UNDERSTANDING THE ROLE OF SEDIMENT WAVES AND CHANNEL CONDITIONS OVER TIME AND SPACE[1]

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Abstract. *Dynamic equilibrium in stream channels has traditionally been applied on the reach scale, where fluxes of water and sediment into a reach result in rapid but minor adjustments of channel dimensions, hydraulics or roughness (equilibrium), or aggradation and degradation (disequilibrium). Such an essentially one-dimensional spatial approach to sediment-channel interactions implicitly avoids a long standing and difficult problem: how do large inputs of sediment travel through channel systems and thereby distribute the fluxes to which channels respond at any time scale?*

Not much is known about sediment waves because they are difficult to observe and model and have highly variable behaviors. Passage of sediment waves may or may not be marked by dynamic disequilibrium but, nevertheless, can have influences on aquatic and riparian ecosystems that should concern land managers. Rapidly propagating, high amplitude waves can cause measurable aggradation degradation and channel instability. Probably more often, however, waves disperse rapidly, translate slowly, and coalesce, and thereby inflict long-term widespread effects on channels and associated ecosystems. Such adjustments may go undetected or fall within the domain of dynamic equilibrium.

Key words: channel conditions, sediment movement, dynamic equilibrium

(Editor's note: This article was transcribed and edited from a tape of Dr. Lisle's oral presentation. Part of this talk was illustrated with slides as well as overhead figures and tables.)

INTRODUCTION

Many geomorphologists, including myself, are comfortable working with the reach scale of stream channels. At this scale, fluxes of water and sediment into a reach result in rapid but minor adjustments of channel dimensions, hydraulics or roughness (equilibrium), or aggadation and degradation (disequilibrium). Such an essentially one-dimensional spatial approach to sediment-channel interactions implicitly avoids a long-standing and difficult problem: how do large inputs of sediment travel through channel systems and thereby distribute the fluxes to which channels respond at any time scale?

If we expand our view of sediment in the reach to the watershed as a whole, we see that sediment often enters the channel in large pulses from landslides, fires, and other disturbances. These pulses are accentuated in both time and space in contrast to an increased supply of sediment in the watershed network as a whole. At some time, the sediment from these pulses is going to be transmitted via a sediment wave that translates and disperses. If in our reach we are concerned with fish habitats, the timing, severity, and duration the sediment impacts will all be determined by the nature of that wave.

One of the first people to describe sediment waves (in fact, his examples stand as premier examples to this day) is G. K Gilbert. He described the movement of hydraulic mining debris to the American and Sacramento Rivers. I take a quote from his 1917 paper that has set the example on how we think of sediment waves today:

> *The downstream movement of a great body of debris is analogous to the downstream movement of a great body of storm water, the apex of a flood traveling in the direction of the current.*

He basically is describing a wave that translates downstream and, in his analogy to a flood wave, he is implying there is also some degree of dispersion of this wave.

Today I'm going to try to talk about the nature of these waves and describe what influences their behavior. I will not be able to provide you practical tools for routing large sediment inputs downstream.

THE NATURE AND BEHAVIOR OF WAVES

Figure 1 is basically what Gilbert described as a translational wave. Over time, the wave translates downstream and disperses as it goes. If we look at the changes at any one point along the channel, we see bed elevations rising and falling. What do we know about the dimensions of such a wave: how fast it progresses downstream, the relative rates of translation and dispersion?

The rate of advance of the leading edge of the wave is a "no-brainer"; that is, sediment waves consist of particles of sediment moving downstream and so the rate of advance of a wave, the front of it, is basically determined by the average transport velocity of the particles in the wave.

Velocities of particles over riverbeds (table 1) is on the order of tens to thousands of meters per year. The wave fronts

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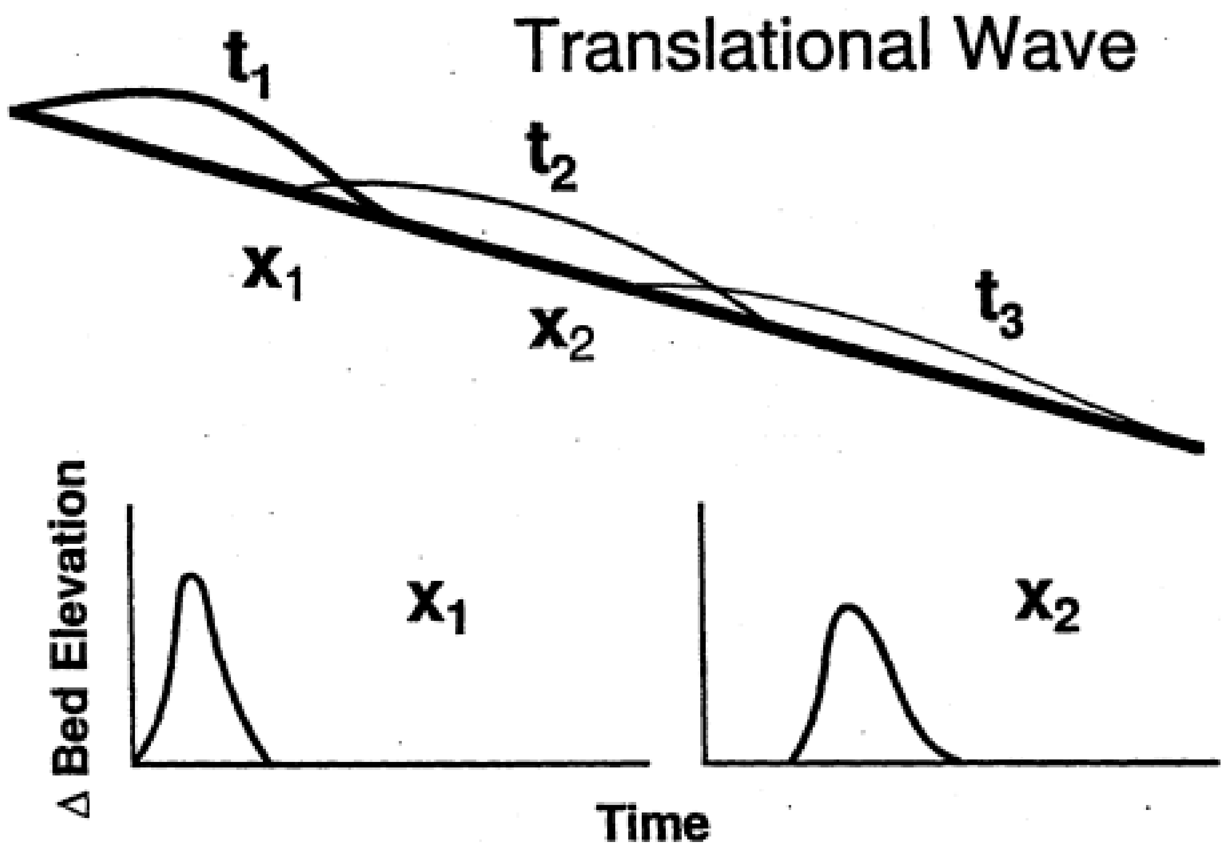

Figure 1. Translational wave, showing changes in the wave profile at times 1, 2, and 3, and variations in bed elevation with time a points X_1 and X_2 along the channel.

Table 1.
Characteristic velocities of bed particles and sediment waves.

CHARACTERISTIC BED PARTICLE VELOCITIES

	Distance traveled (m/yr)
From instantaneous velocities over periods of motion	10^5-10^6
Tagged particles	10^1-10^2
Gravel sheets (Duck & Muddy Cr)	10^2-10^3
Gravel dunes (Toutle R)	10^4
Migrating alternate bars (Rhine)	10^2
Aggradational fronts of sed. waves:	
Mountain Cr, BC	10^1
Madison R, MT	10^1-10^2
MF Yuba R, CA	10^2
East Fork R, WY	10^2
NF Stillaguamish R, WA	10^2-10^3
Sediment wave peaks:	
Yuba R, CA	10^3
Ringarooma & George R, Tasm.	10^2-10^3
Kawerong R, Papua-NG	10^2-10^3
Redwood Cr, CA	10^2-10^3
Matiri R, NZ	10^1-10^2
Feather R. CA	10^3

and peaks of waves travel at about the same rate. If we could predict the average rate of movement each year of sediment particles, we would have a pretty good idea of the rate of advancement of waves downstream.

The height of waves (i.e., the elevation above the former streambed elevation) and wavelength of a number of sediment waves have been described in the literature. As seen in figure 2, the basic message is that these waves are quite low for their length, with the amplitude on the order of 10^{-3} to 10^{-4} times the wavelength. The older, more erosive waves consisting of fine material tend to be longer and lower than the younger waves that consist of coarser material. Just like the garden variety, sediment slugs tend to lengthen as they progress downstream.

This observation brings up one of the fundamental questions I ran into when I first started searching for sediment waves: Where are they anyway? We see examples of large landslides, yet when you go to stream channels to look for the sediment waves that derive from these, they're very hard to find.

Waves in Theory

Let's take a theoretical example and see why this might be: take a channel that has a bankfull depth of 1 meter and a width of 30 meters. Now let's introduce a volume of sediment that is 10,000 cubic meters, which would be enough to fill the channel up to its banks over a reach of 300 meters. Now, let this initial sediment wave disperse until a commonly observed height/length ratio is achieved at about 1:1000. If we did this, the sediment wave would be spread out over a length of 3000 meters and its height would only be about 0.2 meters. I would challenge an experienced geomorphologist without prior elevation data to go to that channel and tell me where the start and end of that sediment wave is, and, in many cases, whether or not it even exists.

Because of the nonuniformity of the channels (i.e., the deeps, the bars, the shallows, the constrictions), we can expect a great deal of variation in the distribution of the added sediment over the stream channel. Nevertheless, it may have some important influences on habitat in terms of the amount of scour of the bed that might effect incubating ova, or filling of pools, or riparian vegetation. The waves may be difficult to find, and yet I still believe that they exist.

What is the relative rate of translation of these waves and the relative rate of dispersion? We gathered a team of people, including Hiroshi Ikeda of Japan, who has large research, facilities and is an expert in conducting experiments on rivers, Jim Pizzuto, a very good modeler, and me. We created an experimental channel that was 160 meters long and 1 meter wide. We introduced water and sediment, and recirculated the sediment through the system until we achieved equilibrium. Then we introduced a sediment wave 4 cm high and 20 m long and eagerly awaited its translation and dispersion downstream.

Since this experiment is not the subject of my talk, I want to cover this very briefly. The first step, after 45 minutes, revealed that the top of the wave has eroded and sediment has deposited upstream and downstream. This wave has induced some deposition upstream because of the decrease in flow created by the wave, which shows that sediment waves are not necessarily a group of the same particles moving downstream, but are a perturbation in sediment transport. We don't see much translation here. In fact, as we follow the time steps in evolution of this wave, we see that there is no translation of the wave; the wave sat there and eroded without translation. At first, this absence was disappointing but the finding sheds light on sediment waves in general: There are real sediment waves that are in fact stationary or could be stationary (figure 3).

Stationary Waves

Jim performed a sediment modeling exercise on this wave and discovered that the wave, in fact, should not disperse. Wave translation was dependent on a Froude number, that is; the ratio of velocity to the square root of depth times gravitational acceleration. If the Froude number is equal to 1, then the flow is near-critical and disturbances tend to remain stationary and are not translated downstream.

I would not like to contradict G. K. Gilbert, but this observation suggests the existence of stationary waves (i.e., waves where the highest apex of the wave remains. stationary and the wave is dispersed both downstream as well as upstream), although we may expect the center of mass of the wave to translate downstream. Just as in a translational wave, if we witness the change of the elevation at a couple of points along the channel, we then see a rise and fall in each place; in fact, the signals look somewhat similar. There seems to be translational waves that Gilbert and other people described, but we also have a stationary wave that is suggested by this experiment.

Translation and Dispersion Factors

The question now becomes: what factors promote wave translation, and what factors promote dispersion? Let's deal first with translation (table 2). If a Froude number of 1 induces or depresses translation, perhaps a Froude number of less than 1 (usually meaning channels with gradients less than 1%) would promote sediment waves to translate. Another influence that would cause a wave to translate is if the material that is introduced to the channel is finer than the preexisting bed material, so that the back of the wave could be eroded by virtue of the mobility of its material, so that the wave translates downstream. Lastly, we may have downstream sedimentation zones, which are areas where deposition is promoted by low slopes or woody debris. These places

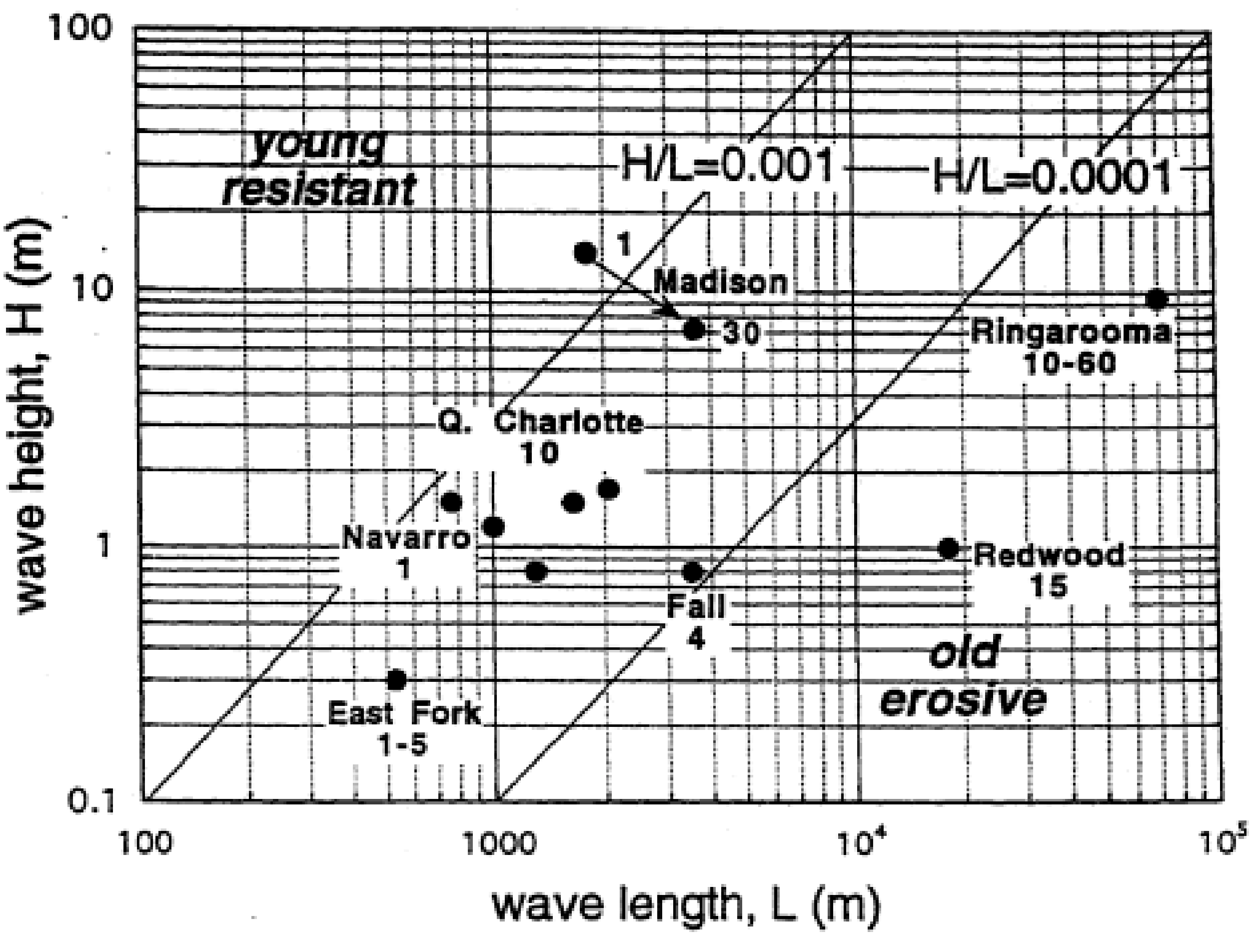

Figure 2. Relation between height and wavelength of sediment waves in natural channels.

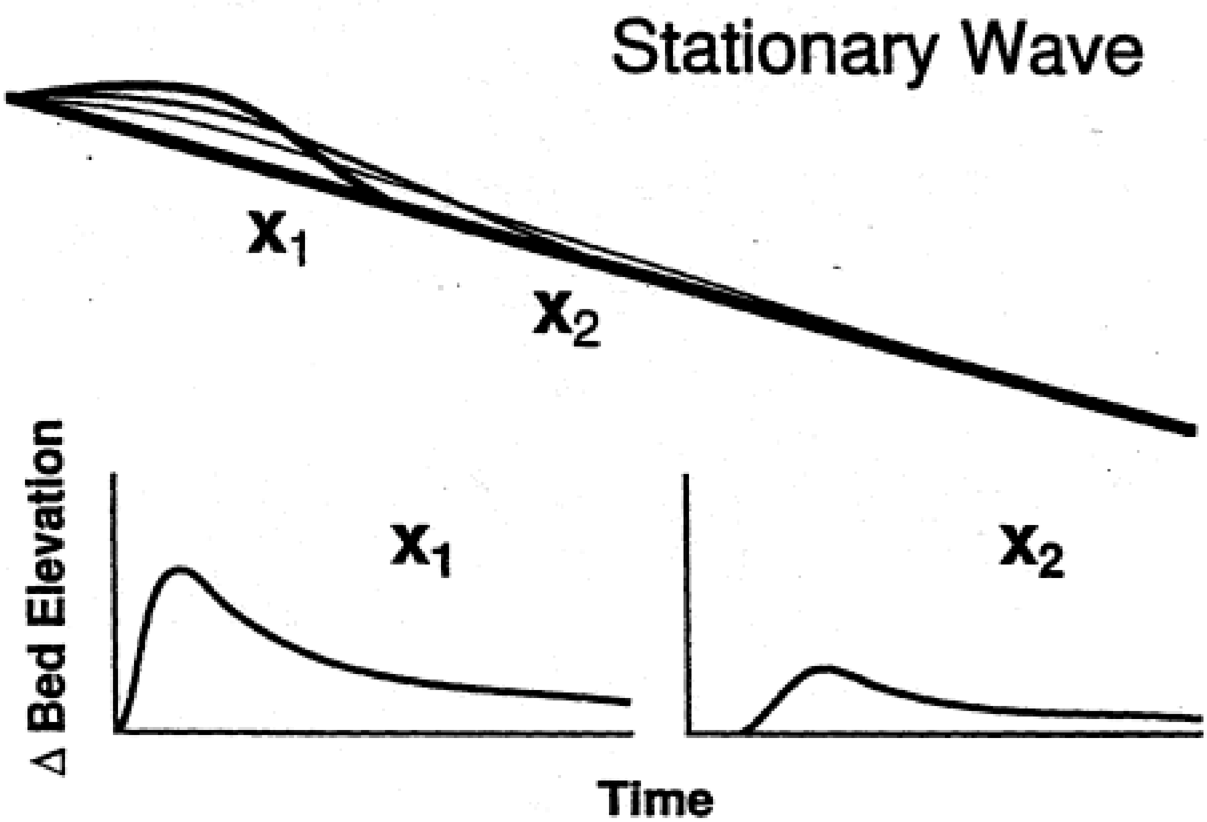

Figure 3. Stationary wave spreading downstream, showing variations in bed elevation with time at points X_1 and X_2 along the channel.

may fill deeply as sediment from a dispersing wave enters them and thus seem to record a translating wave (figure 4).

One of the factors promoting dispersion (table 2) would be supply-limited transport in the channel receiving the sediment input. Supply-limitation causes a strong pavement or armor to form (Dietrich et al., 1989). At the point where sediment is added, the increased supply could cause the bed surface to become finer, make the bed more mobile, and might enable the trailing edge of the wave to be moved downstream. Thus the wave would advance.

Sediment waves that are composed of fine material may both translate and disperse rapidly. In granitic terrain, we often have bimodal streambed material (i.e., the surface of the bed is dominated by cobbles and boulders, but the sub-surface is often sand and gravel). If you collect samples of bedload in these regions, very often it is dominated by these finer sizes. If the supply of the finer sizes is low, the fines tend to sit low in the interstices of larger particles which basically protect the fines from high flow velocities. But as you increase the supply of fine sediments, the fines begin to fill the interstices (figure 5). The bed becomes smoother, the forces exerted near the bed increase, and therefore, sediment transport rate increases.

If you can supply the channel with so much sand that it fills and covers the boulders, then you have a very extreme case of sand transport by virtue of the fact that the steep slope was predetermined not by fine material, but by larger material. It would be very difficult to fill the beds with fine sediment and cover the large particles. More likely, we would shave off any sort of sandy wave in a channel of this type, thus causing rapid dispersion, but the greater mobility of the fine sediment (whether or not it covers the armor layer) might enable it to be translated en masse downstream.

EXAMPLES OF SEDIMENT WAVE BEHAVIOR

I'll describe now a couple of my favorite examples of sediment waves.

Boise River, Idaho

One of them is in a channel like I just described: the North Fork of the Boise River, which is in granitic terrain within the Idaho Batholith. The North Fork experienced widespread and severe fires in 1994. In 1995, some ordinary thunderstorms triggered hundreds of debris flows, including some which blocked the North Fork and introduced large particles as well as an abundance of granitic sand and fine gravel. Upstream of the wave, the channel was ponded and you can see that there is lots of woody debris. Downstream we see an increase in very large particles and woody debris and more complexity of the channel. In fact, the channel below four of these debris flows in the North Fork created habitats that essentially were not there before these debris flows occurred. In these local areas, one can argue that the sediment waves were a benefit to the diversity of the channel. However, downstream there is a large increase of sediment in the fine gravel category, and we almost have a situation where the sand is covering some of the armor layer. At this time, there were high transport rates of sand during low flow. The following year the boulders and cobbles reappeared again and much of the sand that was flushed from the system still resided in eddies behind large obstructions and in pools. So, for very short periods, the sand quickly dispersed over some 20-30 miles of the North Fork downstream.

Navarro River, California

On the Navarro River in Mendocino County, a large slide dammed the river to form a pond upstream. Some of the introduced sediment was coarser than the pre-existing bed material, which promoted wave dispersion by selective transport of the finer sizes. Another factor that promotes dispersion of the wave is a breakdown of particles themselves. The Navarro slide material consisted of greywacke sandstone which quickly breaks down into fine sand and silt. As a result, the downstream leading edge of this sediment wave consists mainly of suspended sediment.

SUMMARY

In summary, what can we say about sediment waves in general? I think that if you look at the factors promoting translation of waves and the factors promoting dispersion of waves, we find that both types are common in natural rivers. Therefore, we can expect a variety in the behavior of sediment waves determined by river conditions and the nature of the material in the wave. You would expect upland channels which tend to have high Froude numbers and receive sediment inputs with wide ranging particle sizes to be dominated by stationary waves that shed finer particles because of selective transport and particle breakdown. However, we also may have translational waves that comes from some geological material that produces finer material that existed in the streambed At any rate, we can expect fairly rapid dispersion in either kinds of sediment waves so that downstream, these waves will be very dispersed. However they may be accentuated in sedimentation zones, low gradient reaches, and reaches where there are frequent logjams.

I cannot offer a practical guide to predicting movement of sediment downstream but I think this kind of analysis points out the value of regarding the sediment load of rivers as a series of sediment waves. Their behavior depends on the nature of the material introduced into the channel, and the nature of the channel itself. We need to pay attention to where we are relative to sediment sources and we need to pay attention not only to the volume of the sediment but the nature of the sediment: How quickly does it break down to other sizes? What is its particle size relative to the bed as a whole? Lastly, I would like to say that help is on the way,

Table 2.
Factors promoting translation and dispersion of sediment waves.

FACTORS PROMOTING SEDIMENT WAVE TRANSLATION

- Froude number <<1 (Channel gradient <0.01)
- Input sediment finer than pre-existing bed material
- Downstream sedimentation zones

FACTORS PROMOTING WAVE DISPERSION

- Supply-limited transport downstream
- $\frac{Q_s}{Q} = f\ (sediment\ supply)$
- Selective transport and abrasion

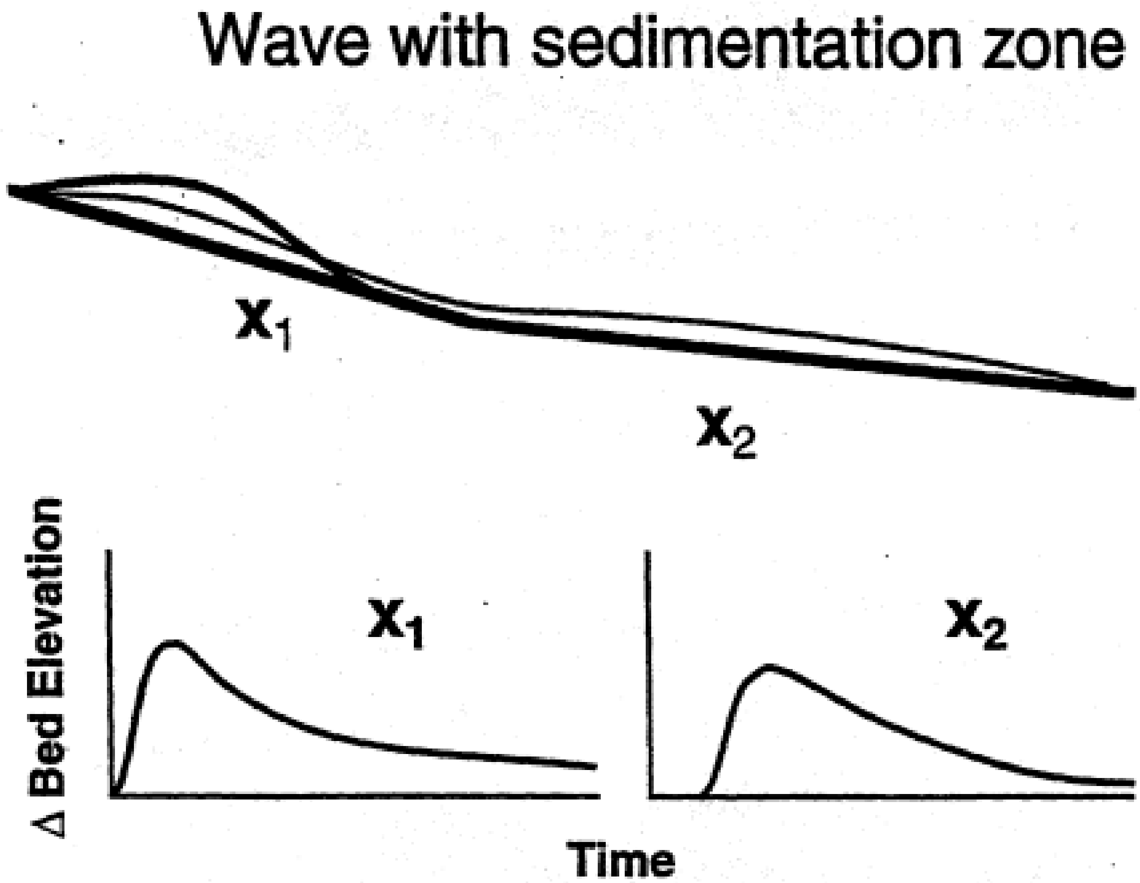

Figure 4. Stationary wave spreading downstream into a sedimentation zone, showing variations in bed elevation with time a points X_1 and X_2 along the channel.

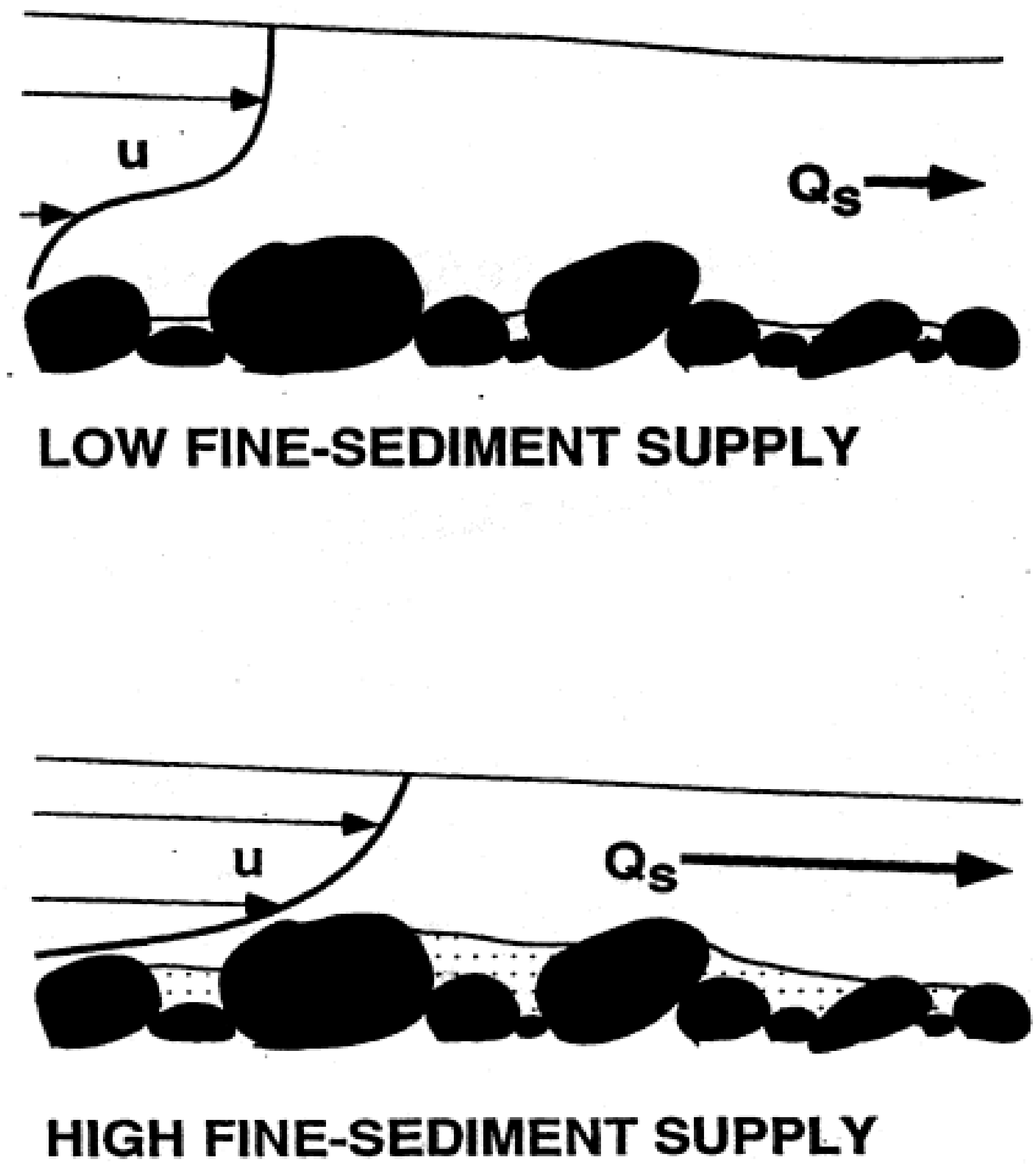

Figure 5. Longitudinal view of a river pavement filled with fine sediment under conditions of low and high sediment supply, and effects on the vertical distribution of flow velocity.

that there is renewed interest in looking at sediment waves and sediment routing.

REFERENCES

Dietrich, W. E., Kirchner, J. W., Ikeda, H., and F. Iseya. 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature*. 340:215-217.

Gilbert, G.K. 1917. *Hydraulic-mining debris in the Sierra Nevada.* U.S. Geological Survey Professional Paper no.105.

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In watershed management

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