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Geomorphic and environmental effects of instream gravel mining

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Abstract

Instream gravel mining involves the mechanical removal of gravel and sand directly from the active channel of rivers and streams. Active channel deposits are desirable as construction aggregate because they are typically durable (weak materials having been eliminated in river transport), well-sorted, and frequently located near markets or on transportation routes. Instream gravel mining commonly causes incision of the channel bed, which can propagate upstream and downstream for kilometers. As a result, bridges and other structures may be undermined, spawning gravels lost and alluvial water tables lowered. In analyzing the effects of instream gravel mining, a sediment budget analysis sheds light on the relative magnitude of gravel supply, transport and extraction. Computer models of sediment transport are simplifications of complex natural processes; they can be useful components of a sediment budget analysis but should not be relied upon alone. A historical analysis of channel change and sediment supply is needed to understand the underlying processes responsible for present conditions. While instream gravel mining can be a useful tool in flood control and river stabilization in aggrading rivers, most rivers in the developed world (certainly the vast majority below reservoirs) are not aggrading and are more prone to incision-related effects of instream gravel mining.

Introduction

Sand and gravel are used for a variety of construction activities including roads and highways (base material and asphalt), pipelines (bedding), septic systems (drain rock in leach fields) and concrete (aggregate mix) for highways and buildings. In many areas, aggregate is derived primarily from alluvial deposits, notably from active river channels, their floodplains, and older terrace deposits (Sandecki, 1989).

Instream gravel mining involves the physical removal of sand and gravel from riverbeds with heavy equipment, which directly alters channel geometry and bed elevation. Depending on the situation, extensive clearing, diversion of flow, stockpiling of sediment and excavation of deep pits may be involved. Active channel deposits are particularly desirable as aggregate because river transport eliminates weak materials by abrasion and attrition and the resulting deposits are of high quality: durable, rounded, well-sorted and relatively free of interstitial fine sediment. Consequently, this gravel requires less processing than gravel from other sources. Moreover, suitable channel deposits are often located near the markets for the product or on transportation routes, reducing transportation costs. In the gravel mining industry, the extraction and processing of the material itself has a relatively low cost, while product price doubles with each 40 km of transport (Randy Sater, Teichert Construction Company, personal communication, 1991).

The environmental costs of instream gravel

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extraction have generally not been factored into production costs, making instream sources more economically attractive than alternatives such as dry terrace mines (where additional processing is often required to remove fine sediment), quarries (from which rock must be crushed, washed and sorted) or distant sources, such as reservoir deltas (involving greater transportation costs).

Depending on the type and amount of mining, the physical effects of instream gravel mining may include improved flood control and channel stability in rapidly aggrading rivers. Instream mining also results in the destruction of aquatic and riparian habitat through large changes in channel morphology (Sandecki, 1989). Impacts described in the literature include: bed degradation; bed coarsening; lowered alluvial water tables; and channel instability (Sato, 1971, 1975; Bull and Scott, 1974; Anonymous, 1986; Peiry, 1987; Harvey and Schumm, 1987; Todd, 1989; Stevens et al., 1990). These physical impacts result in degradation of riparian and aquatic ecology and undermining of bridges and other structures.

The purpose of this paper is to summarize the geomorphic and environmental effects of instream gravel mining and to review approaches to environmental impact analyses. Instream mines are widely viewed as blemishes on the landscape, but the nature of their geomorphic effects are not widely appreciated. While those effects are manifest throughout the world, this paper draws largely upon data for California rivers. Regulation and management of instream gravel mining in California is reviewed by Kondolf (1994).

Types of mining in alluvial systems

The three types of instream gravel mining are dry-pit and wet-pit mining in the active channel and bar skimming. In-channel pit mining involves the excavation of a pit below the thalweg (lowest point in the stream cross section). Dry-pit refers to pits excavated on dry ephemeral stream beds with conventional bulldozers, scrapers and loaders. Wet-pit mining requires the use of a dragline or hydraulic excavator to extract gravel from below the water table level

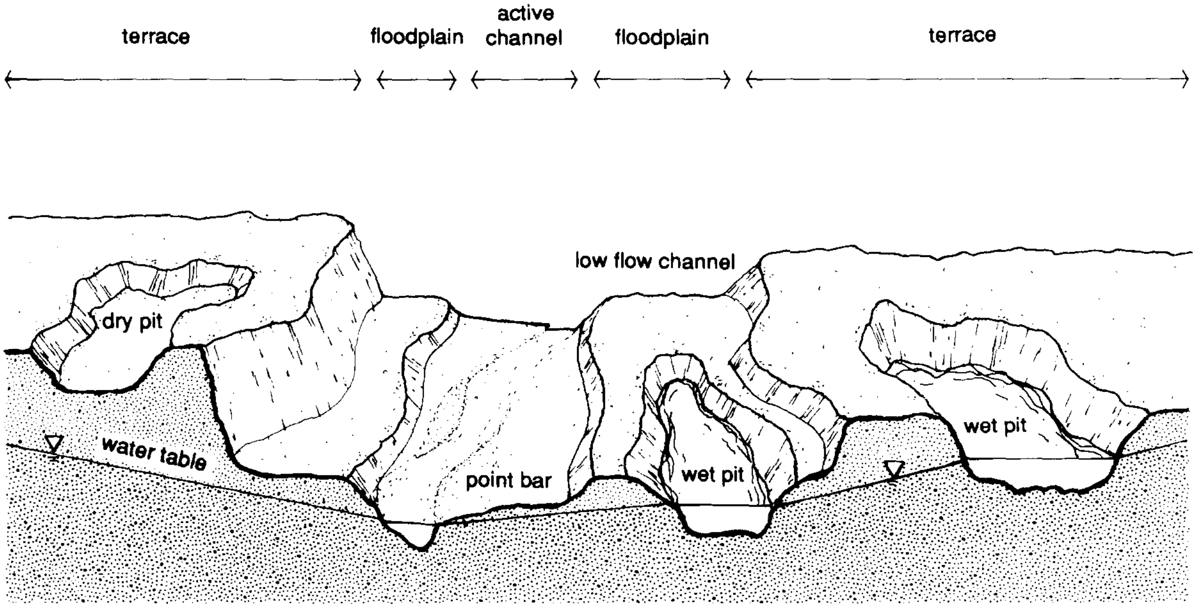

Fig. 1. Alluvial deposits exploited for aggregate depicted in relation to river channel morphology and alluvial water table.

or in a perennial stream itself. Bar skimming involves scraping off the top layer (of variable thickness) from a gravel bar without excavating below the summer water level.

Another important method of gravel mining is the excavation of pits on the current floodplain or adjacent river terraces (Fig. 1). These pits can be located above the water table (dry pits) or below (wet pits), depending on the elevation of the floodplain or terrace surface relative to the baseflow water elevation of the channel.

The effects of terrace and floodplain mining isolated from the active channel are beyond the scope of this paper, but this isolation may be short-term only. In many cases these pits are constructed adjacent to the active channel, separated only by a small levee. During a sudden shift in channel course during a flood (avulsion) or more gradual migration, the channel may shift into the gravel pits. During a major flood in 1971, the Yakima River breached levees and shifted its course to flow through gravel pits near Yakima, Washington (Dunne and Leopold, 1978). Capture of the river channel by gravel pits was observed at 12 of 25 floodplain gravel mines in northern Alaska studied by Woodward–Clyde Consultants (1980). Because floodplain pits can become part of the active channel, they should be considered as being potentially instream when viewed on a time scale of decades. In cases where large upstream reservoirs can completely control even large floods (such as the 100-year flood), floodplain mining could be considered geomorphically isolated from the active channel because the risk of avulsion is greatly reduced.

Effects of instream mining

The geomorphic effects of instream mining are best understood in the context of sediment transport throughout the entire river system. In general terms and on a large scale, many drainage basins can be broken into three zones: the rugged headwaters dominated by erosion and sediment production; a middle zone of sediment transport; and the downstream zone of deposition below sea level (or in lakes or internally drained basins above sea level) (Fig. 2) (Schumm, 1977). This scheme emphasizes the role of the river in moving material eroded from the continental uplands to depositional sites in the ocean. The river bed in the zone of transport acts like a conveyor belt, moving sediment and adding or subtracting sediment from temporary storage sites such as gravel bars, floodplains and terraces. This implies that rivers are dynamic in ways commonly not recognized. For example, the location and form of a gravel bar may be determined by constraints such as bedrock outcrops or other features that control the local reach hydraulics and thus induce deposition in the same site year after year. A gravel bar may be a persistent feature from year to year, but the actual gravel particles may be eroded and replaced every few years by new particles transported from upstream.

The transport of sediment through the river system is continuous on a geological time scale but episodic on a human time scale. Sediment transport occurs as a power function of discharge, so high flows transport proportionately greater sediment loads than moderate flows. On rivers with a wide range in discharge, as is the case for most California rivers, most sediment transport is accomplished by flows that occur a small percentage of the time. On an average basis, 97% of sediment transport on the Santa Clara River occurs in 1.2% of the time, or an average of about 4 days year^{-1} (Envicom, 1979). Moreover, because discharge is highly variable from year to year in California rivers, their sediment loads vary widely from year to year (Fig. 3). Thus, the sediment transport regime in these rivers can be likened to long periods of boredom interrupted by brief moments of terror. Average annual values of sediment transport are statistical artifices more than they are representative of any year.

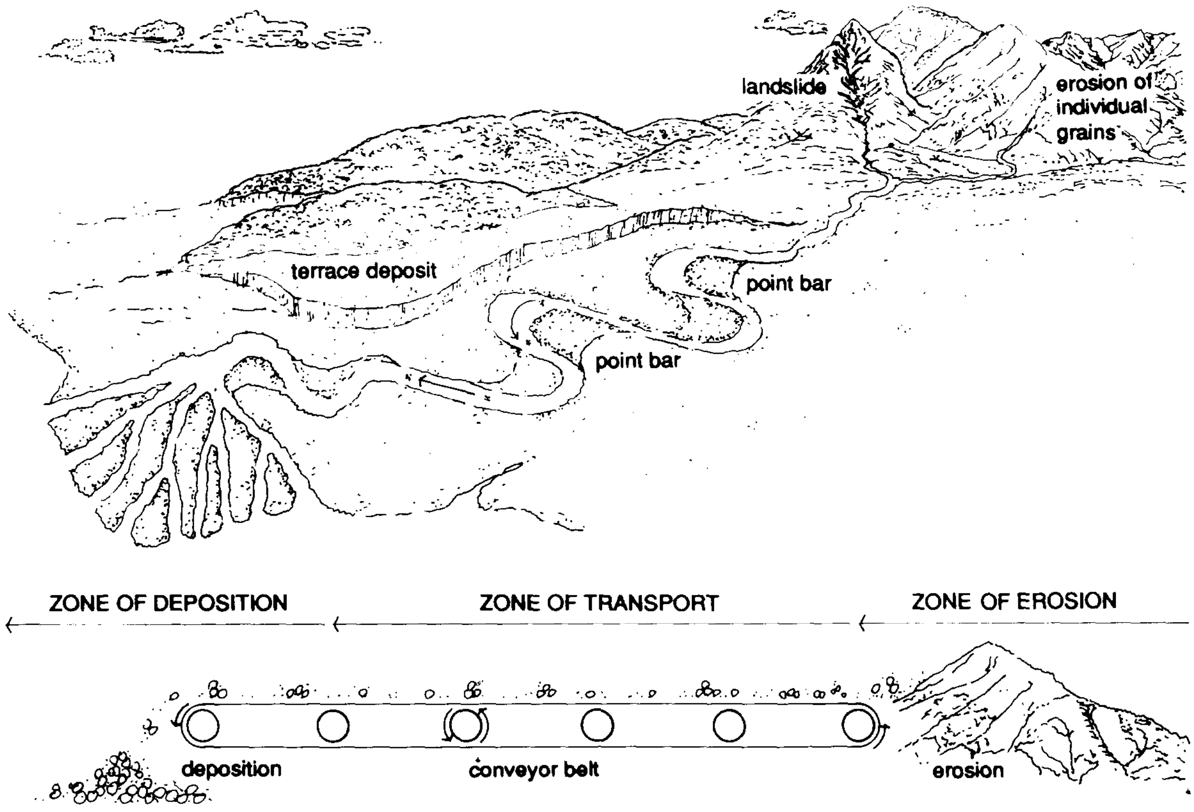

Fig. 2. Diagram of zones of sediment production, transport and deposition illustrating the conveyor belt analogy for the zone of transport.

One implication of this large inter-annual variability in discharge and sediment load is that a river may need to be monitored for years before sediment transport is observed. Because channel adjustments to changes in sediment supply (natural or human-induced) involve sediment transport, many of these adjustments may not take place until significant sediment transport occurs, which could be years after the event to which the channel is responding.

Incision produced by instream mining

The rate of bedload transport depends on the supply of coarse sediment from the watershed and the transporting power of the river, resulting in transport rates that vary over space and time. The size and shape of the stream channel reflects its prevailing flow and sediment load (Leopold et al., 1964). If the bedload transport rate is altered, the river channel adjusts to the changed conditions. By removing sediment from this continuum, instream gravel mining disrupts the existing balance between sediment supply and transporting power.

The most dramatic effects of instream mining occur when pits are excavated in the active channel. The equilibrium profile of the streambed is altered and the channel must adjust to the locally steeper gradient upon entering the pit (Fig. 4). This steeper gradient produces increased stream power and results in bed erosion. This process is known as headcutting or knickpoint migration, and the effects may translate upstream for kilometers (Scott, 1973; Stevens et al., 1990). Incision can proceed up tributaries when instream mining low-

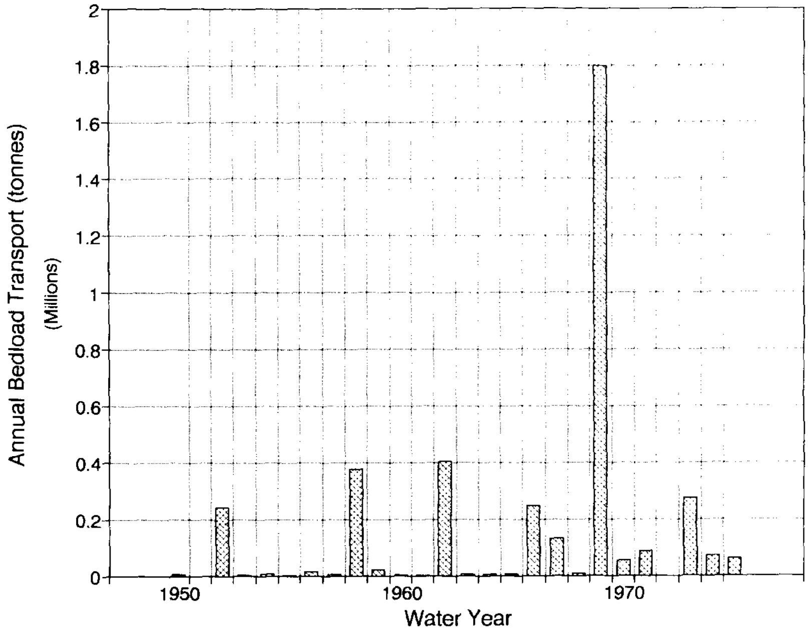

Fig. 3. Computed annual rates of bedload transport in the Santa Clara River at Montalvo, California, for the period 1950–1975. (Data from Brownlie and Taylor, 1981.)

ers the bed of the mainstem, thereby lowering the base level for the tributary (Harvey and Schumm, 1987). Continued extraction may also cause the entire streambed to degrade to the depth of excavation. In severe cases, the degradation will continue until bedrock or older substrates under the recent alluvium are uncovered. In many gravel bed rivers, the stream bed becomes armored, limiting further incision (Dietrich et al., 1989). A dramatic example of knickpoint migration upstream of a gravel pit was documented by Scott (1973) on Tujunga Wash near Los Angeles. During the flood of February 1969, a gravel pit captured first one, then both threads of the active channel, initiating a knickpoint that migrated upstream, ultimately causing a bridge to fail from undermining (Fig. 5).

Pit excavation will also induce incision downstream. Because much of the incoming sediment load will be trapped in the pit, water deprived of its sediment load will exit the downstream end of the pit. The bedload-free 'hungry water' has excess energy and typically erodes its bed and banks to regain at least part of its sediment load (Fig. 4).

Direct effects of incision include undermining of bridge piers and other structures and exposure of buried pipeline crossings and water supply facilities. Incision can also induce channel instability, triggering bank erosion and channel migration in formerly stable reaches. This channel instability can result in widespread loss of riparian vegetation, resulting in direct loss of wildlife habitat, loss of shade and cover to the channel, and other indirect ecological impacts. Channel incision may induce a decline in the alluvial water table, since the banks are effectively drained to a lowered level, potentially affecting riparian vegetation and water supply wells. The Lake County, California, Planning Department (Lake County, 1992) estimated that the range of potential reduction in alluvial aquifer storage from incision in small river valleys with instream mining was 1–16%, varying according to local geology and aquifer geometry. Lowering water tables has also been documented along the

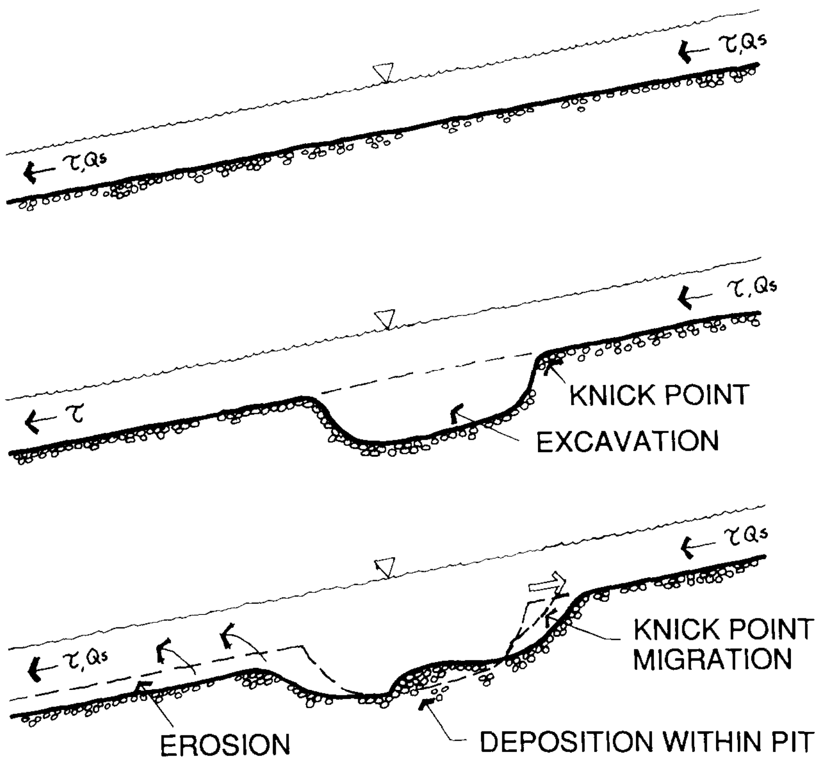

Fig. 4. Incision produced by instream gravel mining. (a) The initial, pre-extraction condition, in which the river's sediment load (Qs) and the force available to transport sediment, the shear stress (τ), are continuous through the reach. (b) The excavation creates a knickpoint on its upstream end and traps sediment, interrupting the transport of sediment through the reach. Downstream, the river still has the capacity to transport sediment (τ) but has no sediment load. (c) The knickpoint migrates upstream and hungry water erodes the bed downstream, causing incision upstream and downstream.

Russian River (Sonoma County, 1992).

Among the best known examples of channel incision resulting from instream gravel extraction is the Russian River near Healdsburg, where extensive wet pit mining in the active channel in the 1950s and 1960s caused channel incision in excess of 3 m over an 11 km length of river, with a maximum incision of 6 m. As a result, the form of the river has been changed from a wide, braided channel to a deeply incised channel with a straighter course. By the mid-1960s, channel pit mining was abandoned and replaced by bar skimming and floodplain pits (Collins and Dunne, 1990). Most of these floodplain pits are located adjacent to the active channel. Levees designed to prevent the river from capturing the pits have thus far prevented the river from migrating naturally across its floodplain and maintaining the diversity of successional stages associated with an actively migrating river (Sonoma County, 1992). However, these levees have finite strength and may fail during a sufficiently large flood.

Another well known case is Cache Creek, in Yolo County, a source of over 80 million tonnes of aggregate from 1905 to 1983. Channel incision of up to 8 m has been documented by changes in the stage–discharge relation at a USGS gaging station and repeat surveys of longitudinal profiles and bridge cross sections (Woodward–Clyde Consultants, 1976). The future management of this reach remains highly controversial and was the subject of a

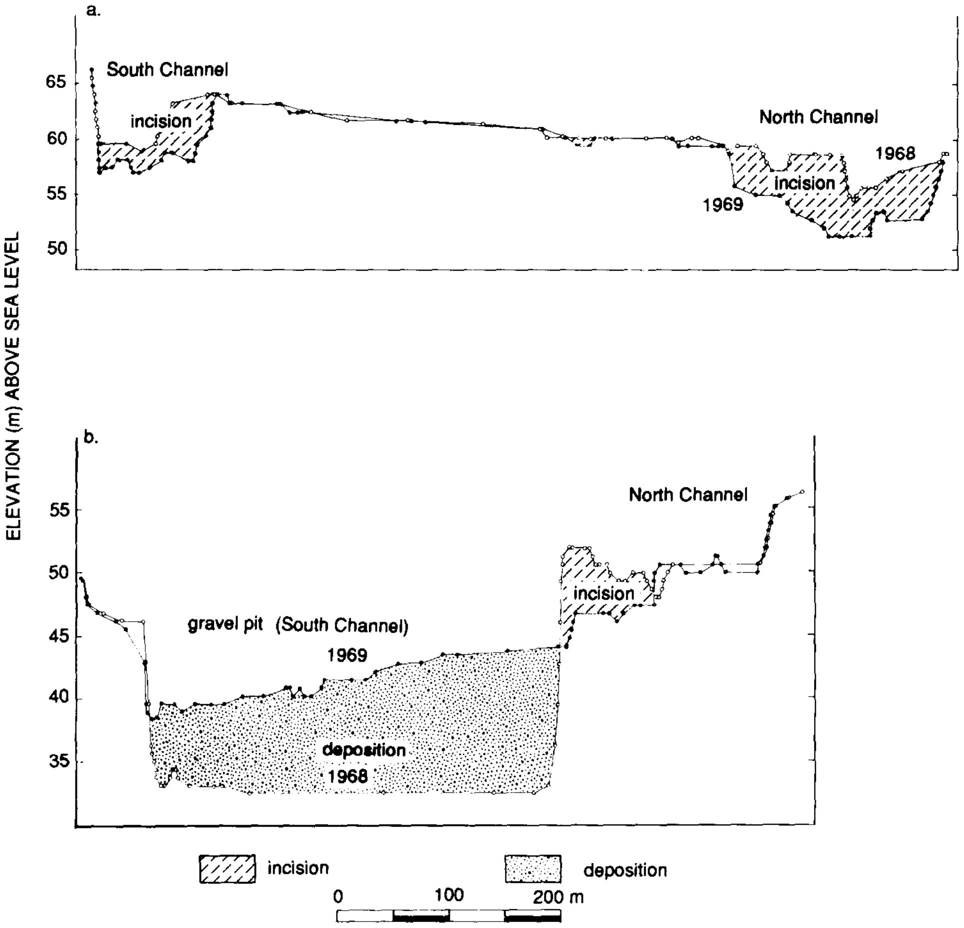

Fig. 5. Channel cross sections of Tujunga Wash in southern California in June 1968 and March 1969, showing changes produced by the flood of February 1969, when both threads of the channel were captured by a gravel pit. (a) Cross section 50 m upstream of the Foothill Boulevard Bridge, showing incision of up to 4 m in the thalweg. (b) Cross section 500 m downstream of the Foothill Boulevard Bridge, showing filling of the gravel pit after capture of the south and north channel. (Adapted from Scott, 1973.)

recent Environmental Impact Report (EIR) and protracted public hearings (Dames and Moore, 1991). The incision of Cache Creek has probably played some role in the loss of alluvial groundwater storage potential, but overdraft is a confounding factor (Yates, 1989).

It may be difficult to distinguish the role of instream mining in causing the incision of a specific channel because of other factors (such as adjustments to reservoir construction) operating simultaneously in the channel. However, temporal and spatial patterns of incision may permit reservoir effects to be distinguished from instream mining effects, as illustrated on Stony Creek (Kondolf and Swanson, 1993). Moreover, in many California rivers, the role of instream mining is apparent because the volumes extracted vastly exceed the rate of supply, commonly by an order of magnitude.

Incision below bridges

The California Department of Transportation (Caltrans) has compiled a partial list of

Fig. 6. Undermining of the Highway 32 bridge over Stony Creek, near Orland, California. The channel incised 5 m, necessitating repairs costing over US $1.5 million. (Photograph by the author, May 1990.)

bridges identified as potentially threatened by incision related to nearby instream mining. Review of sequential bed profiles under many of these bridges (from soundings or surveys recorded in Caltrans bridge files) and compilation of data from more thorough studies, suggest that incision is a serious problem statewide, deserving of systematic study (Kondolf and Matthews, 1993).

Studies of the causes of incision under bridges must account for local scour caused by hydraulic adjustment to bridge piers, which typically occurs within a few years of construction, until the bed stabilizes. The spatial and temporal relation of incision to mining and other potential causal factors may provide the best evidence for cause and effect. At many bridges, after an initial adjustment to bridge piers, the bed remained stable until commencement of instream mining.

The costs of repairing structures undermined by incision from gravel mining, such as pipelines, canal crossings and highway bridges, have not been systematically compiled. A partial inventory of repair costs for state highway bridges through 1984 attributed by Caltrans staff to instream extraction indicated costs of over $6 million. However, this figure was hastily compiled to provide background information for legislation; with further research, the figure for costs through 1984 would probably double (R. Hackett, Caltrans Division of Structures, unpublished memo, 1984). Intensive extraction on the Santa Clara River in Ventura County resulted in failure of the California Highway 118 bridge during the 1969 flood, resulting in repairs costing $730, 000 (in 1969 dollars). The California Highway 67 bridge over the San Diego River was completely replaced in 1981 (at a cost of $3.3 million) as a result of extraction-related undermining. Incision on Stony Creek has necessitated bridge repairs costing in excess of $1.5 million (Fig. 6) (Kondolf and Swanson, 1993).

Bed coarsening

Instream mining has selectively removed gravels suitably sized for salmonid (salmon and trout) spawning from many rivers. Direct removal of gravel and sand by mining, as well as winnowing of gravels and sands from an incising bed, can result in armoring, the development of a lag deposit of cobbles and boulders on the bed. However, bed coarsening from instream mining is commonly difficult to document because grain sizes for initial conditions were not documented for most rivers. Bed coarsening is of particular concern on rivers supporting salmonids because these fish require freshwater fluvial gravels for spawning (Allen, 1969). The maximum size of gravel movable by the spawning fish is a function of fish size, with fish being able to move gravels with a median size up to about 10% of their body length (Kondolf and Wolman, 1993). If smaller gravels are transported from the reach, the remaining lag gravels may be too coarse to be used for spawning by the species present.

One of the best documented examples of bed coarsening is the Upper Sacramento River, in which the impacts of upstream dam construction were compounded by intensive in-channel extraction (for construction of the dam) and subsequent intensive extraction from tributaries (Parfitt and Buer, 1980). Construction of Shasta Dam (completed in 1944) required 5.4 million m^3 of aggregate, which was derived from two large gravel bars in the Sacramento River downstream of the dam site. The entirety of one bar was excavated, locally to a depth of 15 m (Parfitt and Buer, 1980). The gravel remaining in the channel after this massive removal was subsequently transported downstream by clearwater releases from the dam, leaving only a lag of cobbles, boulders and bedrock in the reach near Redding.

With continued urbanization of the northern Sacramento Valley, extensive gravel extraction occurred in tributary channels. On Clear Creek, the combination of intensive mining and subsequent flood flows has resulted in a channel scoured to bedrock in many places and armored with coarse material elsewhere (Parfitt and Buer, 1980). Bed coarsening on these tributaries has eliminated potential spawning grounds in the tributaries themselves and has greatly reduced the remaining gravel supply to the mainstem Sacramento River below Shasta Dam. These tributary effects have contributed to coarsening on the mainstem.

The California Department of Fish and Game and Department of Water Resources has invested in artificial replenishment of spawning gravel in the Upper Sacramento since 1979. By the year 2000, nearly 800 000 m^3 of gravel will have been emplaced in the mainstem and in artificial side channels, at a total cost of over $22 million (Kondolf and Matthews, 1993). Despite these efforts, few would argue that the natural spawning potential of the reach has been restored. Gravels emplaced in the mainstem are subject to scour and loss during high flows, so efforts are now concentrated on construction of side channels with favorable spawning conditions. Ironically, the gravel used in these emplacement projects is typically derived from floodplain or instream mines on tributaries to the Sacramento River.

An example of bed coarsening at a smaller scale is San Simeon Creek in San Luis Obispo County, where bar skimming over a 30 year period has resulted in development of a coarse cobble lag and incision to hardpan over a reach of about 1 km upstream of the extraction (Matthews and Associates, 1991).

Effects of gravel bar skimming

Gravel bar skimming withdraws sediment from the transport system and thus alters supply to downstream reaches, but the volumes removed are typically smaller than those removed for pit mining. Even when rates are small relative to gravel supply, bar skimming can have a profound impact on aquatic habitat by creating a wide flat cross section, eliminating confinement of the low flow channel and resulting in a thin sheet of water at baseflow. Skimming also removes the pavement, the coarse surface layer than occurs on many natural river beds and appears to regulate rates of bedload transport (Parker and Klingeman, 1982; Parker et al., 1982). Pavement removal exposes finer subsurface material to entrainment at low flows (Anonymous, 1986); this fine sediment may be transported downstream to be deposited in gravels and in pools; a coarse cobble lag deposit unusable by spawning fish may remain (Matthews and Associates, 1991).

Channel instability

Channel instability resulting from instream gravel mining may result from disruption of pre-existing channel geometry (Collins and Dunne, 1990). Blackwood Creek, a tributary to Lake Tahoe, was diverted in 1960 through a straight artificial channel to permit extraction of gravel from abandoned meander bends. The consequent channel shortening resulted in incision, breaching of the levees separating the diversion channel from the gravel extraction area, and capture of the channel by the gravel pits. Incision propagated upstream and downstream, caused bank undercutting and erosion, resulting in a four-fold increase in the sediment load of Blackwood Creek (Todd, 1989). Channel incision may cause channel widening from undercutting of banks, as documented upstream of a gravel pit in San Juan Creek, California (Chang, 1987). Stony Creek also experienced channel instability at the Highway 32 Bridge, as the incised channel migrated laterally towards bridge abutments (Kondolf and Swanson, 1993).

Destabilization of spawning gravel deposits by instream mining has become an issue of concern in Washington State. As incision caused by instream mining propagates upstream and downstream, it results in mobilization of gravels (and thus destruction of incubating embryos) in deposits that would otherwise be stable (Bates, 1987).

Other impacts of instream gravel mining

Operation of heavy equipment in the channel bed can produce increased turbidity and suspended sediment for kilometers downstream, reducing populations of benthic invertebrates (or causing changes in their composition) and shifting fish populations to species tolerant of high suspended sediment concentrations (Forshage and Carter, 1973). Instream gravel mining commonly results in loss of riparian habitat, by directly removing riparian vegetation which results in disturbances that can lead to invasion by exotic species. Gravel processing plants and stockpiles are typically located on floodplains adjacent to extraction sites, potentially displacing large areas of former riparian habitat. Moreover, the noise and truck traffic of a heavy industrial operation could be expected to discourage wildlife use of the riparian zone.

By selectively removing gravel-sized fractions, instream gravel mining has resulted in reductions in bed material size in portions of the Lower Mississippi River (Lagasse et al., 1980), with probable impacts on benthic invertebrates requiring gravel substrates. Instream gravel pits in the Naugatuck River, Connecticut, have created over-widened reaches in which water is virtually stagnant at low flows, with low levels of dissolved oxygen; because rates of bedload transport in this river are low, the pits are expected to persist for centuries (MacDonald, 1988).

Analyzing effects of instream gravel mining

Sediment budget analysis

A sediment budget is an accounting of sediment sources, rates of sediment flux through the system, losses to or gains from temporary sediment storage reservoirs (such as gravel bars or floodplains) and losses by export from the basin (Dietrich and Dunne, 1978). The basic sediment budget equation is

$$I \pm \Delta S = O$$

where I is inputs, ΔS is change in storage and O is output. For a given system, various components may be classified under input, storage and output, depending upon how the system is defined.

Sources of information on rates of erosion and sediment yield are reviewed by Collins and Dunne (1990). It is particularly important that historical changes in channel configuration and rates of sediment supply be documented so that current processes are understood in context, as discussed below. A sediment budget can typically indicate whether extraction rates approach or exceed annual bedload transport rates through the extraction reach. Collins and Dunne (1989) developed sediment budgets for three rivers on the Olympic Peninsula of Washington and found that extraction rates exceeded replenishment rates by more than tenfold. The difference between supply and extraction could be accounted for by incision of about 0.03 m year^{-1} (Collins and Dunne, 1989).

Kondolf and Swanson (1993) developed a sediment budget for Stony Creek from Black Butte Dam to its confluence with the Sacramento River near Hamilton City (Fig. 7). Stony Creek is a particularly good case study because of the high natural bedload sediment yield, the magnitude of impacts of dam construction and instream mining, and the fact that the study reach (downstream of Black Butte Dam) traverses an alluvial fan so that there are no tributaries to complicate the picture. Prior to closure of Black Butte Dam in 1963, an annual average of about 100 000 m^3 of gravel was transported from the drainage basin to the study reach. Since closure of the dam, the reach below the dam has incised and laterally migrated, cannibalizing its earlier deposits and regaining through bank erosion about 20% of its pre-dam sediment load. Using extraction volumes reported by the opera-

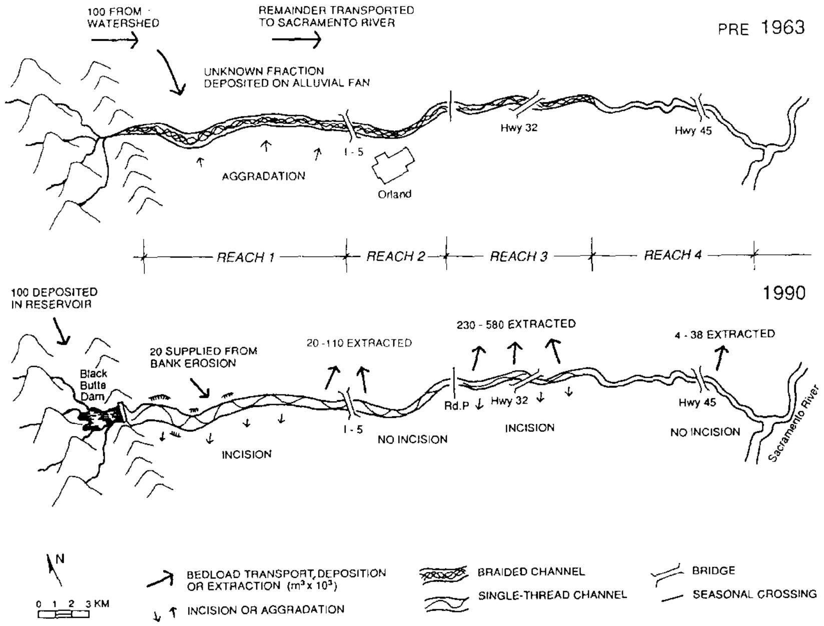

Fig. 7. Sediment budget for Lower Stony Creek, showing situation prior to construction of Black Butte Dam in 1963 (top) and in 1990 (bottom). All values of gravel flux are in $m^3 \times 10^3$. (From Kondolf and Swanson, 1993; permission from Springer Verlag.)

tors, an estimated 260 000–730 000 m^3 is removed annually along the entire length of Stony Creek, of which about 80–90% is concentrated in a 5 km reach centered on the Highway 32 bridge. As a result of the intense mining upstream and downstream of the Highway 32 bridge, the channel degraded up to 5 m between 1974 and 1990 under the bridge (Kondolf and Swanson, 1993).

Complexity of natural sediment transport processes

The processes of bedload sediment transport in streams are still poorly understood. This is due, in large part, to limitations on direct observations and measurements of bedload sediment transport, at least during periods of greatest sediment transport. As a result, there is still basic disagreement about processes of sediment transport in gravel-bed channels. The rate of sediment transport is a function of both the transporting energy available and the sediment volume and grain size. However, bedload transport is conventionally predicted as a function of the transporting energy (flow) only, without changes in supply taken into account. Standard procedures rely on development of a sediment rating curve, a best-fit line through often widely scattered data to predict the dependent variable (sediment transport) from the independent variable (flow) (Fig. 8). Total annual sediment transport is computed by applying the sediment rating curve to the annual hydrograph. The inherent imprecision of this 'rating curve' approach to computation of total suspended sediment transport has been discussed by Walling (1977). Glysson (1987) documented errors from 0% to 1760% using this approach.

One reason why sediment transport is so difficult to understand is the tremendous spatial and temporal variability in the processes of sediment production from the watershed, sediment delivery to the channel, transportation within the channel, and deposition in and along the channel. In gravel-bed rivers, the nature of bedload transport changes with increasing flow when the force per unit area applied to the bed (the bed shear stress) becomes sufficient to disrupt the coarse surface layer (the pavement), liberating finer grained particles from below. As a result, the rate of bedload transport at a given flow may be greater on the recession limb of a flood hydrograph than the rising limb. On the rising limb, the pavement is not disrupted and thus it 'protects' the underlying fine-grained sediment. When the river drops back to the same flow on the recession limb, the pavement is not yet reformed, resulting in greater sediment transport.

In addition, the supply of sediment available for transport may change over the course of a flood (as fresh landslides or bank erosion contribute new material to the channel) or over a period of years. On the Carmel River, for example, massive bank erosion in 1980, 1982 and 1983 delivered large quantities of sediment to the channel. Since then, a number of bank stabilization projects have been undertaken and sediment input from this source (the largest source term in the sediment budget) has been reduced. Sediment transport measurements in 1992 show that the rate of sediment transport at low flows has decreased from values measured in 1982 and 1983 (Fig. 8).

Even when the sediment supply and flow can be considered to be steady, large variations in bedload transport over time have been observed (Carey, 1985; Pitlick, 1988). On sand-bedded streams, variations in transport rate are associated with the passage of dunes and related bedforms. Similarly, large-scale bedforms known as 'gravel waves' (about 1 m high and 1 km long) have been observed on the Waimakariri River near Christchurch, New Zealand, moving downstream at about 1 km $year^{-1}$ (Griffiths, 1979). Bedload transport rates also vary substantially across the channel, with transport concentrated in zones. If these zones migrate across the channel, bedload transport rate at a point will vary.

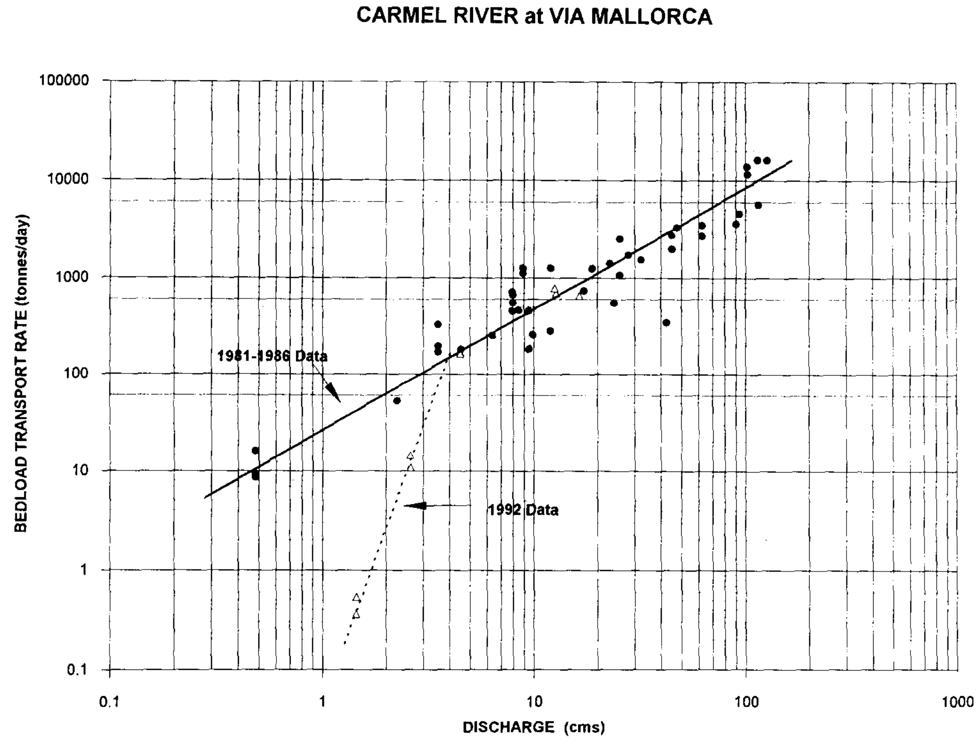

Fig. 8. Bedload rating curve for the Carmel River near Carmel. (Adapted from Matthews and Kondolf, 1993.)

Limitations and use of sediment transport models

Sediment transport models can be useful tools in analysis of river systems, but it is unrealistic to treat model predictions as anything more than attempts to represent, in a very simplified fashion, an exceedingly complex natural system which is still poorly understood. For their input values, sediment transport models must simplify river channel geometry and bed material size. For computation of sediment transport, the models must simulate flows in the river and use one of many conflicting sediment transport equations. Given the above, the results of a state-of-the-art sediment transport model are simply not good enough to accept without sufficient observations of rivers in the region to verify the general nature of the results.

Existing equations to predict sediment transport were developed using imperfect field data (or laboratory data that may not reflect field conditions). The equations are unlikely to be better than the measurements on which they were based. The American Society of Civil Engineers compared numerous sediment transport equations with each other and with field data and concluded "... it is clear that sediment discharge formulas, at best, can be expected to give only estimates," and recommended that "... the selection of a formula ... be based on checking calculated sediment discharge against any observed values of the stream under consideration or on similar ones. Finally, after reasonable checks have been made one can then make some kind of judgement of the reliability of the calculations that should be kept in mind in using them in the planning works." (Vanoni, 1977.)

The National Research Council tested six sediment transport models, including HEC-6 and FLUVIAL-11, and concluded that use of existing models "... cannot be justified in flood insurance studies" because of unreliable formulation of the sediment discharge capacity of flows and the variable friction factor, and inadequate understanding and formulation of coarsening and the mechanics of bank erosion (National Research Council, 1983). Any sediment transport model is only a simplification and generalization of complex field conditions. In this process of simplification, information essential to prediction of sediment transport in field situations may be lost.

Sediment transport models have their greatest value when used to model the effects of proposed alternative management strategies or other changes in controlling variables. For example, Li and Simons (1979) modelled changes in bed elevation in San Juan Creek near San Juan Capistrano, California, under four alternatives. Given the uncertainty in sediment transport modelling, all such models should be calibrated with surveys of actual channel change over floods and, where possible, with sediment transport measurements collected over a range of flows. The inherent difficulty in modeling these river processes should be borne in mind when interpreting the results.

Uncertainty in geomorphic and sediment transport predictions

Uncertainty is inevitable in the study of channel change and sediment transport owing to: (1) numerous independent watershed variables (e.g. precipitation, rock type, land use) that combine in many different ways to produce different flow and sediment regimes; and (2) numerous dependent channel variables (e.g. width, depth, bedforms, sediment transport) that adjust in many different combinations to any given regime (the "indeterminate hydraulics" described by Maddock, 1970). Given the impossibility of exact prediction from science and engineering, geomorphic understanding assumes increasing importance. Although computer models are limited, there is often much historical evidence available to provide insights into the response of a river to particular types of events.

Historical channel studies

Given the complexity of natural sediment transport, the indeterminate nature of channel hydraulics, the inability of simplified models to predict river behavior adequately and the variety of human influences upon river systems, the best guide to a river's future behavior is often gleaned from analysis of its past behavior. Moreover, a historical perspective is essential for placing the present condition in context. In California, large infrequent floods may reshape the channel, stripping the riparian zone of vegetation, transporting boulders, and eroding or depositing large quantities of sediment. The catastrophic channel changes occur suddenly, but recovery may take decades. A stream may seem to behave differently depending on whether it is observed for 2 or 20 years following a big flood. Knowledge of the channel's history of flood response and recovery is essential in order to understand the current conditions and possible responses.

Sources of data for historical channel analysis include historical aerial photographs (coverage extends back to the 1920s or 1930s for much of North America and Europe), historical maps, engineering surveys of some river reaches, surveys at newly constructed bridges, computed bed elevations from gaging station records, narrative accounts and geomorphic evidence (Kondolf and Sale, 1985).

Changes in land use in the drainage basin can produce changes in sediment yield, as illustrated in the Yuba River basin, where hydraulic mining in the 19th century resulted in massive increases in sediment yield. A 'debris plain' covering 100 km^2 was deposited east of Marysville, where the river debouched from the Sierra Nevada onto the floor of the Sacramento Valley. After hydraulic mining was halted in 1884, a wave of sediment continued to pass through the Yuba River, raising bed elevations at the stream gage at Marysville to a peak in 1905 (Gilbert, 1917; Adler, 1980). The Yuba River then incised for decades, as the river gradually flushed out aggraded sediment, a process reinforced by channel training works and construction of Englebright Dam in 1940 upstream of the debris plain. In 1911, the Highway 20 bridge was built over the Yuba River without recognition of this long-term trend, and, as the channel continued to incise over the subsequent decades, the bridge piers were undermined (Kondolf, 1988). An instream gravel mine operating upstream of the bridge probably contributed to the incision at the bridge, but it would be erroneous to attribute all the incision to the gravel mine. Historical evidence suggests that the largest factor was gradual recovery from the historic influx of hydraulic mining debris.

Historical analysis can provide essential insights for understanding and calculating the sediment budget of a reach (Dietrich and Dunne, 1978). For example, the middle reach of the Russian River near Healdsburg was estimated to have a 'safe yield' of about 1 million tonnes based on calculated bedload transport rates, total gravel extraction and the change in storage in the channel bed effected by incision (Simons, Li and Associates, 1980). However, the analysis did not consider the artificially high rates of sediment delivery from Dry Creek, a tributary, from 1946 to 1972. Dry Creek incised in response to lowered base level and headcutting caused by gravel mining in lower Dry Creek and the Russian River mainstem (Harvey and Schumm, 1987). As Dry Creek incised, the sediment formerly stored in its channel bed was transported downstream, replenishing the Russian River mainstem and limiting its incision. Without the temporarily increased influx of sediment from Dry Creek, the Russian River would have incised more and the computed 'safe yield' would have been less.

Instream gravel mining as a flood management tool

Instream gravel mining can serve as flood control and prevent avulsion on rapidly aggrading rivers. Sediment removal is frequently required from river and flood control channels to increase or maintain channel capacity. On the River Usk at Brecon, Wales, 5000–8000 tonnes of gravel are removed annually from a flood control channel that was artificially overwidened and thus acts as a sediment trap (Brookes, 1988). In some cases, commercial extraction has been promoted on the basis of increased channel capacity and consequent flood control benefits (e.g. Bissell and Karn, 1992). However, such claims require objective evaluation, for mining-induced incision can also undermine flood control works, as occurred on the Otaki River, New Zealand (Anonymous, 1985).

The potential benefits of instream gravel mining for river control are illustrated on the Waimakariri River, near Christchurch New Zealand, a braided river draining the rapidly eroding, glaciated Southern Alps. The Waimakariri River transports approximately 150 000 m^3 of bedload annually (Carson and Griffiths, 1989). The river is aggrading in its lower reaches, largely as a result of bank erosion and bed degradation upstream, which has resulted in the downstream migration of gravel waves evident from survey data (Griffiths, 1979). A gravel budget for the lower Waimakariri River shows the 15 km reach near Christchurch (3–18 km above the mouth) aggraded 2.9 m (average over the reach) from 1929 to 1973 (Fig. 9). However, during this period another 5.9 m (average over the reach) of gravel and sand were extracted by instream mining. Without the mining, further aggradation would almost certainly have occurred, potentially leading to channel avulsion by filling the current channel with sediment and causing it to adopt a new course, probably through the city of Christchurch (Basher et al., 1988).

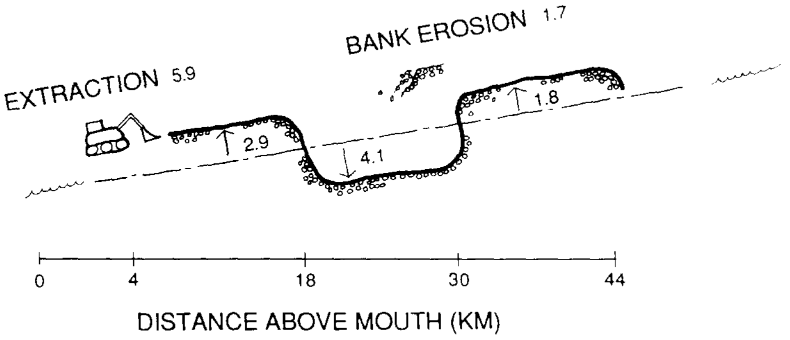

Fig. 9. Gravel budget for the Waimakariri River near Christchurch, New Zealand, 1929-1973. All values in $m^3 \times 10^6$. (Data from Griffiths, 1979.)

Instream gravel mining in this reach has been encouraged by the North Canterbury Catchment Board (and its successor, the Canterbury Council). A recent report by government geomorphologists urged "The Board's policy of encouraging gravel extraction must continue in the future, but we note that the rate of extraction has never kept pace with the supply for any significant period. To be an effective measure in the long term, extraction must get ahead." (Basher et al., 1988.)

Rivers experiencing rapid aggradation, such as the Waimakariri, are less common than rivers experiencing degradation due to a gravel deficit. Even in New Zealand, with high bedload sediment yields from its rapidly uplifting and eroding mountains, there are more reports of rivers with degradation problems (from instream mining, dam construction or channelization) than rivers with aggradation problems (Pemberton, 1974; Williman, 1977; Anonymous, 1985, 1986; Page and Heerdegen, 1985). In alpine rivers of France and Germany, instream gravel mining and upstream reservoir construction resulted in widespread channel incision; instream gravel mining is now prohibited in most of these drainages and grade control structures have been installed to limit incision (Weiss and Mangelsdorf, 1982; Peiry, 1987). In addition, gravels have been artificially added to some rivers, such as the Rhein (Kuhl, 1992) and the Saalach in Bavaria (Weiss, 1991) to prevent bed incision. Aggradation of gravel is relatively rare in rivers below dams, occurring only when tributary derived gravel cannot be transported by reduced mainstem flows (Parker, 1980). Given the extent to which rivers in North America and Europe have been impounded, it can be fairly said that, in these areas, a deficiency in gravel supply is far more likely than an excess.

Summary and conclusions

Instream gravel mining has significant effects on channel form, notably by causing incision upstream and downstream of the extraction site. As a result, bridges and other structures may be undermined, spawning gravels lost, riparian habitat lost and alluvial water tables lowered. Because of the complexity of sediment transport processes in natural channels, it is often difficult precisely to determine the relative roles of instream gravel mining, upstream reservoir construction and other factors in causing incision in a given channel. A sediment budget analysis can indicate relative rates of sediment supply, transport and extraction. A historical analysis is essential to understand the long-term context for current conditions. Computer models of sediment transport can be used to evaluate different alternative management strategies, but only after being calibrated with data from the river under study.

In rapidly aggrading rivers, instream mining can be a tool for flood control and channel stability. However, aggrading rivers are less common than incising rivers in Europe and North America, because numerous reservoirs have eliminated upstream sediment supply.

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