transport pathways to any number of sinks (Green, in preparation). The results show that, in order not to fail any particular target, some capacity of the estuary to assimilate sediment has to be sacrificed. Estuaries are also typically heterogeneous, from the point of view of physical processes, the ecology that we might wish to sustain, and the human values that we attach to estuaries. Hence, it almost certainly will be desirable to set different values for the one type of environmental limit, designed to achieve different objectives, in different parts of a single estuary. To clarify that: we might want to achieve one sedimentation rate in one part of an estuary and another sedimentation rate elsewhere in the same estuary. This situation is dealt with explicitly in the theory of sediment load limits.

As we delve deeper, we can think of more complications. For instance, we may also want to set more than just the one type of environmental limit: a sedimentation rate and a water clarity, say. It is useful here to distinguish between related environmental limits, by which I mean limits that are governed by the same contaminant, and unrelated environmental limits, which are governed by different contaminants. For example, a sedimentation rate and water clarity would definitely be related (because the same contaminant – sediment – governs both), but water clarity and a shellfish pathogen count may not be. If the limits are unrelated, then that presents no special problem, as they can just be analysed separately. Another complication is that multiple stressors can interact in an ecological sense, meaning that the joint ecological effects of multiple stressors are larger (synergistic) or smaller (antagonistic) than the sum of the individual effects. Multiple stressors can also interact in a physical sense. For instance, heavy-metal concentrations are diluted by suspended particulate sediments in stormwater runoff, which reduces their toxicity when deposited in the harbour.

These situations may be amenable to analysis in some circumstances. (The theory of sediment load limits, for example, is extendable to multiple contaminant stressors such as sediments and heavy metals.) But we may also want to step back and ask ourselves at what point such complexity becomes unmanageable, and what we should do when that point is reached. Here, we might be able to exploit the notion of 'co-benefits', which means managing for a relatively simple environmental limit on the understanding that a host of related benefits – the co-benefits – will come along on the back of that one, relatively simple, environmental limit. For instance, the Ministry for the Environment (1994) notes, in the context of estuarine water clarity, that "protection of visual clarity will often protect other optical values and avoid regulatory and monitoring complexity".

I view the annual-average sedimentation rate as the key environmental limit that estuary limits-based management should focus on. Imposing catchment sediment load limits to achieve particular sedimentation rates should improve water clarity, reduce smothering of shellfish beds, improve seagrass health, and retard mangrove spread, simply because less sediment will be entering the estuary. There are other advantages to managing for sedimentation rate: sedimentation rates are simple to understand and to convey to pretty much any audience; sedimentation rates are relatively easily measured; and sedimentation rates can be related directly back to catchment sediment load limits (as I have shown in the example above). Furthermore, we know quite a bit about natural (pre-deforestation) estuarine sedimentation rates, which can provide a good context for setting target sedimentation rates. For example, a target sedimentation might be set as a small multiple of a known natural rate, with associated expectations for environmental outcomes.

Conclusions

Setting limits offers the best prospect for managing cumulative effects of contaminants in estuaries. There is not just one catchment sediment load limit that will deliver any given target sedimentation rate in the estuary receiving waters; instead there is an envelope of sediment load limits. Exploiting the load-limit envelope could benefit planning at the catchment scale in a number of ways, including landuse zoning and designing spatial patterns of mitigation requirements. With this kind of tool, we can also be thinking about how to simplify the real world in order to make it more manageable. For example, managing for annual-average sedimentation rates would deliver a range of co-benefits, is easily explained to different audiences, and is amenable to sophisticated analysis using the load-limit theory. We need to find this conjunction of analysis and simplification where we will be able to implement new limits-based management regimes for estuaries.

Acknowledgements

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