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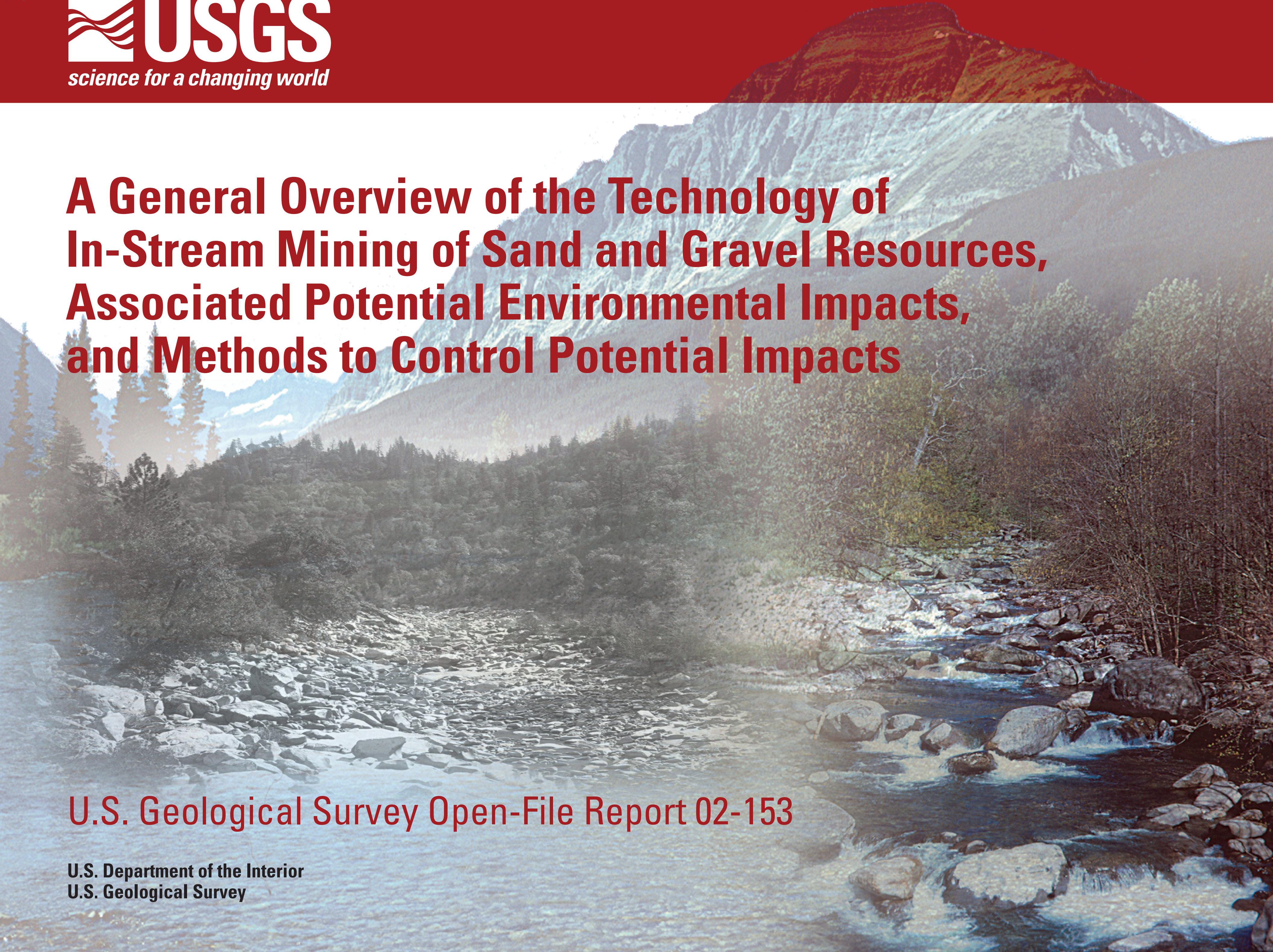

A General Overview of the Technology of In-Stream Mining of Sand and Gravel Resources, Associated Potential Environmental Impacts, and Methods to Control Potential Impacts

U.S. Geological Survey Open-File Report 02-153

U.S. Department of the Interior
U.S. Geological Survey

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by William H. Langer

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U.S. Department of the Interior
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Version 1.0, 2003

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A General Overview of the Technology of In-Stream Mining of Sand and Gravel Resources, Associated Potential Environmental Impacts, and Methods to Control Potential Impacts

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Introduction

Sand and gravel is a widely used construction material that occurs in a variety of natural settings. Large amounts of sand and gravel are extracted from ancient glacial deposits, alluvial fans, ancient marine terraces, and ancient and modern river and stream terraces, floodplains, and channels. In some parts of the country in-stream sand and gravel is the only locally available option for aggregate resources.

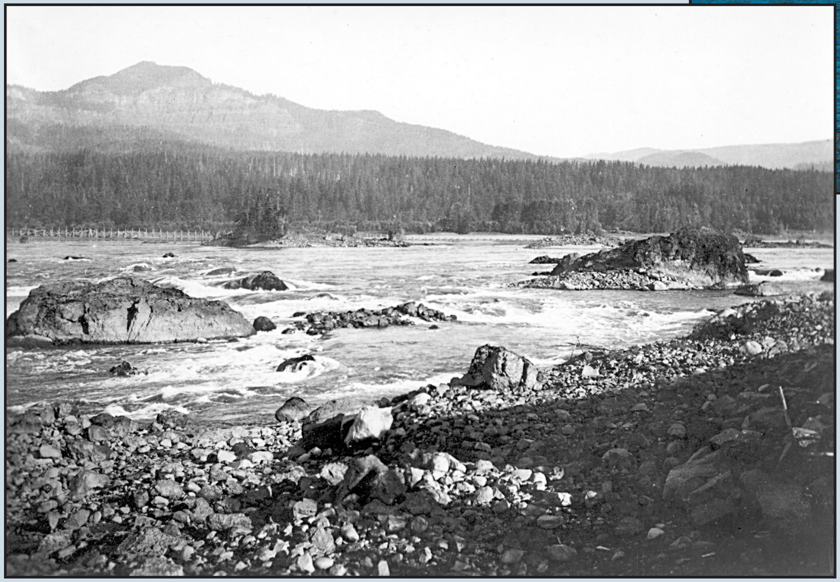
The extraction of sand and gravel from river and stream terraces, floodplains, and channels commonly attracts attention because in some situations excavation of sand and gravel may conflict with other resources such as fisheries, esthetic and recreational functions, or with the need for stable river channels. On one hand it is possible to excavate sand and gravel from sources located in or near river or stream channels within acceptable environmental limits provided that proper safeguards and practices are utilized. On the other hand development of sand and gravel from sources located in or near river or stream channels may create far reaching environmental impacts if proper safeguards and practices are not followed.

There are potential environmental impacts, such as noise, dust, and visual changes that may occur with any type of aggregate operation. Those impacts, and effective methods to control them, have been summarized by Langer (2001) and are not discussed here. In addition, there are many different types of rivers and streams in the United States (fig. 1). Each river or stream has its own unique set of geologic, hydrologic, climatic, and anthropogenic characteristics, and associated list of potential environmental impacts. There are numerous papers in the literature that describe environmental impacts in a number of those varied environments. However, this paper neither refers to all those references nor addresses all the potential environmental impacts.

The purpose of this paper is to describe, by way of selected examples, the broad range of potential impacts, and to describe some techniques to prevent or limit those impacts. The paper begins with an overview of the sand and gravel industry in general. It then describes in-stream mining of sand and gravel including extraction, processing, and reclamation. It follows with a generalized description of stream dynamics. It concludes with a discussion of the potential environmental impacts from in-stream mining and some of the techniques that can be employed to limit those impacts.

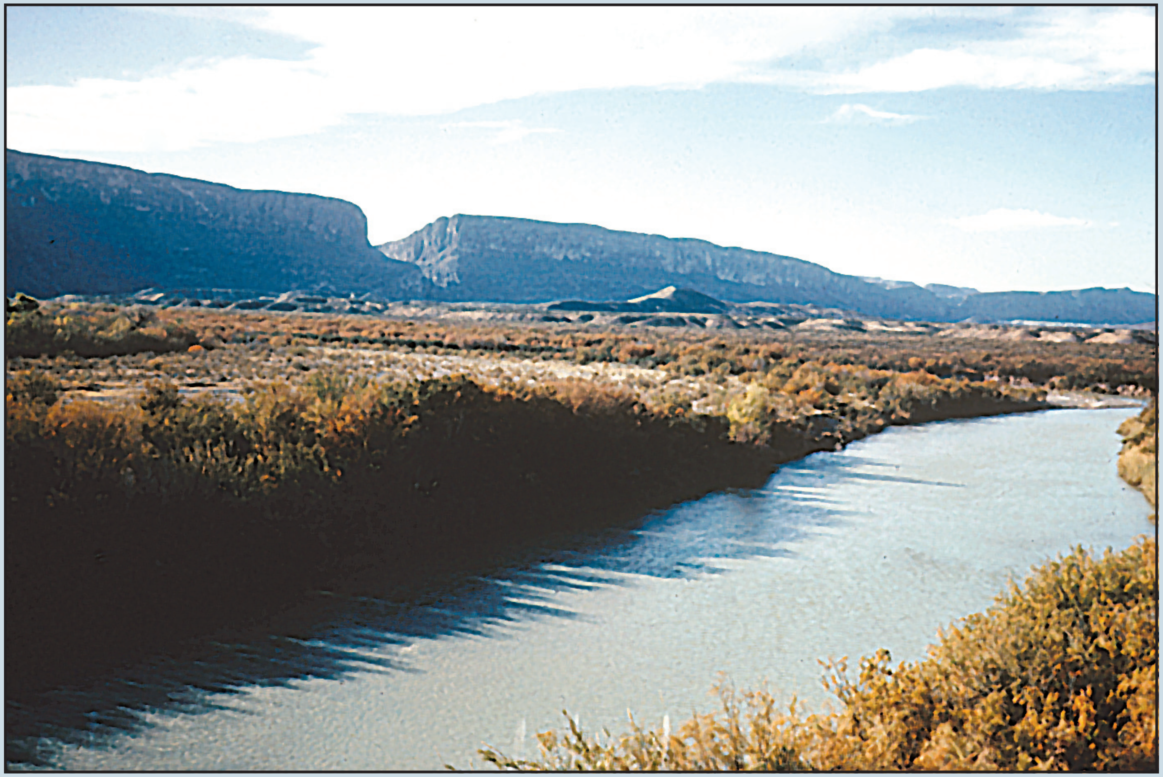
Figure 1. There are many different types of rivers and streams in the United States.

(Right) Belly River, Glacier National Park, Montana. *(Photo by P.E. Carrara, USGS)*



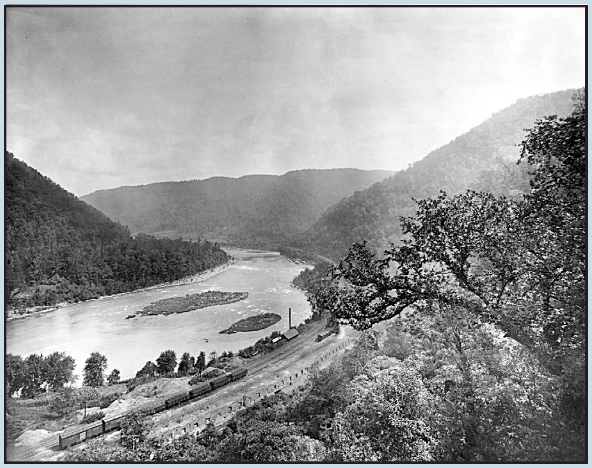
(Below) Cascades of the Columbia River, Hood River County, Oregon. (*Photo by G.K. Gilbert, USGS)*

(Left) Cheyenne River, Niobrara County, Wyoming. A typical stream of the arid regions, nearly dry in the summer. *(Photo by N.H. Darton, USGS)*



(Left) Rio Grande, Big Bend National Park, Texas. *(Photo by R.L. Brown, USGS)*

(Below) Eighteen Mile Creek, New York. *(Photo by G.K. Gilbert, USGS)*



(Right) New River, West Virginia. (*Photo by J.K. Hillers, USGS)*

Background

The skyscrapers, subways, and streets of our cities; the foundations of our houses, driveways, sidewalks, sewer systems, municipal buildings, schools, houses of worship, and shopping centers of the suburbs and towns; the highways, bridges, overpasses, power plants, dams, and water supply systems of the infrastructure serving and connecting our cities suburbs, and towns; all these activities require the use of large volumes of natural aggregate. An average 6-room house requires about 82 metric tons of aggregate; an average size school requires about 14,000 metric tons of aggregate; and one kilometer of 4-lane interstate highway requires nearly 50,000 metric tons of aggregate (Langer and Glanzman, 1993).

Sand and gravel is one of the main sources of natural aggregate; crushed stone is the other (fig. 2). These materials are commonly used construction materials and are used with a binding medium to form concrete, mortar, and asphalt or alone as in highway base courses, railroad ballast, and other similar applications. Sand and gravel and crushed stone and are widely distributed, used throughout the World, and together comprise the number one non-energy mineral resource in the world, both in terms of value and volume.

About 2.76 billion metric tons of natural aggregate worth $14.4 billion were produced in the United States during 2000. Of this amount, about 1.17 billion metric tons, or 42.4 percent, was sand and gravel, with a value of $5.7 billion. The percentage of total aggregate production that is sand and gravel varies widely from state to state (table 1). In Hawaii, 7.7 percent of the aggregate produced is sand and gravel, which is lower that any other state. Sand and gravel comprises about 8.9 percent of the aggregate produced in Georgia, which is the lowest percentage of any of the conterminous 48 states. At the other extreme, the aggregate produced in Delaware, Louisiana, and North Dakota is entirely sand and gravel.

About half of the aggregate (including crushed stone as well as sand and gravel) produced the United States is used in government-funded projects. It is estimated that about 48 percent of the 1.17 billion metric tons of construction sand and gravel produced in 2000 was for unspecified uses. Of the remaining total, about 41percent was used as concrete aggregates; 25 percent for road base and coverings and road stabilization; 14 percent as asphaltic concrete aggregates and other bituminous mixtures; 13 percent as construction fill; 2 percent for concrete products, such as blocks, bricks, pipes, etc.; 2 percent for plaster and gunite sands; and the remainder for snow and ice control, railroad ballast, roofing granules, filtration, and other miscellaneous uses (Bolen, 2001).

Figure 2. Gravel (left) is naturally occurring material, and tends to be rounded with smooth edges. Crushed stone (right) is artificially crushed rocks or boulders, and tends to be angular with sharp edges. *(Photo by W.H. Langer, USGS)*

Table 1. Sand and gravel production for the year 2000 (in thousands of metric tons), and sand and gravel as a percentage of the total aggregate production, by state (Tepordei, 2001).

State	Sand & gravel production (X 1,000 metric tons)	Sand & gravel as percent of total aggregate production
Alabama	15,900	23.4
Alaska	10,000	84.7
Arizona	55,200	85.7
Arkansas	11,100	25.8
California	157,000	72.0
Colorado	46,900	77.0
Connecticut	8,070	53.2
Delaware	2,230	100.0
Florida	27,300	21.8
Georgia	7,310	8.9
Hawaii	500	7.7
Idaho	16,500	80.5
Illinois	30,700	28.0
Indiana	28,500	32.2
Iowa	12,100	22.0
Kansas	10,500	28.8
Kentucky	9,640	14.7
Louisiana	15,400	100.0
Maine	9,160	69.6
Maryland	11,800	32.1
Massachusetts	13,300	50.6
Michigan	75,400	63.1
Minnesota	40,800	75.8
Mississippi	10,600	84.1
Missouri	13,000	14.1
Montana	12,900	81.1
Nebraska	13,600	66.0
Nevada	38,600	84.6
New Hampshire	7,970	63.9
New Jersey	15,100	37.7
New Mexico	12,100	77.6
New York	32,600	41.0
North Carolina	12,300	14.9
North Dakota	11,700	100.0
Ohio	49,400	38.8
Oklahoma	11,200	23.7
Oregon	16,300	39.5
Pennsylvania	19,300	17.0
Rhode Island	1,380	39.7
South Carolina	9,450	24.6
South Dakota	16,900	73.5
Tennessee	8,890	12.4
Texas	99,500	45.3
Utah	31,400	79.7
Vermont	3,840	39.0
Virginia	11,600	14.4
Washington	47,900	71.6
West Virginia	1,490	9.6
Wisconsin	37,600	54.0
Wyoming	4,400	38.6
United States		42.5

Substitutes

A number of materials may be used as a substitute for sand and gravel, including slag, expanded aggregate (certain types of clays that expand when heated to high temperatures), shredded recycled rubber tires, and shells. However, the two most widely used substitutes are crushed stone and recycled concrete or asphalt.

Crushed Stone

Crushed stone is produced by drilling, blasting, and processing rock. Approximately 1.59 billion tons of crushed stone were produced in the United Stated during 2001 (Tepordei, 2002). Much of this material is used interchangeably with sand and gravel, but it commonly is the user, not the producer, who specifies the type of aggregate. Those specifications may limit the substitution of crushed stone for sand and gravel. For example, sand and gravel particles tend to have round smooth surfaces, while crushed stone particles tend to be angular (fig. 2). When sand and gravel is used in Portland cement concrete, it mixes well and finishes easily. Consequently, people working with cement concrete frequently specify the use of naturally occurring sand and gravel. However, the use of crushed stone and the manufactured sand co-produced during the crushing process in Portland cement concrete makes an equally serviceable product. In some applications, for example the runways at Denver International Airport, crushed stone was specified for use in cement concrete to meet specific strength requirements.

On the other hand, the strength of asphaltic concrete (commonly called asphalt or blacktop) comes from the contact between particles, not from the binder. Therefore, specifications for asphaltic concrete commonly call for the use of angular particles (fractured faces on the particles) and prohibit the use of rounded smooth particles typical of natural sand and gravel. If natural gravel is used, it commonly is crushed to create the required angular faces.

Recycled Aggregate

Recycled aggregate occurs as either recycled concrete aggregate (RCA) or recycled asphalt pavement (RAP). The recycling of concrete and asphalt has been taking place in the United States since at least the early 1970's (Nanasy, 1972), and by the 1990's was a well-established activity. Aggregate companies recycled a total of 6.0 million tons (Mt) of asphalt concrete and 9.5 Mt of cement concrete in 2000 (Bolen, 2000; Tepordei, 2000). Nationally, the consumption of recycled aggregates continues to increase, but still constitutes less than 1 percent of total national aggregate demand. By partially fulfilling the requirements for natural aggregate, recycling has the potential to avoid development of sand and gravel deposits in some sensitive areas. Today, some European countries include recycling of concrete and asphalt to be part of an overall aggregate resource management plan.

Recycled aggregate is produced from demolished roads or demolished structures such as buildings and bridges (fig. 3). To substitute for natural aggregate, recycled aggregate must meet the physical specifications required by the end use and must be competitively priced. RCA has successfully been used in a number of applications, including aggregate for Portland cement concrete (Wilburn and Goonan, 1998), and Departments of Transportation in all 50 States allow use of RAP in highway construction (Marek, 1994).

Figure 3. Some construction demolition material is recycled at the demolition site. *(Photo by C.S. Mladnich, USGS)*

Quality

Just because a deposit of sand and gravel or an outcrop of rock occurs nearby does not necessarily mean the material is useful as aggregate. The important properties of aggregate depend primarily on the end use of the aggregate (Langer and Knepper, 1998). Departures from any quality specifications can make sand and gravel or crushed stone unsuitable for specific uses.

Aggregate should be strong, which means it should support the intended load, and it should resist mechanical breakdown resulting from the action of mixers, mechanical equipment, and (or) traffic. Aggregate should be sound, which means it should be able to withstand stresses caused by repeated freezing and thawing or wetting and drying. Suitable aggregate should be composed of essentially clean, uncoated particles of proper size and shape for the intended use. Sand and gravel commonly meets these requirements because the natural abrasion processes of streams tend to eliminate weaker particles.

Figure 4. Aggregate sometimes adversely reacts with the cement in concrete. When this happens it can cause damage to the concrete structure. *(Photo by W.H. Langer, USGS)*

Figure 5. The oil on the surface of this road had been "stripped" from the aggregate because of the incompatible electrochemical properties of the aggregate and the bitumen binder. *(Photo by D.W. Jahn)*

Aggregate used in the manufacture of cement concrete should not cause adverse chemical reactions with the cement. For examples, certain types of quartz minerals and certain types of domolite can cause adverse chemical reactions (fig. 4), and in asphaltic concrete (fig. 5), the electrochemical properties of rock may affect the ability of the bitumen to adhere to the gravel (Hoiberg, 1965). In either case, additives can be mixed with the cement or bitumen to prevent or limit adverse reactions.

Extensive engineering tests are conducted to determine compliance with specification requirements (commonly set by purchaser) to ensure thorough quality controls, to assure that the customer is receiving the same material that is being produced at the plant site, and to obtain measurements of the physical properties used in engineering design (Marek 1994). These tests commonly expose aggregate to conditions that simulate the conditions under which the aggregate will be used.

The most common guidelines for testing procedures and specifications for natural aggregates are those described by the American Society for Testing and Materials (ASTM). ASTM standards are based on exhaustive material testing and the service records of those materials in actual use. National specifications are broad and, at best, serve as general guidelines. Local specifications commonly reflect specific uses, availability and quality of local aggregate, and local climatic conditions.

Accessibility

Construction and maintenance of the infrastructure is dependent on raw materials such as aggregate. Aggregate is a low-cost commodity, and to keep hauling costs at a minimum, the operations are located as close to the market as possible. Despite this dependence, society often works to the detriment of the production of those essential raw materials by building over those resources and by opposing permitting of new, nearby aggregate operations. For example, a city of 100,000 can expect to pay an additional $1.3 million for each additional 16 kilometers that the aggregate it uses must be hauled (Ad Hoc Aggregate Committee, 1998).

The old idea that aggregate resources can be found anywhere is false. New aggregate operations may need to be located long distances from the markets, and the additional expense of the longer transport of resources ultimately will be passed on to consumers. In addition, the new deposit may be of inferior quality compared with the closest source, yet it may be used to avoid the expense of importing high-quality material from an even more-distant source. Any savings in transportation costs may be offset by decreased durability of the final product.

Sand and gravel commonly occurs in areas that are also favorable for other land uses. Frequently, urban growth occurs without any consideration of the resource or an analysis of the impact of its loss. Prime sand and gravel resources are precluded from development if permanent structures such as roads, parking lots, houses, or other buildings are built over them. Once development has taken place, for whatever purpose, the value of the improvements probably will permanently preclude any further development of sand and gravel at that location. Such a situation is referred to as "sterilization" of the resource.

In addition to encroaching on aggregate resources, urban growth often encroaches upon established aggregate operations (fig. 6). Some residents in the vicinity of pits and quarries object to the noise, dust, and truck traffic that may be associated with the aggregate operation. Some citizens do not support mining in general. Most individuals personally buy very little, if any, aggregate and they may not recognize aggregate mining as a necessary land use even though their houses, driveways and sidewalks would not exist without it. For these and other reasons, some citizens prefer that stone and sand and gravel not be mined nearby (Langer and Glanzman, 1993). This "not in my back yard" syndrome may restrict aggregate development. Furthermore, governments require permits, impose regulations, or establish land use zones, some of which may preclude mining.

Figure 6. The houses in the background of this photograph are built upon prime gravel deposits, and have precluded the development of those deposits. In addition, the houses have encroached upon the already-existing gravel operation, and have complicated the ability of the operation to conduct business. *(Photo by Cooley Gravel Company)*

A study by the New England Governors' Conference (Socolow, 1995) estimated that at least 90 percent of the sand and gravel supplies in New England could be unavailable because of increased zoning and environmental restrictions. The failure to plan for the protection and extraction of aggregate resources often results in increased consumer cost, environmental damage, and an adversarial relation between the aggregate industry and the community.

Figure 7. Stream deposits are the source of large amounts of sand and gravel. *(Photo by P.E. Carrara, USGS)*

Occurrence of Sand and Gravel Resources

There are numerous types of rivers and streams that occur in a wide variety of climatic settings (fig 1). The amount of gravel available in those rivers or streams and their associated terraces are determined in large part by the geologic, hydrologic, climatic, and anthropogenic characteristics of the area drained by the stream or river.

Sand and gravel produced in the United States is of either alluvial, glaciofluvial, or marine origin. Stream-channel, floodplain, and stream-terrace deposits of sand and gravel (fig 7) – the subjects of this discussion – are widely distributed throughout the United States, and in many parts of the country are the only sources of sand and gravel. The primary exceptions are that many of the extensive sand and gravel deposits in the northern latitudes and higher elevations of the United States are products of ancient glaciations, many of the sand and gravel deposits in the arid and semiarid areas of western United States occur as alluvial fans, and some of the sand and gravel deposits that occur in the Atlantic, Pacific, and Gulf coastal areas are ancient marine deposits.

When exposed near the surface of the Earth, such as in hilly or mountainous areas, bedrock is chemically and physically weathered and is progressively broken into smaller and smaller particles. Some less resistant minerals are broken down into very small silt or clay particles; some other less resistant minerals are dissolved. The more-resistant minerals remain as rock fragments and, with the silt and clay, create a residual soil. Depending on the composition and structure of the bedrock and the climate, land cover, and topography of the region, the residual soil may range in thickness from almost nothing to many tens of meters and may range in composition from nearly all clay through mixtures of clay, silt, sand, and gravel to nearly all sand and gravel. Gravity slowly (such as by soil creep) or rapidly (such as by landsliding) moves residual material downslope where it accumulates in stream valleys (fig. 8). Streams pick up the rock fragments, transport them downstream, and subject them to abrasion and rounding. The stream-transported material is deposited on floodplains as alluvium, which consists of variable mixtures of clay, silt, sand, or gravel. The alluvium is alternately eroded, transported, and deposited, and if given enough time, ultimately is transported to the sea or other major water bodies.

Over geologic time, some rivers or streams incise their channels into the floodplain, leaving the older channel and floodplain deposits as terraces that stand above the modern floodplain (fig. 9a and 9b). Repeated downcutting can result in the formation of a series of terraces or terrace remnants. In some places, these terraces can also be valuable sources of sand and gravel.

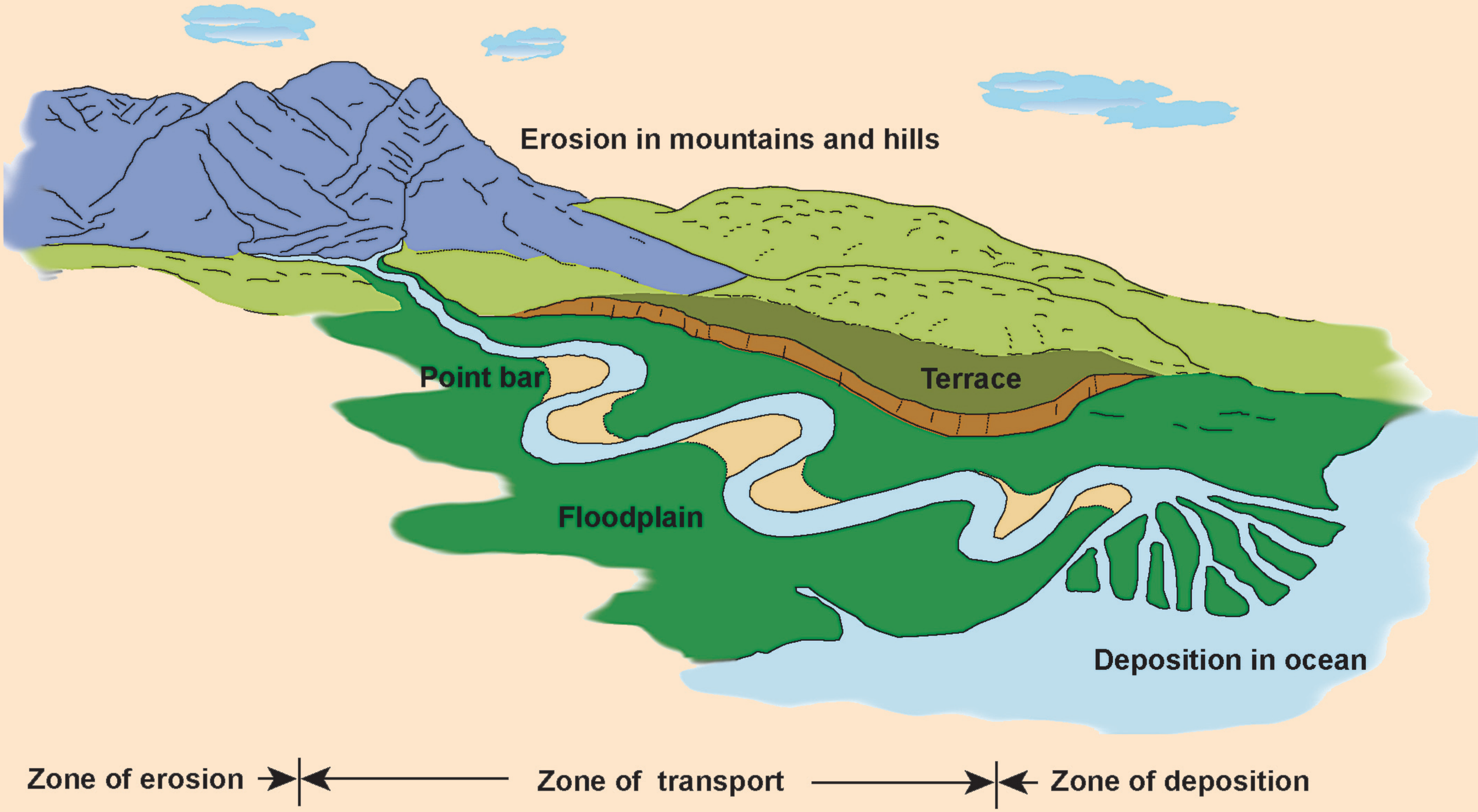


Figure 8. Origin, transport, and deposition of stream sediments (modified from Kondolf, 1997).

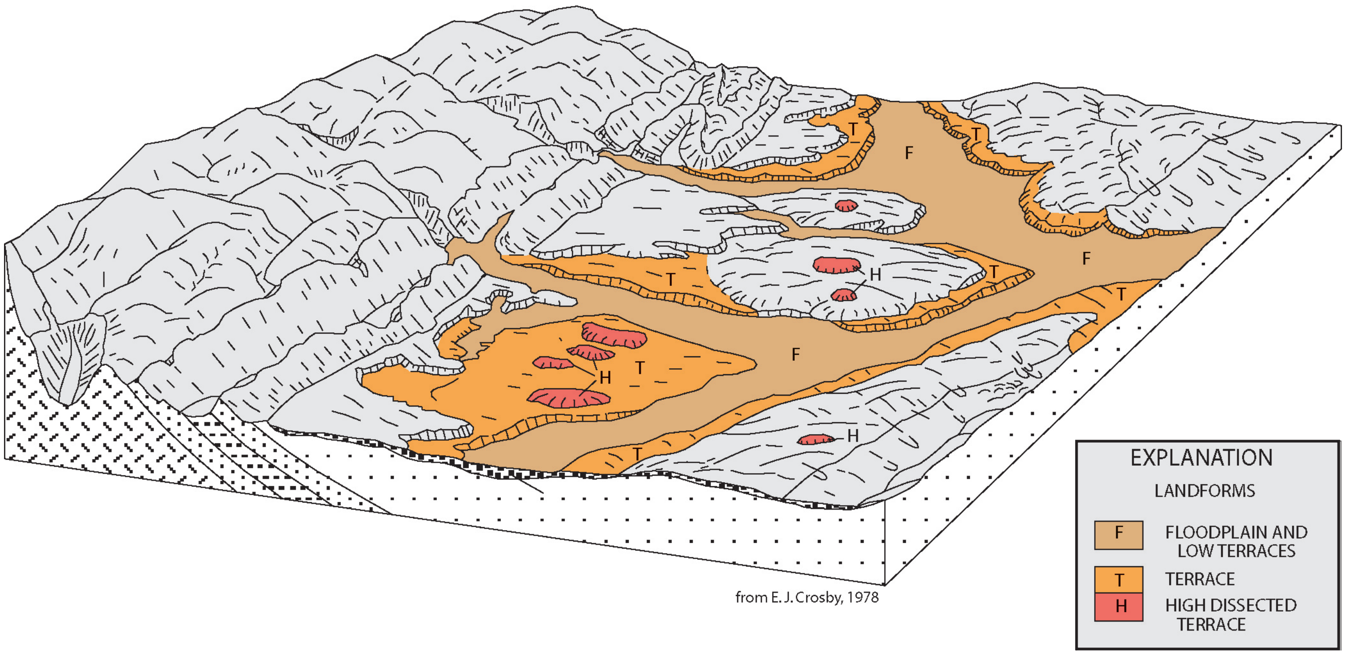


Figure 9a (above). Repeated downcutting can result in the formation of a series of terraces or terrace remnants.

Figure 9b (left). Terraces along Cantua Creek, California. The fence is on a low terrace and two higher terraces occur between it and the skyline. *(Photo by W.B. Bull, USGS)*

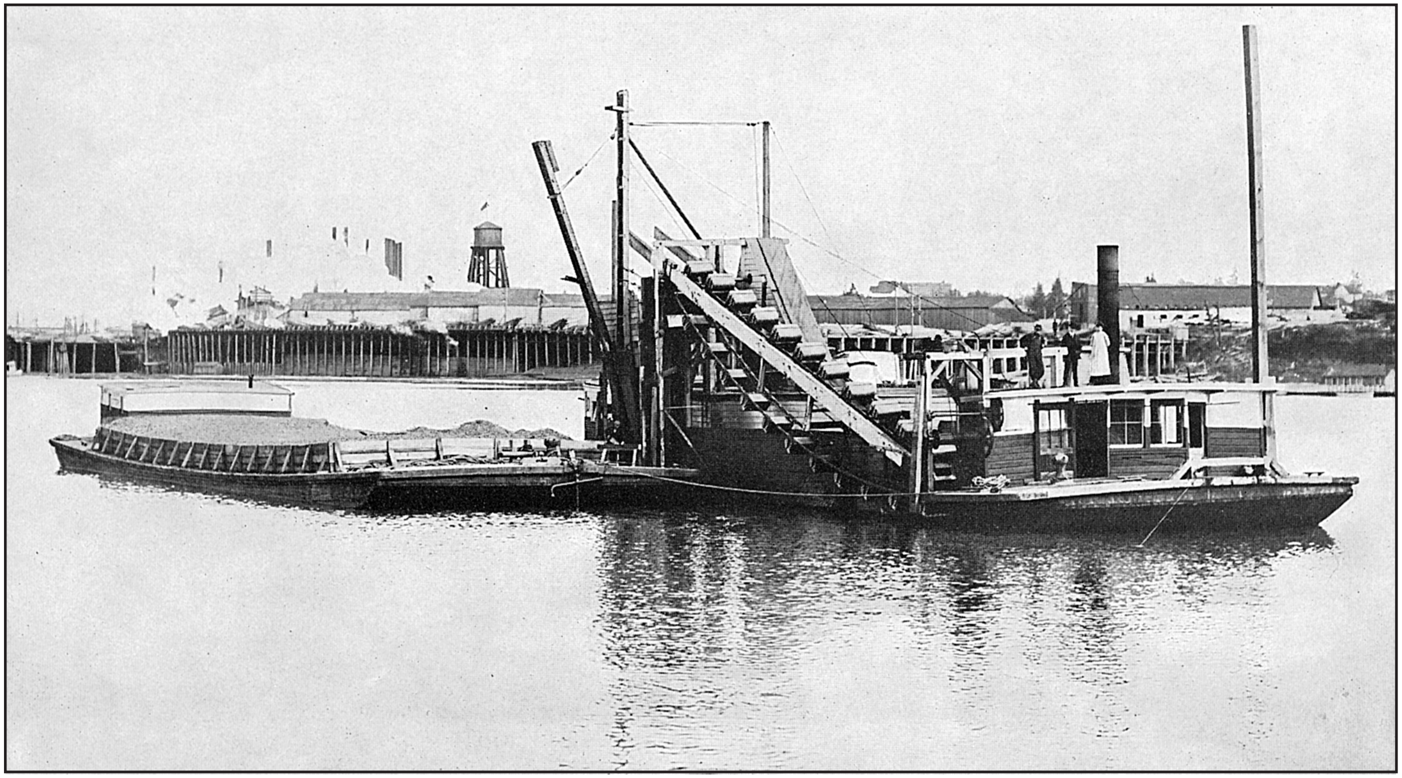


Figure 10. Dredge for raising gravel from the bed of the Willamette River near Portland, Oregon, circa 1909. *(Photo by N.H. Darton, USGS)*

In-Stream and Near-Stream Sand and Gravel—Extraction and Processing

Extraction

Sand and gravel has been extracted from rivers and streams in the United States for nearly as long as there has been an aggregate industry (fig. 10). Operations range from floating operations on large rivers that excavate, process, and load material directly onto barges, to small land-based operations on small streams that excavate a few hundred tons per year using a backhoe.

There are numerous methods to extract sand and gravel. The method chosen commonly depends on the nature of the deposit and on operator preference (Langer, 2001). In upland areas, such as high stream terraces, marine terraces, some glaciofluvial deposits, and on dry ephemeral streambeds, the sand and gravel may be largely within the unsaturated zone. If sand and gravel mining does not penetrate the water table, then the aggregate is dry and can be extracted by using conventional earth-moving equipment, such as bulldozers, front loaders, track hoes, and scraper graders (fig. 11).

In some areas, such as low terraces, some glaciofluvial deposits, and some ephemeral streambeds, sand and gravel mining may penetrate the water table and may be mined wet or dry. In some geologic settings, wet pits can be made dry by collecting the groundwater in drains in the floor of the pit and pumping the water out of the pit (fig. 12). Slurry walls or other barriers to ground-water flow around the pit may be required (fig. 13). After ground water drains or is diverted from the deposit, sand and gravel can be extracted by using dry mining techniques.

Figure 11. If sand and gravel is above the water table it can be excavated using conventional equipment. *(Photo by W.H. Langer, USGS)*

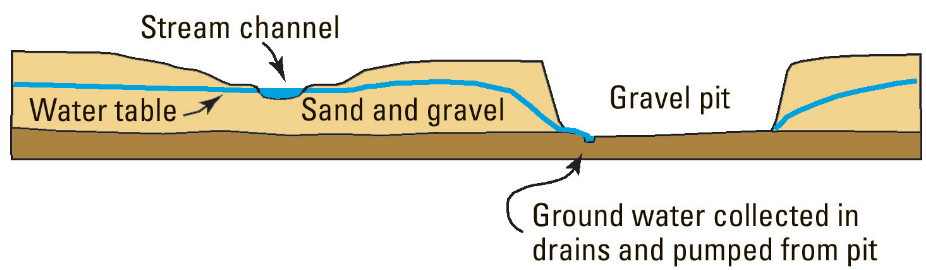


Figure 12. Ground water can be collected in drains in the floor of gravel pits. *(Photo by W.H. Langer, USGS)*

In some situations where the sand and gravel pits penetrate the water table, such as on low terraces and floodplains, the pit may not be able to be drained and the operator must extract the material by using wet mining techniques. Material may be excavated from the bank by using draglines and clamshells, or by floating barges (fig. 14) using hydraulic or mechanical methods.

In some areas sand and gravel can be excavated directly from stream channels, from embayments in the shoreline dredged off of stream channels, or from bars in the channels (Langer, 2001; Colorado Division of Minerals and Geology, 1998). This type of operation is referred to as in-stream mining. Depending on the nature of the water body and operator preference, sand and gravel can be excavated using conventional earth moving equipment such as backhoes, front loaders, or bulldozers (fig. 15); excavated from the streambed under water using land-based drag scrapers or draglines (fig. 16); or dredged from the channel using floating dredges (fig. 14) equipped with hydraulic (suction) dredges or mechanical devices such as a bucket and ladder or clamshells.

During times other than flooding, aggregate can be skimmed from the surface of bars in stream channels by using draglines or conventional earth-moving equipment (fig. 17). Excavation typically occurs when the river is at its lowest flow; subsequent higher flows may restore the bars. It is desirable that bars have a considerable volume of material above the low flow level, have a low percentage of fines, and are poorly vegetated.

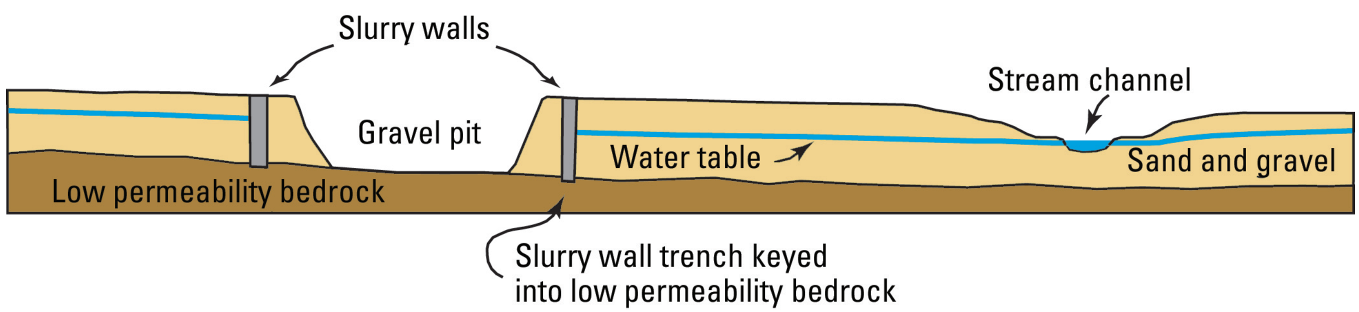


Figure 13. In some situations ground water can be diverted around a pit by the construction of a slurry wall. *(Photo by W.H. Langer, USGS)*

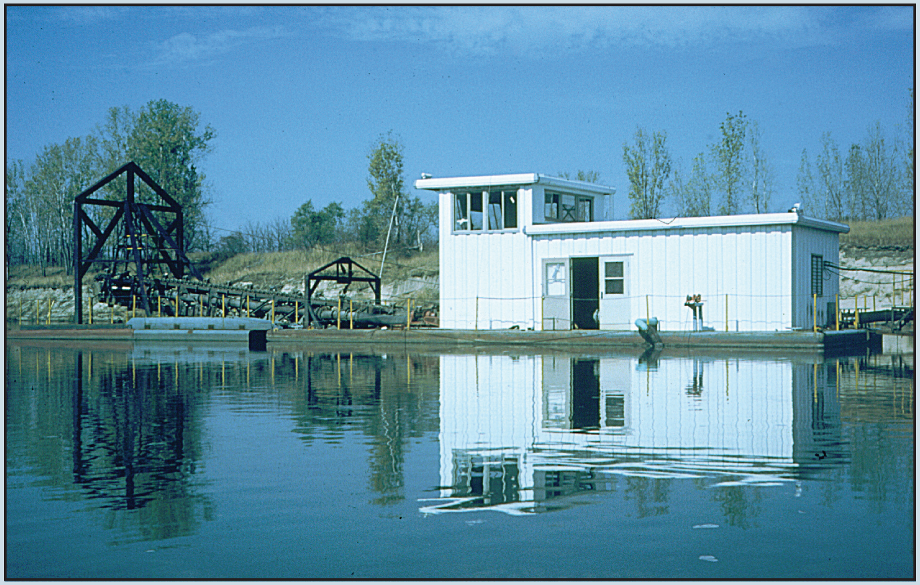


Figure 14. Sand and gravel can be excavated from underwater using a floating barge equipped with a hydraulic dredge. *(Photo by Kansas Geological Survey)*

Figure 15. Excavating gravel from stream channels using conventional earth moving equipment.

Figure 16. Draglines can be used to excavate sand and gravel from a stream channel. *(Top photo by Joann Mossa)*

Figure 17. Aggregate being "skimmed" off the surface of a bar.

Figure 18. Split channel mine on the North Fork of the Gunnison during high flow. During mining the narrow channel (towards the viewer) would carry water while the widened channel (away from the viewer) would be completely dry. *(Photo by Western Slope Environmental Resource Council)*

Stream channels may be temporarily or permanently diverted to allow for aggregate extraction using conventional earth-moving equipment in the natural streambed. A variety of methods can be used to divert the channel including the construction of a new diversion channel, split-channel mining (fig. 18), and the construction of harvest pits (Colorado Division of Minerals and Geology, 1998). In arid areas some stream channels or washes only occasionally have stream flow. Dry, ephemeral channels can be mined during dry periods using conventional excavation equipment.

Processing

After mining, sand and gravel may be used as is, which is called "bank-run" or "pit-run" gravel, or it may be further processed (fig. 19). The amount of processing depends on the characteristics of the deposit and the intended use of the aggregate. If the gravel deposit contains very large cobbles or boulders, that material may be run through a series of crushers. Crushing to the proper size usually occurs in stages because rapid size reduction accomplished by applying large forces commonly results in the production of excessive fines (Rollings and Rollings, 1996). Crushers use compression, impact, or shear to break the rock into smaller pieces. The material is screened after each crushing cycle to separate properly sized particles ("throughs" – those that go through the screen) from those needing additional crushing ("oversized" – those that go over the screen). Additional washing, screening, or other processing may be required to remove undesirable material. The material is then stockpiled awaiting shipment. Sand and gravel processing usually does not involve the use of chemicals.

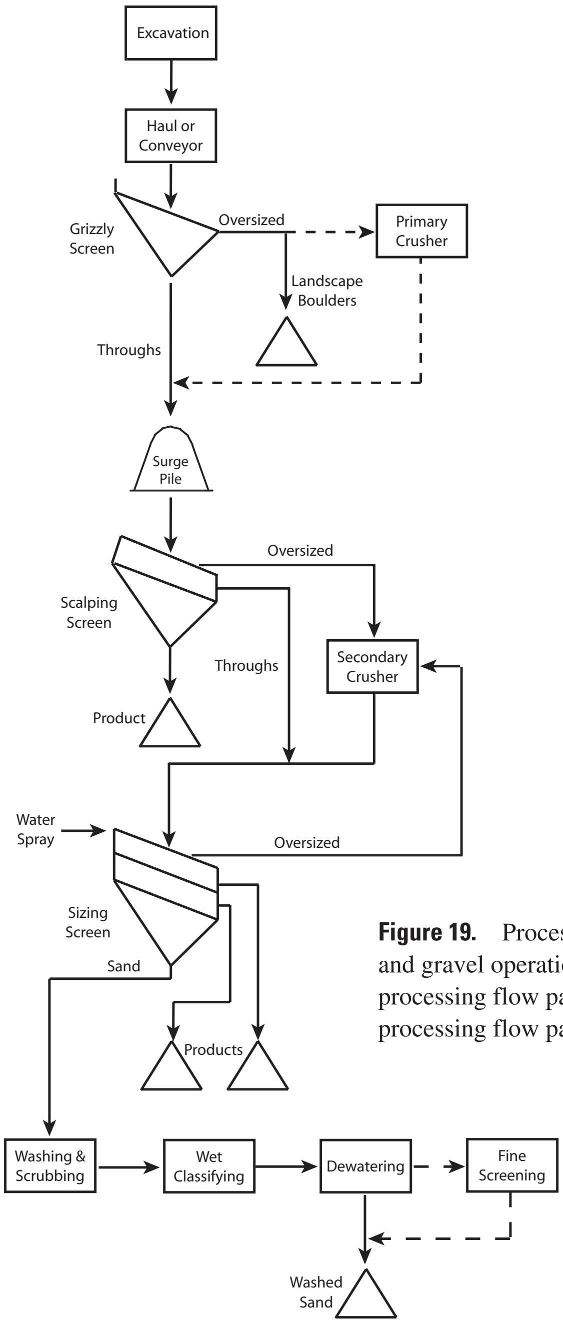


Figure 19. Process flow diagram for a typical sand and gravel operation. Solid lines show common processing flow paths. Dashed lines show optional processing flow paths.

Stream Dynamics

Rivers are complex, dynamic geomorphic systems whose major function is to transport water and sediment. The climatic, geologic, topographic, vegetative, and land-use character of the drainage basin determines the work demanded of a river, including the amount of water (discharge) and amount of sediment (load) it must handle under a variety of flow rates. The climatic and geologic character of the drainage basin also determines the location, type, and amount of sand, gravel, and other sediments present along various stretches of the river.

The type of channel pattern (meandering, wandering, braided, and so forth) of the river and the slope of the river along its length (gradient) are other characteristics controlled by the basin environment. Each channel pattern originates in a specific manner and develops to facilitate the work of a river. Channel patterns also give clues about the type of sediment (coarse versus fine) and amount of sediment present in the river (fig. 20).

Each river, over time, develops a particular combination of channel width, channel depth, channel slope, channel roughness, bed particle size, and water velocity (the combination of these variables is called the hydraulic geometry) that allows the river to function in the most efficient manner. Once established, the pattern will be maintained as long as variations in discharge and load are within the limits of the existing hydraulic geometry.

The normal small variations of discharge and load of a river commonly can be accommodated without major changes to the channel. Most river channels form and reform during a distinct range of relatively large flows referred to as the dominant discharge. After a dominant discharge event, the river establishes a new equilibrium by adjusting its hydraulic geometry. Because the hydraulic variables are mutually interdependent, a change in one variable requires a response in one or more of the others. Because the hydraulic variables are continuously adjusting, equilibrium as a steady-state condition can never be attained. At best, the river might achieve a state of quasi-equilibrium.

The time that it takes for a river to return to its quasi-equilibrium form after a dominant discharge event is called the recovery time. In humid climates the recovery time is in the order of 1 to 20 years, while in semiarid to arid regions the recovery time tends to be much longer. For a river to return to its state of quasi-equilibrium, the recurrence interval of a dominant discharge event must be greater than the recovery time. If a river is exposed to major long-term changes in climate or basin tectonics, the previous quasi-equilibrium between dominant discharge events may not be obtained, and the river ultimately will create a new quasi-equilibrium form.

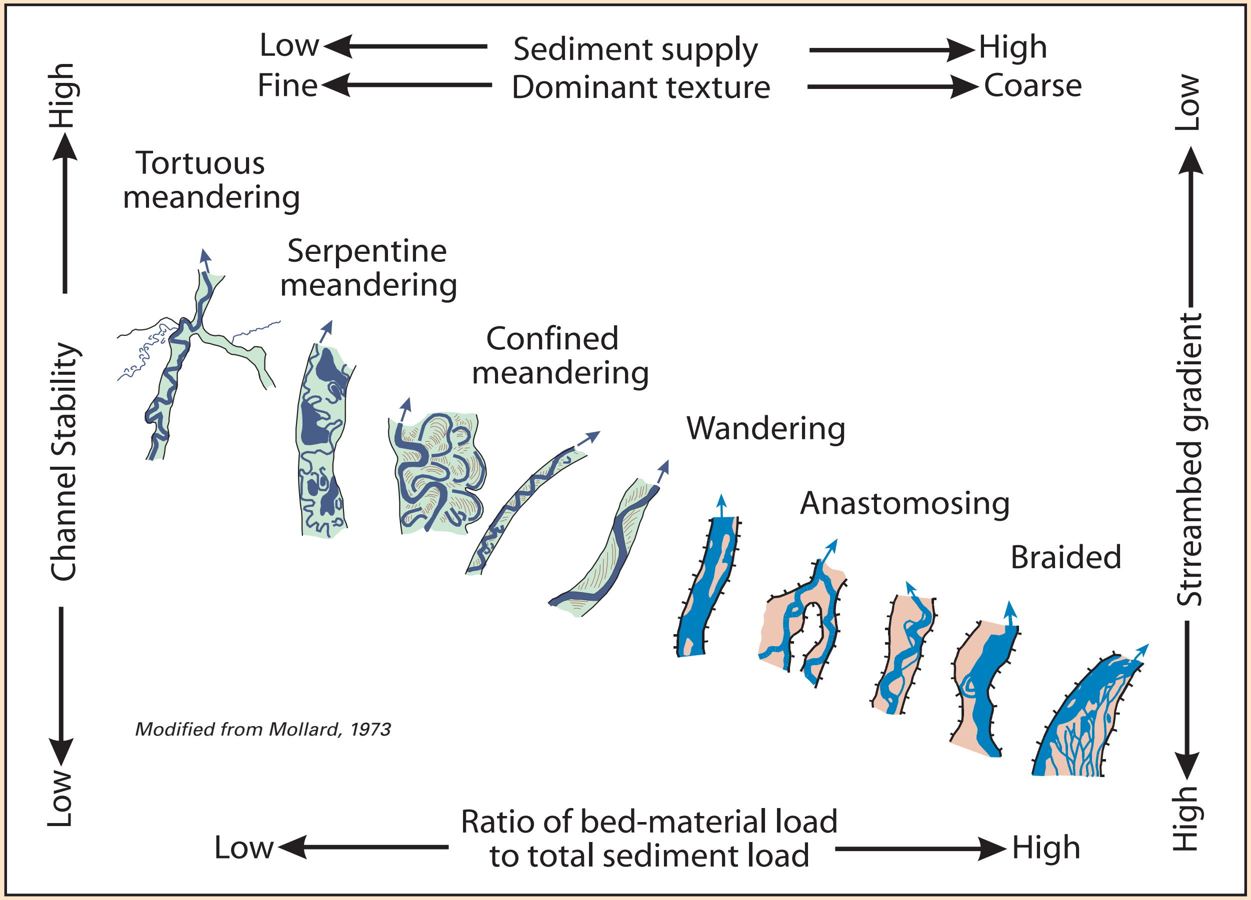


Figure 20. The relationships of stream geomorphology to sediment size and supply.

Environmental Impacts

Active stream channels are dynamic and respond rapidly to outside stimuli including aggregate extraction. Many rivers and streams can accommodate the removal of some portion of their bedload without creating adverse environmental impacts provided that the mining activities are kept within the hydraulic limits set by the natural system. But in-stream mining of sand and gravel should be conducted only after careful consideration, and then only with extreme prudence because failure to do so might lead to serious, long-lasting, and irreversible environmental consequences, either in the vicinity of the site or at locations distant from the site.

Human activities that cause problems on some types of streams may not cause problems on other types of streams. Similarly, human activities that cause problems along some sections of a stream may not cause problems along a different section of the same stream (fig. 21).

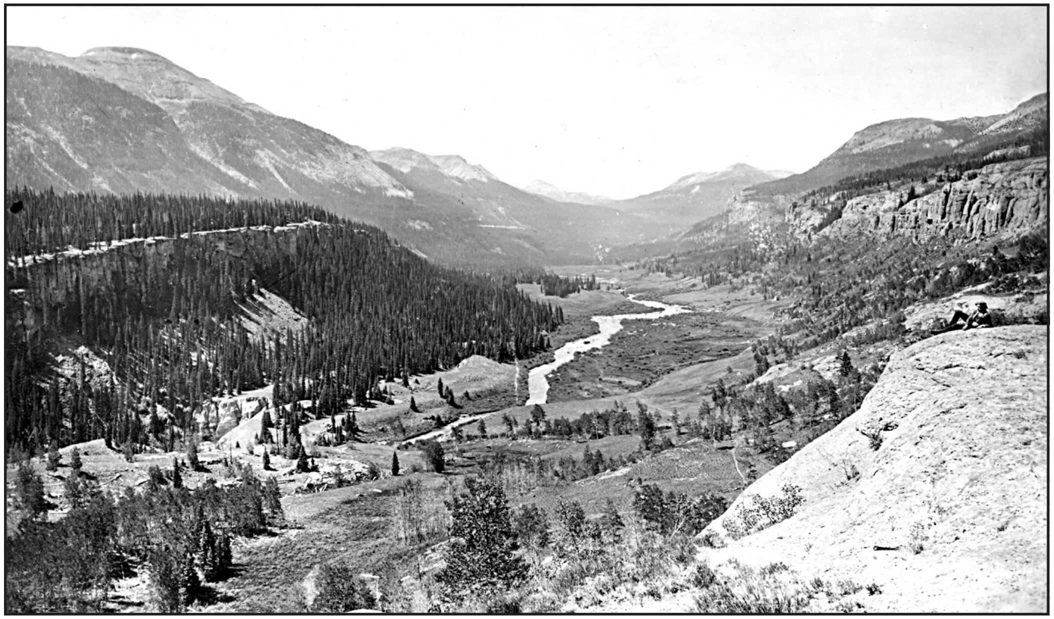


Figure 21. The Rio Grande changes character as one goes from its upper reaches of (top photo) to its lower reaches (lower photo). Because of these different characteristics the response of the river to human activities may be quite different throughout the length of the river. *(Top photo by W.H. Jackson, USGS. Bottom photo by R.L. Brown, USGS)*

The nature and severity of potential environmental impacts from in-stream mining are highly dependent on the geologic setting and characteristics of the stream, the type of extraction techniques employed, the location of extraction, and the amount of material extracted. If a river is exposed to regional human induced changes in the river basin, such as agriculture or urbanization, the average discharge or sediment load may be altered to a point where relatively small adjustments of the existing hydraulic geometry can no longer maintain the most efficient system. The river will reestablish the greatest fluvial efficiency (and will reach a new quasi-equilibrium form) by making major adjustments such as dramatic changes in the width-depth ratio of the channel, changes in channel patterns, changes to the channel substrate, and major changes in erosional and depositional patterns. These changes are considered to be environmental impacts and sometimes are erroneously blamed on aggregate extraction.

Another way a river can change its form is if local human activities such as bridge construction, channelization, or in-stream mining, occur within the channel or active floodplain and alter one or more critical hydraulic variables at a particular site or combination of sites along a river. If one or more variables are altered so much that the river can no longer maintain the most efficient means of accomplishing its work, the system will adjust, thus causing environmental impacts.

In-stream mining can be conducted without creating adverse environmental impacts provided that the mining activities are kept within the hydraulic limits set by the natural system. Many rivers can accommodate the removal of some portion of their bedload without serious effects (Kondolf, 1994). For example, Golder Associates (1999), in a report prepared for the Nature Conservancy, concluded that sand and gravel dredging on the Chattahoochee River, Ga., does not substantially adversely affect water quality, viewshed/aesthetics, recreation, or biodiversity. However, if in-stream aggregate mining changes the river system to where it can no longer transport water and sediment in an efficient manner, the river will attempt to create a new, more efficient system, and the resulting changes in the hydraulic variables may produce environmental impacts.

Most environmental impacts to streams and rivers have more than one cause and are a combination of regional and local human activities. Furthermore, because rivers are dynamic systems, some of the environmental impacts caused by human activities, including improper in-stream mining, are cascading impacts where one impact is the initiating event for a second impact, which is the initiating event for a third impact, and so on. Cascading impacts, whether a result of in-stream mining or some other human activity, can result in major changes to aquatic and riparian habitats and to the fish and wildlife occupying those habitats.

Figure 22. Extensive modification to stream channel caused by gravel extraction.

Environmental impacts to river systems where in-stream mining has been improperly managed have been described by Collins and Dunne (1990), Kanehl and Lyons (1992), Mossa and Autin (1998), Kondolf (1997, 1998), Florsheim and others (1998), Norman and others (1998), as well as other authors. Impacts may, but do not necessarily, include:

- Channel modifications such as widening or deepening the channel, creation of deep pools, loss of riffles, alteration of bedload, alteration of channel flow, and degraded aesthetics (fig. 22).
- Upstream and downstream erosion and related impacts.
- Modifications of aquatic habitat including spawning beds, nursery habitat, shellfish habitat, and riparian habitat.
- Degradation of water quality including increased turbidity, reduced light penetration, increased temperature, and resuspension of organic or toxic materials.
- Bridge scour and other impacts to infrastructure (fig. 23).

The principal cause of impacts from in-stream mining is the modification of channel characteristics, especially the removal of more material than the system can naturally replenish. Impacts can be a result of extracting too much material at one site, or the combined result of many small but intensive operations (Rowan and Kitetu, 1998). The removal of gravel from a stream creates a change in the cross section of the stream. Removing too much sand and gravel may cause an increased gradient at the site of excavation. Increasing the gradient of the stream may cause upstream incision. Removing too much sand and gravel from streams, particularly reaches of streams that are eroding or downcutting, may cause a decrease in bedload. A significant decrease in bedload can cause downstream incision. The stream may change its course, thus causing bank erosion and the undercutting of structures. Improper in-stream mining can also result in creation of deep pools, loss of riffles, channel shortening, overwidening channels, and changes in aesthetics.

Major off-site impacts from extracting sand and gravel from floodplains or low terraces might occur if, during flooding, the stream leaves its channel and creates a new channel (referred to as an avulsion) through the pit (referred to as the pit capturing the stream). After pit capture a stream most likely will deposit its entire bedload in the pit. This may result in downstream erosion and associated impacts. The impacts from stream avulsion and pit capture can be avoided by constructing a controlled spillway in a levee along the stream (see page 25).

Meador and Layher (1998) have summarized the impacts of improper in-stream aggregate mining on aquatic habitat. Erosion caused by in-stream mining can cause bank failure, which can cause loss of riparian habitat and loss of shade along stream banks (fig. 24). Channel shortening can increase flow rates, which can reduce the occurrence of coarse woody debris in the channel. In-stream mining can result in channel bed armoring, destabilization of spawning gravels and nursery habitat, increases in suspended sediment load, lowering of alluvial water tables, and stagnant low flows. All these impacts can result in major changes to aquatic and riparian habitat.

Figure 23. The upper photograph shows a bridge abutment in 1992. The lower photograph shows the same abutment during 1995. The bridge scour (erosion of river beds at bridge foundations) is due in part to in-stream mining and in part to channelization of the river. *(Photo by North Fork River Improvement Association)*

Effects of in-stream mining on fish communities vary within and among streams. Fine sediment (from many sources, not just in-stream sand and gravel mining) is one of the major environmental factors in the degradation of stream fisheries (Waters, 1995). Increases in turbidity can result in reduced light penetration, reduced photosynthesis, shifting composition of benthic invertebrates, and shifting fish populations to those tolerant of high suspended sediment. Freshwater mussels are particularly sensitive to substrate alteration (Parmalee, 1993). Gravel-dredging operations in the Brazos River, Texas, were associated with a decrease in sport fishes and benthic macroinvertebrates (Forshage and Carter, 1973). Gravel mining on floodplains in Alaska produced severe channel alterations, which were thought to have resulted in elimination or reduction in fish populations (Woodward-Clyde Consultants, 1980). On the other hand, no major differences in fish species composition, diversity, relative abundance, or biomass were reported in a comparison of dredged and non-dredged control areas in the Tennessee and Cumberland Rivers in Tennessee (Nelson, 1993).

Wash-water discharge, storm runoff, and dredging activities from improper sand and gravel operations can increase the turbidity of streams. Turbidity is generally greatest at dredging sites or wash-water discharge points (fig 25). Turbidity decreases with distance downstream, and can be controlled by containing runoff and by filtering or containing wash water.

Water temperature and dissolved oxygen of streams can be changed if in-stream mining reduces water velocity or spreads out the flow over shallow areas. Changes in some situations are local in nature and subtle (Nelson, 1993). Webb and Casey (1961) reported increases in temperatures downstream from dredging activity on an unspecified stream in Idaho. In contrast, Forshage and Carter (1973) investigated a dredge site and an upstream reference area on the Brazos River in Texas and found no significant differences between the sites in dissolved oxygen, pH, specific conductance, chlorides, or hardness. Martin and Hess (1986) found that dissolved oxygen, temperature, pH, and total hardness were similar in dredged and reference areas in the Chattahoochee River, Georgia, but reported decreases in dissolved oxygen downstream from dredged areas.

Figure 24. The upper photograph, taken during 1988, is located about 8 kilometers upstream from a 32-kilometer stretch of river heavily impacted by illegal sand extraction. The lower photograph, taken at the same location about 5 years later demonstrates the effects of headcutting. *(Photos by P. Hartfield)*

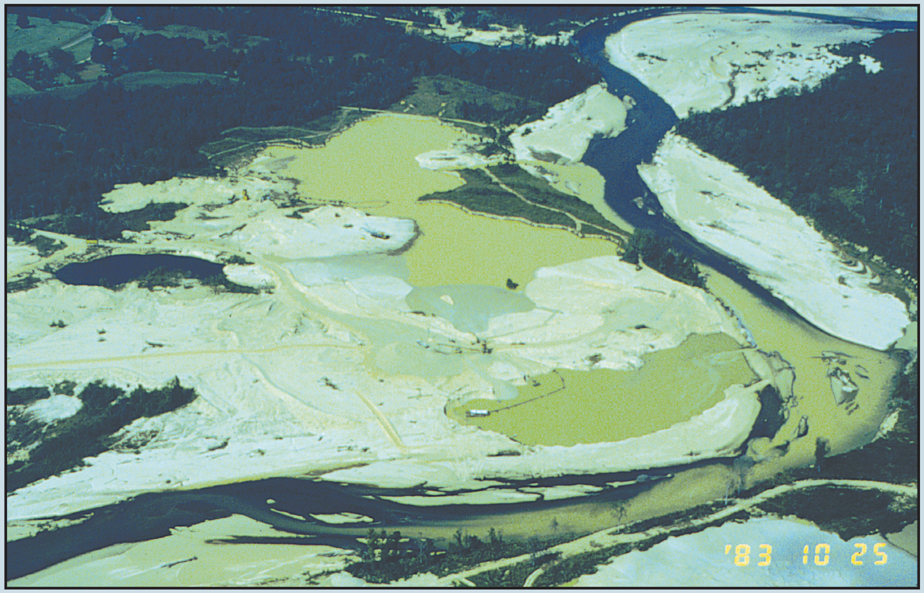


Figure 25. Dredging can increase turbidity of the water in rivers. *(Photo by Joann Mossa)*

Preventing or Limiting Environmental Impacts

The numerous types of rivers and streams in the United States behave differently from one another, and what measures that can be taken to limit environmental impacts differ from river to river, stream to stream, and upstream or downstream on the same river or stream. Similarly, what works or does not work in small streams may not necessarily work in large rivers.

There are a number of engineering techniques that can be employed to reduce or eliminate the environmental impacts from excavation of sand and gravel from stream channels, floodplains, and terraces. The specific techniques employed should be designed within the parameters of the natural hydrologic system.

One of the principal causes of environmental impacts from in-stream mining is the removal of more sediment than the system can replenish. Coarse material transported by a river (bedload) commonly is moved by rolling, sliding, or bouncing along the channel bed. Some researchers believe that environmental impacts from in-stream mining can be avoided if the annual bedload is calculated and aggregate extraction is restricted to that value or some portion of it. To accurately limit extraction to some portion of bedload, the amount of sediment that passes the in-stream mining site during a given period of time must be calculated. There is a large amount of uncertainty in the process of calculating annual rates of bedload transport (National Research Council, 1983). How much coarse material is moved, how long it remains in motion, and how far it moves depends on the size, shape, and packing of the material and the flow characteristics of the river. Downstream movement commonly occurs as irregular bursts of short-distance movement separated by longer periods when the particles remain at rest. Because bedload changes from hour to hour, day to day, and year to year, estimating annual bedload rates is a dynamic process involving careful examination.

In addition, there is no method for computing what percentage of the bedload should be allowed to pass on downstream. The problem can be addressed empirically by observing channel changes that result from various rates of gravel extraction. Channel changes can be determined from a series of aerial photographs, or from ground-based surveys. This technique may be an acceptable approach, even if the bedload calculations are bypassed.

Some sections of a stream are more conducive to aggregate extraction than others. Most stream erosion takes place during high-flow events. Constant variations in the flow of the river make the channel floor and riverbanks a dynamic interface where some materials are being eroded while others are being deposited. The net balance of this activity, on a short-term basis, is referred to as scour or fill. On a long-term basis, continued scour results in erosion (degradation), while continued fill results in deposition (aggradation). Removal of gravel from some aggrading sections of a river may be preferable to removing it from eroding sections (fig. 26). A general indicator of the stability of a stream relates to the amount of vegetation present. Gravel bars that are vegetated, or where the gravel is tightly packed, generally indicate streams where the gravel supply is in balance. Streams with excessive gravel generally have gravel bars with little or no vegetation, and are surfaced with loosely packed gravel (fig. 27).

Figure 26 (right). Oak trees “drowned” by gravel in the aggrading bed of the Yuba River near Parks Bar Bridge, Yuba County, California. June 6, 1905. *(Photo by G.K. Gilbert, USGS)*

Figure 27 (below). Gravel bars with little or no vegetation, and loosely packed gravel, indicate aggrading streams. *(Photo by W.H. Langer, USGS)*

Even if a stream reach is eroding, aggregate mining may take place without causing environmental damage if the channel floor is, or becomes, armored by particles that are too large to be picked up by the moving water. For example, some sections of rivers underlain with large gravel layers deposited under higher flow rates than those prevailing at the current time may support gravel extraction with no serious environmental impacts. Jiongxin (1996) described such a situation on the Hanjiang River in China where downcutting stopped when coarse bed material was reached. A similar situation commonly occurs in modern stream valleys that are occupied by slow-flowing river, but were filled with sediment deposited thousands of years ago by torrential glacial meltwater streams.

The impacts from stream avulsion and pit capture can be avoided by constructing a levee along the stream. The levee is designed with armored spillways that control where the levee will be "breached" by the stream during flooding. The spillway allows water to leave the channel and temporarily flow over the floodplain but keeps stream from creating a new channel and keeps the bedload in the stream.

There are some general relationships between environmental impacts, where the extraction site is located (fig. 28), whether or not the excavation penetrates the water table, how deep the excavation is, and the size and shape of the river or stream. These relationships can be used as a general guide for the design of in-stream and near-stream aggregate extraction. All other things being equal:

- In general, sand and gravel extraction will have less impacts to the river or stream hydrologic processes the higher up in the landscape the extraction site is located. Extracting sand and gravel from floodplains generally is preferable to removing sand and gravel from stream channels. Extracting sand and gravel from terraces is generally preferable to extracting sand and gravel from floodplains.
- Extracting gravel from a water-filled excavation located away from an active stream channel should cause little or no change to the natural hydrologic processes of the stream unless the stream captures the pit during periods of flooding. The exception is that changes in evapotranspiration, recharge, and runoff may create minor changes to the ground-water system, which may in turn affect stream flow.
- Extracting gravel from an excavation that does not penetrate the water table and is located away from an active stream channel should cause little or no change to the natural hydrologic processes unless the stream captures the pit during periods of flooding. The exception is that changes in evapotranspiration, recharge, and runoff may create minor changes to the ground-water system, which may in turn affect stream flow.
- Extracting gravel from an excavation that penetrates the water table, is mined dry by draining the ground water, and is located away from an active stream channel may change the natural hydrologic processes of the stream due to lowering of the ground-water system, which may in turn affect stream flow.
- Limiting extraction of material in floodplains to an elevation above the water table generally disturbs more surface area than allowing extraction of material below the water table.
- In-stream extraction of gravel from below the water level of a stream generally causes more changes to the natural hydrologic processes than limiting extraction to a reference point above the water level.
- In-stream extraction of gravel below the deepest part of the channel (the thalweg) generally causes more changes to the natural hydrologic processes than limiting extraction to a reference point above the thalweg.
- Excavating sand and gravel from a small straight channel with a narrow floodplain generally will have a greater impact on the natural hydrologic processes than excavations on a braided channel with a wide floodplain.
- Extracting sand and gravel from a large river or stream will generally create less impacts than extracting the same amount of material from a smaller river or stream.

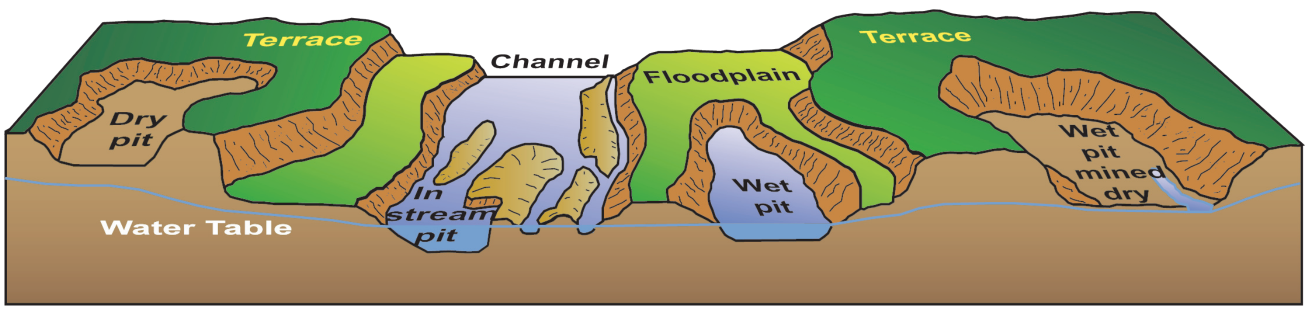


Figure 28. Aggregate extraction can take place in a number of in-stream or near-stream environments.

There are some general operating practices that can be followed to limit environmental impacts from in-stream mining. They are:

- Extracting sand and gravel from areas of riffles commonly should be avoided because removing gravel from riffles commonly results in increased erosion and threatens important fish habitat.
- Relocating or straightening stream channels commonly should be avoided because such actions shorten the stream, which results in increased stream velocity and associated erosion.
- Settling ponds for sand and gravel wash water should properly sized, should be protected so that they are not inundated during flooding, and should be located far away from the channel so that the warm, silty wash water cannot enter the stream.
- Berms, dikes, and stockpiles can modify flood levels and flow patterns. Berms and dikes should be designed with this in mind, and stockpiles should be located out of the floodplain or as far away from the channel as possible.
- An undisturbed buffer should be maintained at the top of the bank for the length of the excavation, and the access areas should be replanted once excavation is completed.
- Mining should be avoided during spawning seasons or other critical habitat times if sand and gravel extraction causes increased turbidity.
- Clearing of riparian woodlands should be avoided when sufficient material can be obtained in less densely vegetated areas.
- Waterlogged trees, deadheads, and large boulders can be placed along streamside to provide diversity of habitat.
- Aggregate extraction can add to habitat diversity by varying configuration, slopes, and elevations of graded areas during final reclamation.

Risk Analysis

Risk analysis is an alternate method to identify potential impacts that could be initiated by in-stream mining. Some approaches to risk analysis are linear, assume only one causal factor, and tend to overemphasize stability. However, river systems should be studied holistically in as much as they change over time and are composed of numerous diverse elements linked by strong interactions. A systems analysis approach to risk analysis emphasizes natural processes, focuses on multiple interactions among the elements of a system, and integrates time, feedback, and uncertainty (Langer, in press; Langer and Kolm, 2001a; 2001b).

The systems analysis method is iterative and begins with the creation of conceptual models that provide a preliminary understanding of how the river system behaves at the extraction site and at off-site areas that might be impacted. Conceptual models can be based on field observations and on stream classification systems such as those proposed by Rosgen (1994), Schumm (1963, 1977), Nanson and Croke (1992), or any of many other researchers (see Rosgen, 1994 for a discussion of stream classification systems). Conceptual models are tested and revised using scientific principals, existing data, new field or laboratory data, and experience. Study of the past behavior of a reach of a stream during various intensities of sand and gravel extraction can yield results that can cautiously be applied to similar reaches of the same stream or other similar streams in the region.

Each iteration of the process increases the understanding of the total system and, thus, reduces uncertainties. Because the understanding of each part of a system depends on an understanding of the others, analyses of the individual natural systems are integrated with one another. The process results in the characterization of the entire environmental system.

After the stream is characterized, an approach to sand and gravel extracting and processing is selected based on the characteristics of the site. The method then determines how sand and gravel extraction will impact the entire hydrologic system, including the atmospheric, land surface, geomorphic, subsurface, and ground-water systems. This requires learning how the various parts of the natural system (including the human part) create and transmit impacts and the resulting condition of the impacted system.

The process continues by identifying initiating events and consequences caused by the proposed mining techniques. Human initiating events include excavating, dewatering, transport of material, crushing, screening, and washing material. Human activities outside a sand and gravel pit can also be initiating events. For example, a change in land use from a natural area to a paved area (such as urbanization or highway construction) could create increased runoff and cause an aggregate operation to become flooded. Many human initiating events are neither planned nor started at the time an environmental analysis is being conducted, thus making prediction very difficult.

Natural initiating events include climatic events (droughts, heavy precipitation, and precipitation during critical periods), seismic activity, landslides, natural groundwater level changes, and natural fluvial processes. Most natural initiating events are difficult to predict.

One consequence may be the initiating event for a subsequent consequence (as discussed in the section on stream dynamics). For example, extracting too much gravel, extracting gravel from the wrong part of the stream, or excavating too deeply (all initiating events) can create a change in the cross section of the stream (consequence). Changing the cross section can be the initiating event that creates an increased gradient at the site of excavation (consequence). Increasing the gradient of the stream can be the initiating event that causes upstream incision – otherwise known as headcutting (consequence). Headcutting can cause bank erosion (consequence), which can cause trees to fall over (consequence), which can cause loss of shade along stream banks (consequence), which can result in loss of aquatic and riparian habitat. And on, and on.

Logic trees (fig. 29) are an analytical method that may be used to develop an understanding of the component inputs to environmental impacts by organizing the sequence of events and establishing the role and relationship of the variables affecting the outcome (Dryden and Beer, 1999). Logic trees may be event-driven, and show all the consequences that may result from one initiating event, consequence-driven and show all the events leading to one consequence, or a combination showing how one event can have multiple paths to the same consequence. Logic trees can also show methods to control or limit consequences.

The next step of the process is to determine the likelihood that a potential consequence will become real. Likelihood estimates can be described in many ways, such as the likelihood of a specific consequence occurring per unit of time, per unit of area mined, or per unit weight or volume of material produced. Sometimes, such as with a rare or endangered species or with a sensitive ecosystem, the relevant measure may be a probability of occurrence of the consequence within the life of the operation.

The next step of the process, environmental risk evaluation, combines the outputs from the consequence and likelihood analyses to create an estimate or indication of the likelihood of defined adverse outcomes (fig. 30). An environmental risk describes the consequences if the impact becomes real and the likelihood that the impact will become real. There can be environmental risks without any environmental consequences. The question is, can the operator successfully manage the risks?

Environmental risk management is a continuing process. After all systems have been analyzed and all risks have been characterized, an assessment of the adequacy of process is conducted. If the process is judged to be incomplete or inadequate, the process is repeated at whatever step or level is required. If the process is judged to be complete, aggregate extraction can begin. Information learned while excavating aggregate is plugged back into the site characterization, thus further reducing the uncertainty.

An example of the application of risk analysis to in-stream mining has been published by the Society for Mining, Metallurgy, and Exploration (Annandale and Gilpin, 1992). Although the risks analyzed in this example are those that relate to the mining operation, the approach is similar to one that could be applied to analyzing risks to the environment.

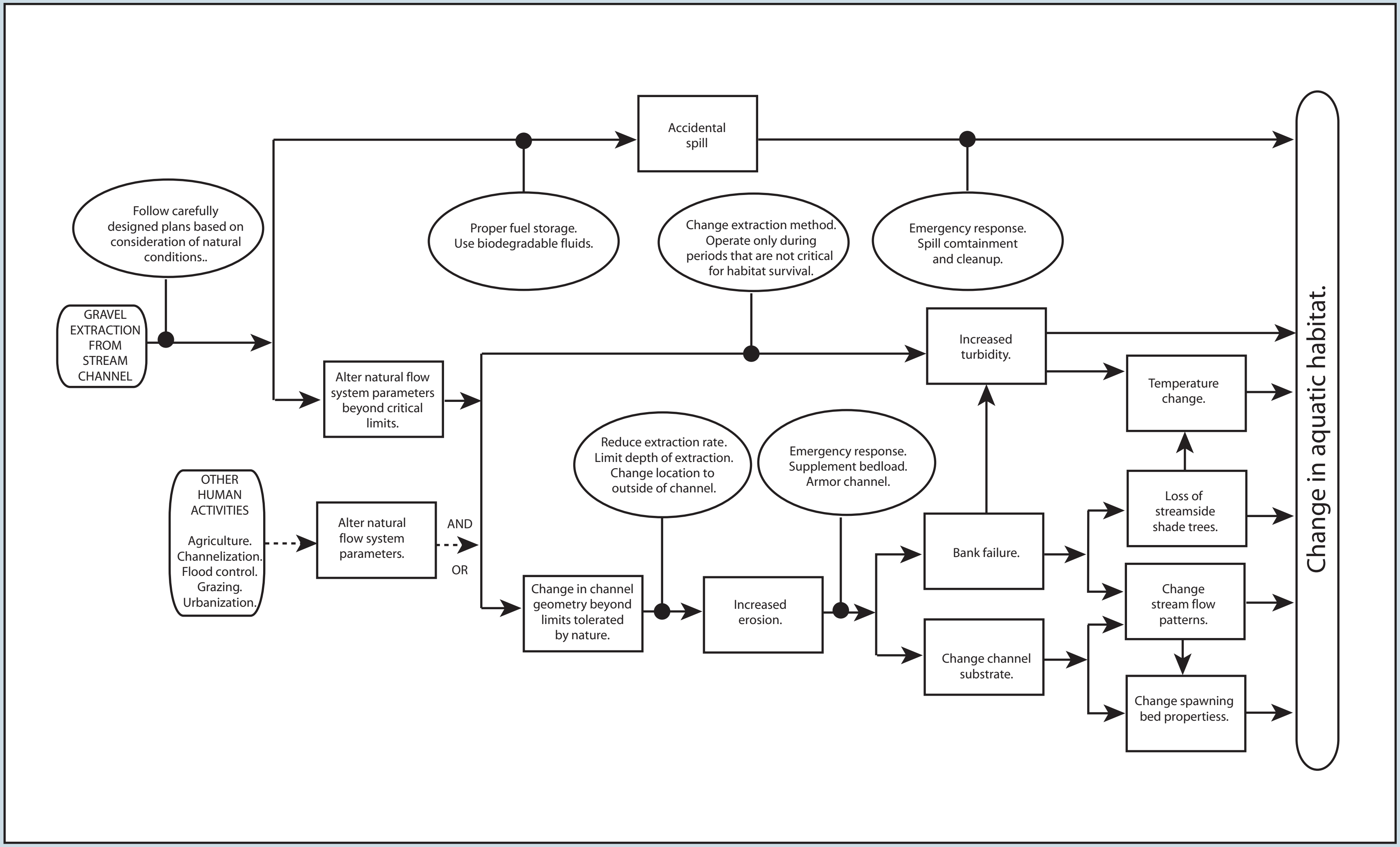


Figure 29. Example logic tree showing potential changes in aquatic habitat resulting from hypothetical in-stream sand and gravel extraction. Ovals represent actions to prevent or limit changes.

Restoration and Reclamation

Allowing the natural restoration of the impacts of in-stream mining may require reduction or cessation of sand and gravel extraction. The Giffre River in the northern part of the French Alps rehabilitated itself following extensive extraction of gravel from the river channel (Piégay and Peiry, 1997). River restoration was largely due to the fact that after the amount of material extracted from the channel was reduced, the bedload supply greatly exceeded extraction.

The time required for a stream to naturally recover from impacts caused by sand and gravel mining is highly dependent on the local geologic conditions. Recovery in some streams can be quite fast. Using streambed elevation data, Jacobson (1995) reported that the Meramec River, Missouri, recovered within two years after channel dredging stopped. The relatively quick recovery of streambed elevation in the river was indicative of a river with an abundant bedload. Conversely, the Big Rib River, Wisconsin, was only in the early stages of recovery 20 years after the stream had been mined (Kanehl and Lyons, 1992).

Natural restoration of rivers may possibly be enhanced through gravel replenishment. In some areas, the construction of dams has created environmental impacts that are similar to, but more severe than, those from in-stream mining. Adding gravel to the stream to replace the sediment lost to dams (fig. 31) has restored salmon habitat in streams below dams. Gravel replenishment has been done on streams in California and on the Rhine River on the border between France and Germany (Kondolf, 1997).

Natural restoration or human reclamation of the stream-side environment commonly is a complicated process, and involves many other human changes in addition to those related to in-stream mining. Arbogast and others (2002) describe how the landscape along Clear Creek, a stream near Denver, Colorado, evolved in response to agriculture, urbanization, and aggregate mining (fig. 32).

Human reclamation of river or stream environments requires a design plan and product that responds to a site's physiography, ecology, function, artistic form, and public perception (Arbogast and others, 2000). Understanding design approach can turn features perceived by the public as being undesirable (mines and pits) into something desirable (fig. 33). Forward-looking mining operators who employ modern technology and work within natural restrictions can create a second use of mined-out sand and gravel operations that often equals or exceeds the value of the pre-mined land use.

Industry trade publications contain numerous examples of reclamation techniques applied to in-stream mining sites. As examples: Reilly (1999) describes an experimental salmon enhancement project on Oregon's Applegate River. Techniques included excavation of off-channel alcoves to serve as habitat for fish during high water events and during summer low flow. Habitat construction also included planting of willow, alder, and cottonwood. Weaver (1996) describes how gravel operations on a terrace above the floodplain of the Cache la Poudre River in Colorado were reclaimed as a golf course and lakeside residential property.

	Consequence				
	Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood					
Almost certain	S	S	H	H	EX
Likely	M	S	S	H	EX
Moderate	L	M	S	H	H
Unlikely	L	L	M	S	H
Rare	L	L	M	S	S
Unknown	S	S	H	H	EX

EX	Extreme risk: Project not viable without major redesign
H	High risk: Effective control measurements, monitoring program, and hazard response program must be demonstrated
S	Significant risk: Effective control measurements and monitoring program must be demonstrated
M	Moderate risk: Program for reduction must be specified
L	Low risk: Manage by routine procedures

Figure 30. Matrix characterizing environmental risk by combinations of consequences and likelihoods.

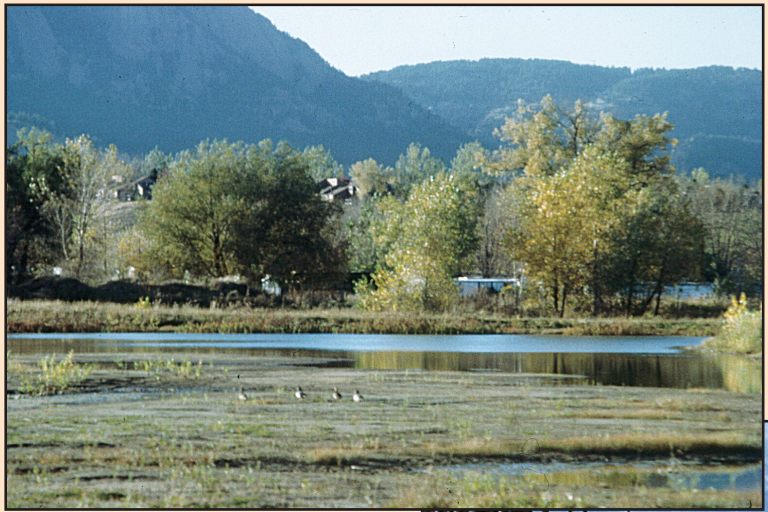
Similarly, some State geological surveys describe in-stream mining restoration techniques. For example, Norman (1998) described how ponds resulting from aggregate mining along the Wyonoochee River in Washington have been reclaimed for off-channel salmon habitat. Requirements for successful reclamation are that the ponds have good access for fish to enter and leave the main river channels; low risk of avulsion, flooding or drought; and adequate food supply, cover, and water quality.

Most aggregate permits issued today require a formal reclamation plan. Natural factors that impact how a sand and gravel operation can be reclaimed include the configuration of the pit, whether or not the pit penetrated the water table, the local geology, and the local climate. Examples of how to guide planning and reclamation of in-stream gravel mining operations through use of scientific information have been published by a number of agencies including the Colorado Division of Minerals and Geology (1998) and the California Division of Mines and Geology (Collins and Dunne, 1990).

Figure 31 (above). Gravel pile injection near old dam site. *(Photo courtesy USDA NRCS)*

Figure 32 (right). Contrasting aerial photographs of Clear Creek. Top photograph was presumably taken from a balloon about 1900. Bottom photograph is a similar view taken during 2000. *(Top photo by Colorado Historical Society, (negative no. 34.889). Bottom photo by B.F. Arbogast, USGS)*

Figure 33. Understanding design approach can turn in-stream and near-stream aggregate operations into something perceived by the public as being desirable. All photographs above show areas reclaimed from aggregate operations, either in-stream operations or operations on flood-plains or adjacent stream terraces.



(Left) Wildlife habitat. *(Photo by Western Mobile)*

(Above) Wetlands and suburban nature park. *(Photo by Raymond Sperger)*

(Right) Residential lakefront property. *(Photo by B.F. Arbogast, USGS)*

Recreation. *(Photo by Cooley Gravel Company)*

Residential lakefront property. *(Photo by B.F. Arbogast, USGS)*

Municipal water storage. *(Photo by B.F. Arbogast, USGS)*

Summary and Conclusions

1. During the year 2000, the United States consumed 2.76 billion metric tons of natural aggregate worth $14.4 billion. Of this amount 1.17 billion metric tons, or 42.4 percent, was sand and gravel, with a value of $5.7 billion. The percentage of total aggregate production that is sand and gravel varies widely from state to state. Hawaii consumes 7.7 percent sand and gravel, which is lower that any other state. Delaware, Louisiana, and North Dakota all consume 100 percent sand and gravel. About half of the aggregate (including crushed stone as well as sand and gravel) is used in government-funded projects.

2. Most sand and gravel produced in the United States is of alluvial, glaciofluvial, or marine origin. Stream-channel or terrace deposits of sand and gravel are widely distributed throughout the United States, and in some areas these are the only sources of any type of natural aggregate. In some areas, sand and gravel does not meet the physical or chemical requirements for certain uses. The resource may not be accessible because of conflicting land use, environmental restrictions, zoning and regulations, or citizen opposition. There are large regions, and even entire counties, where the places to obtain sand and gravel are extremely limited. In these areas, importing sand and gravel from outside the area or substituting another material for sand and gravel may be necessary.

3. The two most widely used substitutes for sand and gravel are crushed stone and recycled concrete or asphalt. Potential sources of crushed stone are widely distributed throughout the United States, but some large areas contain no potential sources; sand and gravel is the only source of aggregate. Aggregate companies recycled a total of 14.5 Mt of asphalt or cement concrete in 2000, which constitutes less than 1 percent of total national aggregate demand. Furthermore, it is the user, not the producer, who commonly specifies the type of aggregate, and in some applications the user will not accept a substitute for naturally occurring sand and gravel.

4. Rivers are complex, dynamic geomorphic systems whose major function is to transport water and sediment. The climatic, geologic, topographic, vegetative, and land-use character of the drainage basin determines the discharge and sediment load it must handle under a variety of flow rates, as well as the location, type, and amount of sand, gravel, and other sediments present along various stretches of the river.

5. The normal variations of discharge and load commonly can be accommodated by a river without major changes to the channel. If a river is exposed to major long-term changes in climate or basin tectonics, or is exposed to certain types of human activities, such as agriculture, urbanization, bridge construction, channelization, and in-stream mining, the river may adjust its channel geometry if one or more variables are altered beyond certain limits.

6. There are numerous methods to extract sand and gravel from stream channels including excavation with conventional earth moving equipment, channel dredging, channel diversion, and mining from ephemeral channels. The method chosen commonly depends on the nature of the deposit and on operator preference.

7. In-stream mining can be conducted without creating adverse environmental impacts provided that the mining activities are kept within the hydraulic limits set by the natural system. Many rivers and streams can accommodate the removal of some portion of their bedload without serious effects. However, if in-stream aggregate mining creates too large a change in specific hydraulic variables, those changes may produce environmental impacts. The nature and severity of the impacts are highly dependent on the geologic setting and characteristics of the stream.

8. The principal cause of impacts from in-stream mining is the removal of more bedload than the system can replenish, or shortening of the stream channel. A decrease in bedload or channel shortening can cause headcutting and downstream erosion. The stream may change its course, thus causing bank erosion and the undercutting of structures. In-stream mining can also result in creation of deep pools, loss of riffles, channel shortening, overwidening channels, increased turbidity, and changes in aesthetics. All these impacts can result in major changes to aquatic and riparian habitat, and associated impacts to the biota occupying those habitat.

9. Environmental impacts from in-stream mining may be avoided if the annual bedload is calculated and aggregate extraction is restricted to that value or some portion of it. Defining a minimum elevation for the deepest part of the channel and restricting mining to the volume above this elevation may allow gravel extraction without adverse impacts. Some sections of a river are more conducive to aggregate extraction than others, and removal of gravel from some aggrading sections of a river may be preferable to removing it from eroding sections. Even if a section of river is eroding, aggregate mining may take place without causing environmental damage if the channel floor is, or becomes, armored by particles that are too large to be picked up by the moving water. Risk analysis is an alternate method for identifying potential impacts by in-stream mining.

10. Restoring streams or mitigating the impacts of in-stream mining requires reduction or cessation of sand and gravel extraction. The time required for a stream to recover from impacts caused by sand and gravel mining is highly dependent on the local geologic conditions, and mad-made impacts upstream and downstream. Some streams can recover from in-stream mining in a few years, while other streams may take decades to recover. Wisely restoring our environment requires a design plan and product that responds to a site's physiography, ecology, function, artistic form, and public perception.

In-stream gravel mine reclaimed as natural wildlife area. *(Photo by Jonathan Eady)*

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