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Geomorphic Context and Effects of Instream Gravel Mining and Bank Stabilization Activities, Moniteau County, Missouri

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Introduction

Dimensions of stream channels adjust to carry the water and sediment supplied to them. When the balance of water and sediment is altered, channels inevitably readjust toward a new form with different dimensions and capacity to support aquatic life. Removal of sediment from streams through instream gravel mining changes the balance of water and sediment causing a general increase in energy of water in the stream channel – so-called "hungry water". Excess energy and sediment deficits typically result in channel widening or deepening, which can lead to increased bank-erosion rates, increased channel incision, and, in many cases, propagation of channel instability upstream and downstream. Direct changes in channel morphology caused by filling of the channel, pit excavation, inadequately engineered structures, or stockpiles of sediment can cause concentrations of flow energy that lead to increased channel instability. Channel instability presents threats to stream ecosystems, private property, and public infrastructure (Kondolf, 1994a).

Society expects many services from streams, including water supply, aggregate supply, hydropower, recreation, and ecosystem services such as flood mitigation, cleaning of polluted water, and maintenance of a diverse gene pool. Society's use of stream resources is predicated on the idea that extraction of goods and services from a stream will not significantly diminish the resource or cause harm to others or their property. The challenge is to identify sustainable levels of resource exploitation that minimize harm to other users.

While fluvial geomorphology – the science of understanding disturbances and adjustments of streams – cannot predict exactly what will happen upstream and downstream as a result of stream disturbance at a particular site, the science can predict general types of adjustments, trends of adjustments, and implications for humans and other biota living in the river corridor. Common-sense and thoughtful approaches to best management practices can minimize the risk that disturbances will result in unacceptable, perhaps irreversible, damage to streams.

This article is intended to provide an overview of fundamental principles of geomorphology, a brief history of how streams in the Ozarks of Missouri have changed over the last 100 years, and an analysis of two sites of stream instability in Moniteau County, Missouri. This report was written at the request of the Office of the U.S. Attorney for the Western District of Missouri, U.S. Department of Justice, Kansas City, Missouri.

Fundamentals of Fluvial Geomorphology

Sediment load and hydrology are recognized as the master variables controlling channel dimensions, associated aquatic habitat, and rates of change in channel

characteristics. Channel form results from the delicate balance of erosion and deposition as determined by these master variables. The balance does not result in a static channel; rather, it results in a channel that is continually adjusting through small feedbacks to maintain its dimensions. This condition of adjustment of stream channels around an average form has been called "dynamic equilibrium" (Hack, 1960).

The balance is illustrated by a diagram attributed to E.W. Lane (fig. 1). The primary drivers of the balance are stream discharge (hydrology) and sediment load, both of which are subject to human-induced and natural changes. If either of these changes, the balance swings toward degradation (channel erosion, resulting in deepening and/or widening) or aggradation (channel deposition, resulting in a smaller, perhaps shallower channel). Secondary effects are changes in stream slope, bed substrate size, and hydraulic roughness. Hydraulic roughness is an important variable because it affects water velocity. A common human-induced disturbance is removal of bank and bar vegetation, which can result in lower hydraulic roughness, increased velocity, and subsequent channel degradation.

While the precise mechanics of water flow, sediment transport, and bank erosion are quite complex, the simplification in figure 1 is a useful description of the direction of adjustments that can be expected when sediment load or hydrology are changed. This illustration of basic river mechanics documents the fundamental fact that a persistent change in sediment load by gravel mining will cause channel degradation, unless balanced by a proportional decrease in water discharge. Channel degradation will result in deepening and/or widening of the channel. When sediment – especially sediment that

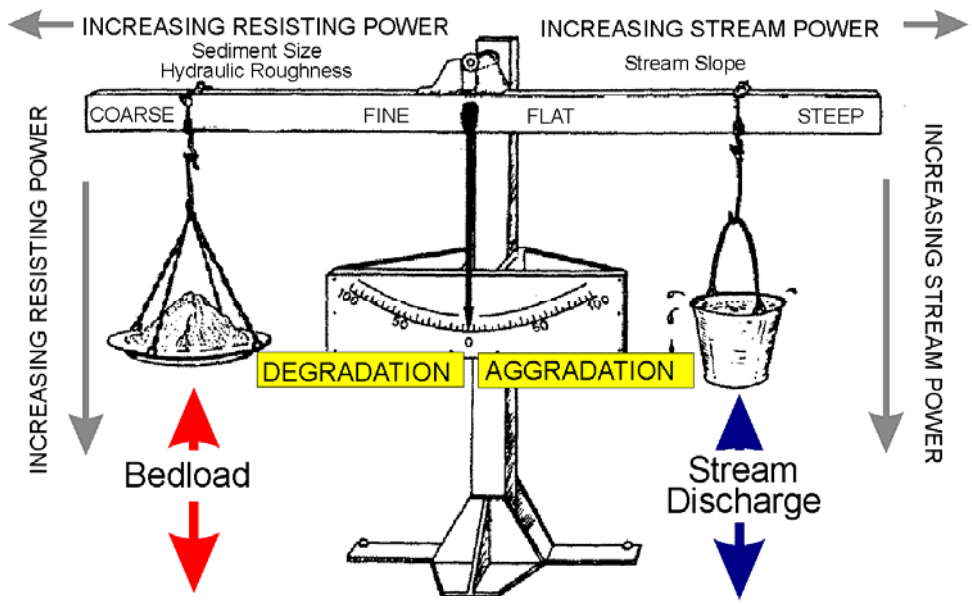

Figure 1. Diagram showing general balance of discharge and sediment load in determining channel instability. After E.W. Lane, n.d., cited in Chorley and others, 1984.

makes up the bed of the river – is removed from the sediment budget, the excess energy of the remaining water is dissipated by increased erosion to make up the sediment load.

Whether excess erosional energy is expended on eroding the bed of the channel or the banks depends on the relative strength, or resisting forces, of the bed and bank materials. Erosion of unconsolidated streambanks composed of alluvial sediments is a complex process because erosion depends on bank vegetation, groundwater flow, and bank geometry (Thorne, 1990). Streambanks add an element of *threshold* behavior to channel adjustment. Threshold behavior refers to a rapid change in properties of the system when some threshold is overcome. When banks are at low angles and convex upward in shape (fig. 2), the low angle and continuous armor of root strength minimize bank failure. On the other hand, if the armor of vegetation is penetrated, the bank can erode to a vertical geometry where gravity is much more effective in causing bank failure and vegetation provides negligible strength. Whether extraction of bedload will be associated with large increases in bank erosion rates relative to vertical downcutting depends in many cases on the geometry of the bank and state of vegetation.

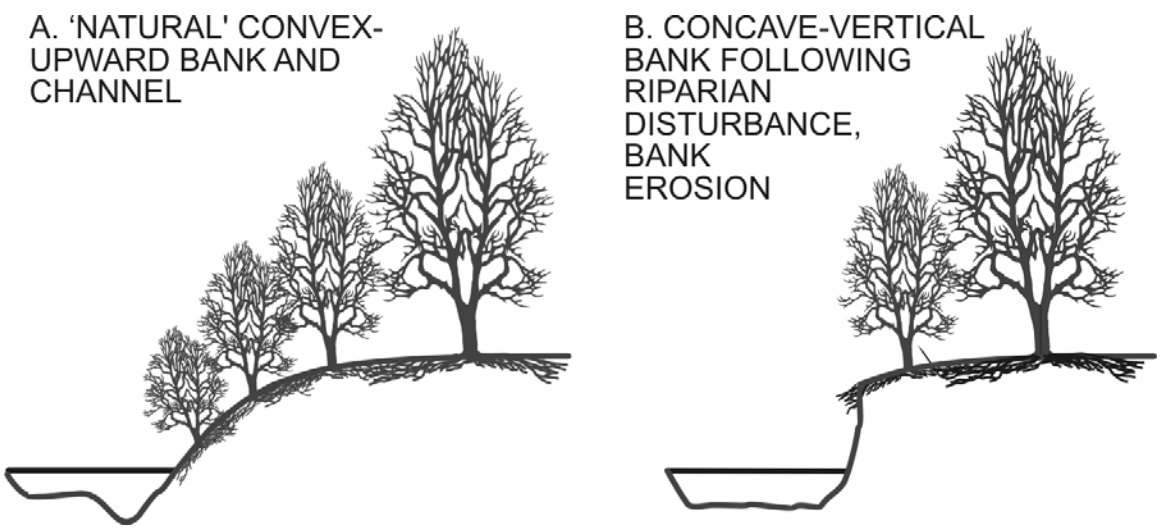

Figure 2. Illustration of the bank-erosion threshold. Vertical, unvegetated banks are much easier to erode than convex-upward banks with vegetative armoring.

Channel adjustments occur at a range of spatial scales. Channel length, slope, width, and depth can all change as the stream adjusts to carry the water and sediment load supplied to it. Channels also adjust to small features that affect water flow by creating areas of flow convergence or divergence that concentrate or dissipate flow energy. Structures placed directly in stream channels, for example bridge piers, parked machinery, or stockpiles of sediment, effectively narrow the channel and constrict flow. Constricted flows are deeper and faster, with concentrated flow energy resulting in local channel incision or scour. Conversely, unnaturally widened channels have diminished velocity and sediment transport capacity, resulting in dissipated energy and sediment deposition. Structures that create rapid constriction and expansion, such as wing dikes or rock spurs, can create extremely energetic secondary flow cells (eddies) downstream. These strong eddies can apply highly erosive flows to the banks if the geometry of spur

dikes is not carefully engineered to avoid it. Natural channels adjust their geometry to minimize these discrete zones of concentrated velocity, erosion, and deposition.

Stream-channel adjustments occur at a range of time scales as well. Whereas direct changes in channel dimensions will alter flow depth and velocity immediately, bank erosion resulting from disturbance may take days to years to decades to develop, depending on the sequence of floods and bank condition. Fine sediment delivered to the stream at bank erosion sites will affect stream ecosystems almost immediately and have relatively short-lived effects, whereas coarse sediment (gravel and cobble-size particles) can take decades to centuries to travel through stream systems (Jacobson, 1995). Because of the slow speed at which coarse bedload moves through stream systems, effects of stream disturbance can cause stream instability long after and at long distances from the original disturbance.

Stream instability can also move through a stream network, both upstream and downstream. Most instabilities propagate in the downstream direction with the direction of water transport – for example, fine sediment resulting from bank erosion at a site, or excess water energy. Exceptions are knick points, locally oversteepened sections of stream channel where erosive water energy is concentrated. Knick points (sometimes referred to as headcuts) are most easily defined where they cut through a resistant upper layer into a non-cohesive lower layer of streambed. Erosion of the non-cohesive layer maintains the steepness of the head cut and undermining of the upper layer produces upstream movement of the knick point over time. Knick points can be created by instream gravel mining or channelization, both of which can oversteepen the streambed (Kondolf, 1997). On Soldier Creek in Kansas, upstream knick point migration from a channelized reach was documented at 0.7 – 1.2 miles/year (Juracek, 2003). Upstream movement of knick points and associated channel instability can be expected to create a series of additional sediment pulses moving downstream long after an episode of instream gravel mining.

Downstream movement of moderate volumes of excess sediment in the channel network can result in unexpected and extensive channel instability as sediment from multiple tributaries meets and grows in volume (Jacobson and Gran, 1999). Areas of accumulation can result in channel instability, increased ecosystem disturbance, or in the case of navigable waters, decreased navigability. The result of sediment from various sources and various disturbance events, added together, is referred to as a cumulative effect. Prediction of channel responses to disturbance is complicated by the cumulative effects, time lags, and thresholds. Difficulties in prediction are compounded when effects on stream biotic communities are considered.

Effects of Channel Instability on Stream Ecosystems

Stream dimensions, bed and bank sediment, and adjacent riparian vegetation determine the physical habitat template for the aquatic ecosystem. Physical stream habitat is defined, in general, as the three-dimensional structure in which organisms live, including the interstices between bed-sediment (substrate) particles (Gordon and others, 1992). Stream habitat results from interaction of water with the morphology of the stream channel and adjacent flood plains. The interaction creates specific parts of the

channel referred to as hydraulic habitat units or mesohabitat units (Rabeni and Jacobson, 1999; McKenney, 2001): pools, riffles, glides, backwaters, and forewaters. Habitat units have different combinations of depth, velocity, substrate, and water quality that can be exploited by different groups of stream-dwelling organisms.

The diversity of habitat units is a first-order template for determining biological diversity and aquatic ecosystem health. Ecologists generally accept that biological diversity is associated with habitat diversity because a greater range of physical environments allows more species to coexist in the stream channel (Gorman and Karr, 1978; Schlosser, 1987; Jeffries and Mills, 1990). Greater diversity of channel elevations within a stream reach, for example, assures that during low-flow periods, more wetted area will be available. At high flows, greater physical diversity will create refuge areas for fish to escape high velocities and shear stresses. Therefore, physical processes that homogenize habitat by filling pools or eroding riffles are expected to diminish habitat diversity and ecological health.

More specifically, physical habitats of Missouri streams have been shown to be highly associated with specific ecological processes, individual species, or assemblages of species. For example, net community productivity has been found to be significantly higher in riffles and glides than in pools (Whitledge and Rabeni, 2000). Peterson and Rabeni (2001) found that long-ear sunfish (Lepomis megalotis), smallmouth bass (Micropterus dolomieu), and shadow bass (Ambloplites ariommus) were highly associated with pools in Ozarks streams, whereas species such as rainbow darter (Etheostoma caeruleum) and Ozark minnow (Notropis nubilus) were highly associated with higher velocities in riffles and races. These authors also found that habitat affinities varied by season and stream size. Similarly, Doisy and Rabeni (2001) documented that benthic invertebrate community composition, diversity, and functional groups in a Missouri Ozarks stream were correlated with basic hydraulic descriptors, indicating a strong physical habitat control on benthic communities.

While fish species can swim to take advantage of habitats that move from place to place because of channel instability, benthic invertebrates are more dependent on stability of the substrate that comprises their habitat. Some relatively immobile organisms, like mussels, require stable substrate over periods of seasons to decades, whereas many benthic insects depend on stability for a year or less (Barbour and others, 1999). For maintenance of habitats for the less-mobile benthic invertebrates, the stream should contain patches of substrate that are subject to neither deposition nor erosion. Absolute stability, however, usually is not considered desirable since accumulation of fine sediment may diminish the volume and quality of benthic habitat. Periodically, flows capable of entraining the bed are needed to flush fine sediments and rejuvenate the substrate (Milhous, 1982).

Physical habitat also varies over time as hydrologic variations influence environmental variables such as temperature, dissolved oxygen, and turbidity. Life stages of aquatic species may be synchronized to periods of high or low flow because of the associated environmental variables (Poff and others, 1997). Alterations in channel morphology that affect temperature – for example operations that would create a wide, shallow, unshaded channel -- can result in an increase in periphyton production, decreased dissolved oxygen, and alterations of the fish community (Petersen, 1998).

Importantly, it is the interaction of flow variation with channel dimensions that create the mosaic of habitats needed to support the ecosystem.

History of Stream Disturbance in Missouri

Land-use changes with the potential to create landscape disturbance at the drainage-basin scale began in southern Missouri in the 1830's. Initial rural settlement in valley bottoms was followed by timber harvest and conversion of uplands and alluvial terraces for crop production (Jacobson and Primm, 1997). From early settlement until the mid 20th century, fire also was commonly used to manage pasturelands. From the early 1800's to the present, Missouri's watersheds have been affected by agriculture, roads, and urbanization, all of which have potential to increase sediment supply and runoff to streams. It is generally accepted that the peak of agriculturally induced alteration of runoff and sediment load has passed and best management practices have diminished runoff and soil erosion (Jacobson and others, 2001). On the other hand, large localized pulses of sediment delivery are still typically associated with urban construction and road building (Wolman, 1967), and agricultural augmentation of stream nutrients continues (Rabalais and others, 2002).

Sediment liberated from past land-use practices is in transit through Missouri streams. Fine sediment (silt, sand, and clay-size particles) moves relatively rapidly, but can be deposited into temporary storage on streambanks, where it is susceptible to remobilization by subsequent flooding and bank-erosion events. Fine sediment is of a concern as a pollutant because of its ability to smother benthic habitats and because of nutrients and contaminants that can be adsorbed on it. Coarse sediment (gravel and cobble-size particles) moves much more slowly through the stream network. Accumulations of excess, land-use-derived gravel have been identified and mapped in some streams in the Ozarks (Jacobson, 1995; Jacobson and Gran, 1999). The locations of excess gravel deposits are controlled in part by accumulation at tributary junctions and in part by the history of slow transport through the stream network. As a result of this history, smaller streams tend to have gravel deficits and mid-size streams tend to have variable gravel accumulations (Jacobson, 1995, 2004; fig 3).

While scientific research on heavily studied streams in southern Missouri supports the general model of source, transport, and accumulation of gravel, specific information needed to predict where gravel accumulations occur on most streams in Missouri is lacking. In general, it is not known whether a particular stream reach has a gravel excess or deficit. Those with gravel deficits are particularly susceptible to instability when additional gravel is removed because they already have excess transport capacity; additional transport capacity will be expended on bed or bank erosion. Those stream reaches with excess gravel may be sources that can be exploited with minimal effects on the aquatic ecosystem, but identification of these reaches would require extensive historical analysis, and scientific studies. Stream reaches with excess gravel accumulations also tend to be highly susceptible to additional instability because in adjusting to excess bedload, the streams have created tight bends with eroding, unvegetated cutbanks. Mining in these reaches would require careful technique to minimize additional instability. In sum, the cumulative history of land-use disturbance

and stream instability has lowered the resiliency of Missouri streams to present-day stresses.

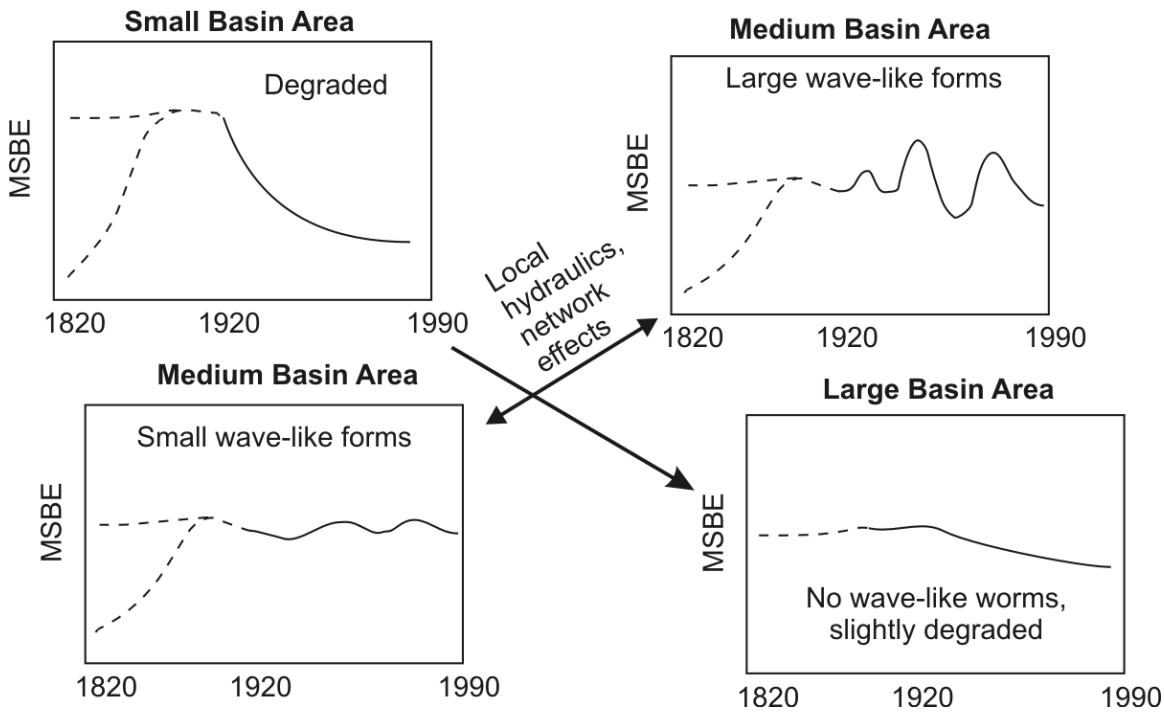

Figure 3. Conceptual mean streambed elevation (MSBE) plots summarizing streambed elevation changes in Missouri streams. Small basins have degraded channels indicating sediment deficits. Medium-size basins have variable accumulations of sediment from cumulative downsteam transport. From Jacobson (2004). Data from Jacobson (1995).

Instream Gravel Mining

Stream aggregate is an important economic resource in many areas of the country (Langer and Glanzman, 1993) Extraction of aggregate resources from the bedload of streams inevitably alters the stream's sediment budget and therefore carries the risk of destabilizing the stream (Kondolf, 1994b). "Hungry" water deprived of its sediment load has excess energy that can lead to on-site, downstream, and upstream channel instability, thereby putting stream ecosystems, private property, and public infrastructure at risk (Kondolf, 1997; Bull and Scott, 1974). Of particular concern are downstream effects on navigable waterways. The question faced by society is how to regulate instream gravel extraction so effects to stream systems are limited to acceptable levels.

Only a few studies have quantified comprehensive costs of channel instability caused by instream gravel mining. A study in five streams in northern Arkansas (Kaminarides and others, 1996) determined that costs to society of instream gravel mining ($7.58 million annually, including lost farm revenue, lost real estate value, lost fisheries resources and recreational value) outweighed economic benefits ($6.56 million annually including direct and indirect revenues from mined gravel). Case studies of

effects of specific gravel-mining operations illustrate potential risks to public infrastructure and private property. Knick-point migration and instability from an instream gravel mine on Linn Creek in Camden County, Missouri resulted in more than $914,000 of off-site costs in repairs for public infrastructure and buy-outs of private homes (Roell, 1999). Knick-point migration on Mill Creek in Phelps County, Missouri contributed to failure of three bridges costing at least $200,000 (Roell, 1999).

The concept of a "safe yield" of instream gravel mining has been promoted by some engineers as the amount of gravel that can be mined from a stream without exceeding the stream's natural resiliency to accommodate disturbances, when best management practices are used to minimize direct impacts. Excess gravel in transport, if the amount could be quantified, would certainly be within the definition of safe yield. In cases where excess gravel load has not been identified, safe yields are typically determined to be anything less than the annual bedload transport rate (U.S. Army Corps of Engineers, 1989) to 50% or less of the annual bedload transport rate (Bates, 1987). This site-specific approach to calculating a safe yield does not account for the deficit that will be experienced by downstream reaches. A fundamental constraint on managing by safe yield is that few potential mining sites have data sufficient to estimate reliably annual bed load transport rates. Missouri, for example, lacks any bedload transport monitoring stations for reliable calculation of annual transport rates.

While the complex response of stream channels and ecosystems to present and past disturbances limits prediction of exactly how much aggregate can be extracted without creating unacceptable instability, some common sense guidelines have been proposed by scientists to minimize negative effects. One set of best management practices are incorporated into U.S. Army Corps of Engineers General Permit NWKGP-34M.

On-site mining techniques can directly affect aquatic ecosystem health and channel stability. Actions that homogenize the natural diversity of habitat units will diminish the numbers and types of aquatic species, thereby decreasing ecological diversity and likely diminishing productivity and recreational fishing values (Brown and others, 1998). Removal of large woody debris (LWD) from the channel or channel margins can have a significant effect because of the special role of LWD in creating hydraulic roughness and fish habitat in the form of structure and cover (Gregory and others, 2003). Practices that keep machinery out of streams and avoid rearranging the stream channel can minimize these effects.

Excavation below adjacent water level on bars or in the stream channel by drag lines or other means creates oversteepened stream sections and zones of energy concentration. Deep mining below water level has been associated in many cases with upstream and downstream propagation of channel instability, resulting in frequent damage due to undermining of public infrastructure such as roads, bridges, and pipe lines (Kondolf, 1997; Biedenharn and others, 1997). While caused by deep vertical excavations, knick-point instabilities often propagate into accelerated channel widening due to bank collapse (Chang, 1997). To avoid creating knick-point instabilities, excavation should not extend below water level in the channel or leave abrupt topographic breaks or ledges that can cause flow separation.

Direct channel disturbance by machinery can destroy populations and habitats of invertebrates dwelling within the interstices of gravel substrate (Brown and others, 1998). Machinery operation in the channel also disrupts the armor layer that protects gravel sediments from accelerated erosion; when the armor layer is disrupted, erosion of the underlying sediment liberates much greater proportions of fine sediment than would ordinarily be transported. Fine sediment introduced to streams because of gravel mining at low-water periods of the year can be especially effective in clogging substrate interstices and filling pools. Direct effects to stream-channel habitats can be prevented by keeping machinery out of the channel.

Ecological recovery of a mined gravel bar (and retention of additional gravel resource) can be encouraged by leaving vegetation on the bar, particularly on the upstream end and in a buffer between channel and the mined area. Longitudinal patches of willows and sycamores are very effective at trapping and stabilizing gravel (Jacobson, 2004; McKenney and others, 1995, fig. 4).

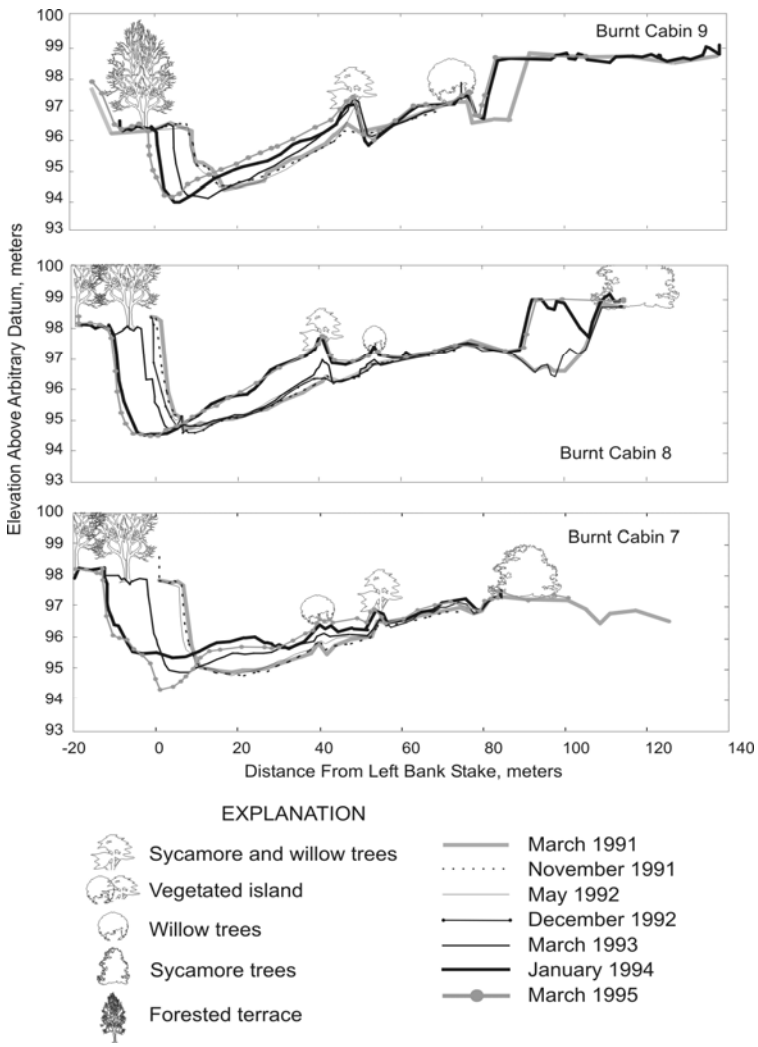

Figure 4. Resurveyed cross sections of a gravel bar, Jacks Fork, southern Missouri, showing retention of gravel in vegetation bands. Jacobson, 2004.

Bank Stabilization

Streams naturally erode their banks as they expend available energy. Bank stabilization techniques that do not dissipate this erosional energy will transfer the energy downstream or laterally where it can result in erosion on the opposite bank. Successful bank stabilization techniques utilize engineering designs that work with stream energy to divert flow from the bank and dissipate it so it does not cause downstream instability (Biedenharn and others, 1997).

Continuous bank riprap is a commonly used method for stabilizing banks. Design considerations generally include stabilizing channel grade (channel elevation), stabilizing the toe of the bank with large rock, reshaping the bank, and emplacing rock that is large and heavy enough to resist transport (Biedenharn and others, 1997). The size of riprap protecting a bank should be substantially larger than the bed material currently in transport by the stream.

Discontinuous methods (barbs, vanes, dikes) are also possible stabilization methods, as well as more structural alternatives such as gabion baskets, sheet piles, and concrete retaining walls. These methods cover a range of costs and associated risks; more expensive and comprehensive methods are chosen to protect more expensive structures or infrastructure.

All well-engineered bank-stabilization activities seek to protect the bank without causing flow perturbations that would transfer erosional energy downstream. Inadequate designs can lead to propagation of instability downstream. Failure of bank-stabilization projects can create extensive on-site instability by causing constrictions, flow separation, or secondary currents that would accelerate channel degradation or bank erosion. Emplacement of riprap that is too small and is easily eroded by the stream reflects not only a substantial waste of resources, it can also increase stream instability if the riprapped bank is flanked or eroded, and riprap consequently accumulates in the channel.

Similar to instream gravel mining, technique is extremely important in streambank stabilization efforts. Inadequate engineering can cause increased channel instability with consequent degradation of ecosystem values, private property, and public infrastructure.

Effects of Instream Gravel Mining and Bank Stabilization Efforts in Moniteau County

As discussed above, any extraction of aggregate from the sediment load of a stream unbalances the sediment budget and can result in increased channel instability. Operations within the banks that alter channel dimensions, substrate quality, or the distribution of flow energy increase the likelihood of stream destabilization and habitat degradation. These activities have the potential to damage the stream ecosystem, private property, and public infrastructure upstream and downstream as well as at the specific site. Potential for harm is affected not only by the type of activity, but also by the techniques used. While the risk to streams cannot be reduced to zero, best management practices – like those in the U.S. Army Corps of Engineers NWKGP-34M General Permit -- can minimize negative effects on streams.

Field investigation reports of two sites where gravel was extracted in 2001 and 2002 in Moniteau County (Little Moniteau Creek and Splice Creek, fig. 5) documented on-site effects that can be attributable to mining and channel-modification operations (U.S. Army Corps of Engineers, Jefferson City, Missouri, unpublished file reports). These sites were visited in January 2004 to evaluate the ongoing effects of these activities. Although natural processes had returned some of the morphological and

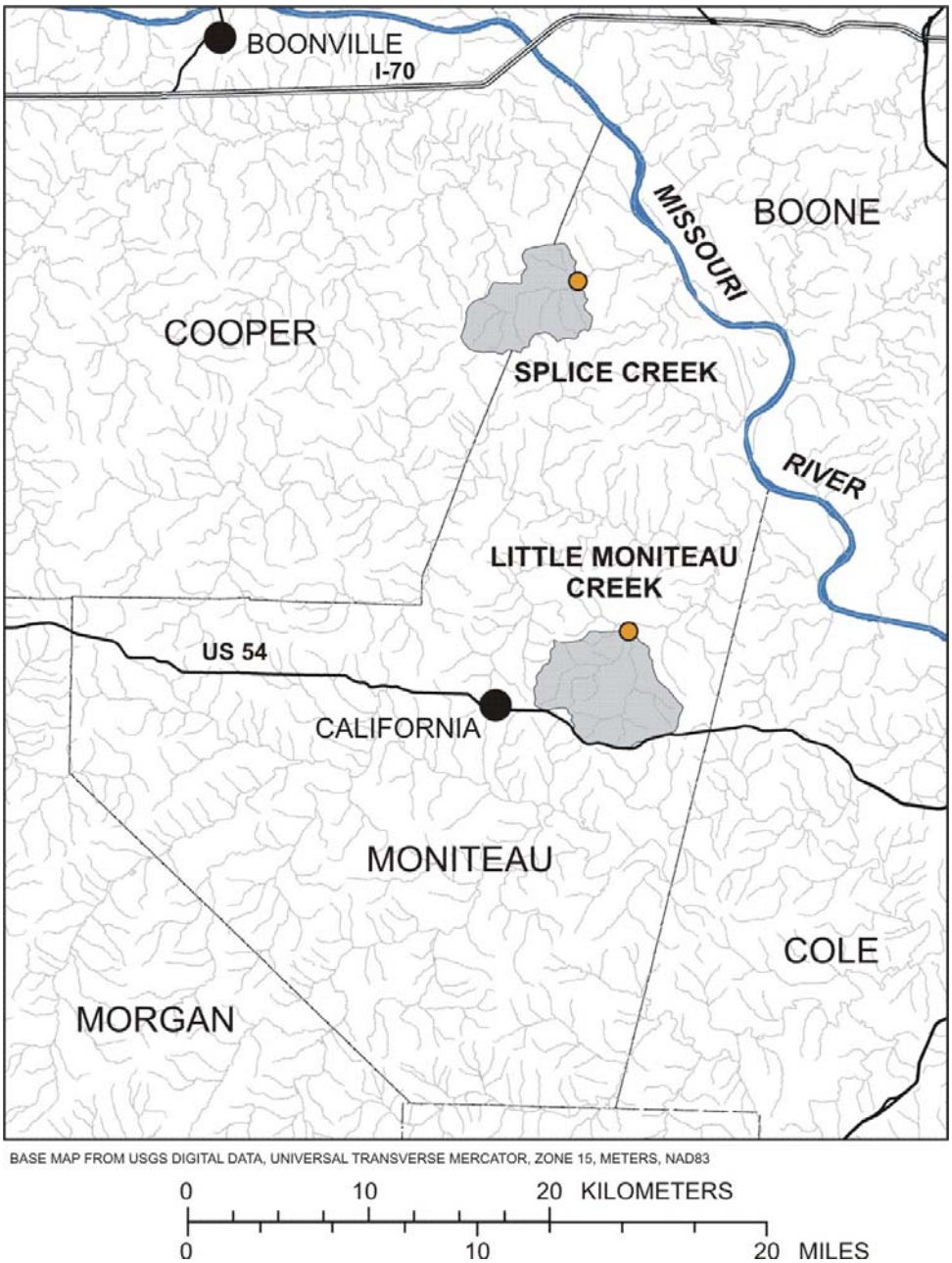

Figure 5. Location map showing Moniteau County, Missouri, and Little Moniteau and Splice Creek locations. Orange circles indicate stream sites investigated for this report. The gray areas are the upstream contributing drainage areas.

sedimentological characteristics of the sites to a more natural condition, many of the effects documented as resulting from 2001-2002 activities persisted. The following sections summarize the activities documented in the field investigation reports, the persistent effects of these activities as assessed in January 2004, and inferences as to the probable physical and biological effects, based on informed scientific judgment. Basic scientific understanding indicates the potential and likelihood that physical and biological effects occurred as a result of these activities. However, without systematic measurements before, during, and after the activities, the severity and spatial extent of impacts to the stream and its biota cannot be determined.

Little Moniteau Creek

Little Moniteau Creek is tributary to Moniteau Creek and the Missouri River. The site in question on Little Moniteau Creek is approximately 12.5 stream miles upstream of the Missouri River; the contributing drainage area is about 14.3 square miles. Activities at Little Moniteau Creek included construction of a haul road with several creek crossings, removal of a gravel bar, filling and relocating a channel away from an eroding bank, and pushing bed sediment up against the eroding bank. Effects of these operations on channel and ecosystem processes were not quantified at the time, but can be inferred.

Operation of machinery in the stream channel would have disrupted the armor layer, degraded benthic habitats, and increased turbidity and downstream transport of sediment during low-flow period when suspended sediment concentrations would normally have been low. Increased suspended sediment probably contributed to infilling of downstream pool habitats and smothering of open-work gravel substrate used by invertebrates and fish for benthic habitat. Clean gravel substrate is also used by other fishes for spawning habitat. The Federally endangered Topeka Shiner (*Notropis topeka*), for example, a resident of the Moniteau Creek watershed, requires clean gravel substrate for spawning (Pflieger, 1975).

Direct disruption of the armor layer in the stream channel would decrease the critical shear stress needed for bed-sediment transport, leading to accelerated gravel transport from the site and probable downstream channel destabilization.

Construction of low-water crossing causeways without culverts would have caused deposition of fine sediment and increased temperatures in upstream ponded areas. Without ability to exit these pools, some fish and invertebrates were put at increased risk of predation and desiccation, as well as subjected to diminished water quality. Flow over non-culverted causeways can cause hydraulic jumps and flow separation resulting in concentrated flow, channel incision, knick-point propagation, and consequent channel instability and increased bank erosion.

The gravel bar was removed without retention of a vegetated buffer, resulting in decreased hydraulic roughness and increased erodibility of remaining sediments in the channel. Decreased hydraulic roughness decreases potential for sediment retention during subsequent sediment-transporting events and probably has resulted in less gravel aggradation than would have occurred had a vegetative buffer been retained. Increased erodibility of the remaining sediment has probably resulted in substantial on-site channel instability.

Filling in the stream channel destroyed the existing habitat units, causing mortality or relocation of invertebrates and fish. By January 2004, the relocated stream channel was shallow and wide (fig. 6). Wide, shallow channels have higher stream temperatures than narrow, deep channels, and may act as a barrier to fish passage. The relocated channel was also apparently actively eroding the opposite (right descending) bank.

Removal of all gravel-bar vegetation in the process of relocating the channel decreased hydraulic roughness and erosional resistance of the gravel bar, resulting in increased velocities and probably resulting in additional gravel erosion. Increased velocities over the gravel bar would also increase velocities against the streambank, and work counter to attempts to stabilize the banks. By January 2003, evidence of erosion in the previous channel position indicated that the stream was attempting to move back to its former location.

Bed material (gravel and cobble size) that had been pushed up on the bank was eroding from the downstream end of the bank, exposing unvegetated, easily eroded sediment behind it. This activity is ineffective for bank stabilization and could cause additional instability when the pushed-up material is subsequently eroded and deposited in the stream.

Figure 6. Photograph of Little Moniteau gravel bar site, looking upstream. The channel was relocated from the right (left descending bank) to the left where it is now eroding rapidly into a new cutbank.

Under BMP's (for example, U.S. Army Corps of Engineers General Permit NWKGP-34M), direct access of machinery in the stream channel and consequent effects on fish and invertebrate habitats would have been minimized. Culverts in stream crossings would have prevented ponding, sedimentation, and stream temperature increases. Retention of vegetated buffers would have minimized direct channel disturbance during mining and would have retained some hydraulic roughness to help trap sediment subsequently transported through the reach. Under BMP's no attempt would have been made to fill in and relocate the channel. A permitted bank stabilization design would have been much more effective and long lasting, albeit considerably more expensive.

Splice Creek

Splice Creek is tributary to the Missouri River. The site on Splice Creek is approximately 4.8 stream miles upstream of the Missouri River, with a contributing drainage area of about 10.6 square miles. Activities at Splice Creek included removal of gravel bars, pushing bed sediment up against eroding banks, and emplacement of gravel-filled turkey crates for bank stabilization.

Operation of machinery in the stream channel would have disrupted the armor layer, degraded benthic habitats, and increased turbidity and downstream transport of sediment during low-flow periods when suspended sediment concentrations would normally have been low. Increased suspended sediment probably contributed to infilling of downstream pool habitats and smothering of open-work gravel substrate used by invertebrates and fish for benthic habitat, and by other fishes for spawning habitat.

The gravel bar was removed without retention of a vegetated buffer, resulting in decreased hydraulic roughness and increased erodibility of remaining sediments in the channel. Decreased hydraulic roughness decreases potential for sediment retention during subsequent sediment-transporting events and probably has resulted in less gravel aggradation than would have occurred had a vegetative buffer been retained. Increased erodibility of the remaining sediment has probably resulted in substantial on-site channel instability.

Storage of machinery and sediment piles on the gravel bar within the ordinary high-water elevation had the potential to cause flow concentrations, accelerated sediment transport, and increased channel instability.

In January 2004, bed material (gravel and cobble size) that had been pushed up on the bank was eroding from the downstream end of the bank, exposing unvegetated, easily eroded sediment behind it (fig. 7). This activity is ineffective for bank stabilization and could cause additional instability when the pushed-up material is subsequently eroded and deposited in the stream.

Figure 7. Splice Creek site, looking downstream. January 2004. Remnants of pushed up gravel shoved in foreground. In background, pushed up gravel has been eroded, allowing continued erosion of bank.

In January 2004, the turkey crates were undermined and in process of falling into the creek. The crates were installed without being keyed into the bank or deep enough into the bed to avoid scour and undermining. Because they did not extend far enough downstream, they were in the process of being flanked by erosive eddies at the downstream end (fig.8). If these structures were to fail completely and fall into the creek they would have a very high potential to cause accelerated streambank erosion and channel instability, putting the adjacent county road at risk of erosion.

Figure 8. Splice Creek, January 2004, looking upstream at turkey crates installed as bank stabilization measures. Crates were not installed deep enough into bed and are now being under mined, and consequently are sagging toward the creek. Flow separation at the downstream end (right of photograph) is causing scour downstream and behind the crates.

Under BMP's (for example, U.S. Army Corps of Engineers General Permit NWKGP-34M), direct access of machinery in the stream channel and consequent effects on fish and invertebrate habitats would have been minimized. Retention of vegetated buffer strips on bars would have minimized direct channel disturbance and would have retained some hydraulic roughness to help trap sediment subsequently transported through the reach. A permitted bank stabilization design would have provided a robust solution to bank erosion instead of an ineffective measure with high potential to create additional instability.

Summary and Conclusions

The history of stream disturbance in the central and southern portions of Missouri has resulted in streams that are at varying stages of recovery and with generally lowered resilience to disturbance. Land-use changes over the last 200 years have resulted in transient waves of gravel and associated stream stability, slowly working their way downstream. The result of this history is that stream systems are composed of reaches with both deficits and excesses of gravel bed load. Although reaches with excess gravel load may be sites where aggregate could be mined with minimal effects to the ecosystem, identification of such reaches is challenging and would require extensive site-specific study. Conversely, mining in reaches with gravel deficits would maximize stream instability and ecosystem disturbance.

The principles of fluvial geomorphology help predict the consequences of in-stream activities involving extraction of gravel, altering channel form, or stabilizing streambanks. Removal of sediment from the stream channel inevitably changes the delicate balance of water and sediment, resulting in an increase in erosional energy. The

energy is typically dissipated through increased erosion downstream, sometimes resulting in damage to adjacent private property or public infrastructure. Damages to stream ecosystems are also possible, due to direct disruption of habitat, isolation of pools, downstream sedimentation, and increased heating of the water column. Changes in channel morphology accompanying gravel extraction can increase stream instability by altering flow patterns and decreasing hydraulic roughness.

Although stream responses to extraction of sediment from its load are inevitable, management practices can minimize effects. Practices that minimize changes to the bed armor and profile, avoid changes to channel morphology that produce converging or diverging currents, and avoid decreasing flow resistance on streambanks and bars can minimize detrimental effects. Similarly, technique is very important in streambank stabilization, as under- or improper design can result in exacerbated stream instability in addition to ecosystem degradation. Guidelines for best management practices are available in publications like the U.S. Army Corps of Engineers General Permit NWKGP-34M.

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