ENVIRONMENTAL IMPACTS OF MINING NATURAL AGGREGATE

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Abstract. Nearly every community in nearly every industrialized or industrializing country is dependent on aggregate resources (sand, gravel, and stone) to build and maintain their infrastructure. Indeed, even agrarian communities depend on well-maintained transportation systems to move produce to markets. Unfortunately, aggregate resources necessary to meet societal needs cannot be developed without causing environmental impacts.

Most environmental impacts associated with aggregate mining are benign. Extracting aggregate seldom produces acidic mine drainage or other toxic affects commonly associated with mining of metallic or energy resources. Other environmental health hazards are rare. Most of the impacts that are likely to occur are short-lived, easy to predict and easy to observe. By employing responsible operational practices and using available technology, most impacts can be controlled, mitigated or kept at tolerable levels and can be restricted to the immediate vicinity of the aggregate operation.

The most obvious environmental impact of aggregate mining is the conversion of land use, most likely from undeveloped or agricultural land use, to a (temporary) hole in the ground. This major impact is accompanied by loss of habitat, noise, dust, blasting effects, erosion, sedimentation, and changes to the visual scene.

Mining aggregate can lead to serious environmental impacts. Societal pressures can exacerbate the environmental impacts of aggregate development. In areas of high population density, resource availability, combined with conflicting land use, severely limits areas where aggregate can be developed, which can force large numbers of aggregate operations to be concentrated into small areas. Doing so can compound impacts, thus transforming what might be an innocuous nuisance under other circumstances into severe consequences. In other areas, the rush to build or update infrastructure may encourage relaxed environmental or operational controls. Under looser controls, aggregate operators may fail to follow responsible operational practices, which can result in severe environmental consequences.

The geologic characteristics of aggregate deposits (geomorphology, geometry, physical and chemical quality) play a major role in the intensity of environmental impacts generated as a result of mining. Mining deposits that are too thin or contain too much unsuitable material results in the generation of excessively large mined areas and large amounts of waste material. In addition, some geologic environments, such as

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active stream channels, talus slopes, and landslide-prone areas, are dynamic and respond rapidly to outside stimuli, which include aggregate mining. Some geomorphic areas and (or) ecosystems serve as habitat for rare or endangered species. Similarly, some geomorphic features are themselves rare examples of geologic phenomena. Mining aggregate might be acceptable in some of these areas but should be conducted only after careful consideration and then only with extreme prudence. Failure to do so can lead to serious, long-lasting environmental consequences, either in the vicinity of the site or even at locations distant from the site.

Mining generates a disturbed landscape. The after-mining use of the land is an important aspect of reducing environmental impacts of aggregate extraction. The development of mining provides an economic base and use of a natural resource to improve the quality of human life. Wisely restoring our environment requires a design plan and product that responds to a site's physiography, ecology, function, artistic form, and public perception. Forward-looking mining operators who employ modern technology and work within the natural restrictions can create a second use of mined-out aggregate operations that often equals or exceeds the pre-mined land use. Poor aggregate mining practices, however, commonly are accompanied by poor reclamation practices, which can worsen already existing environmental damage.

With environmental concerns, operating mines and reclaimed mine sites can no longer be considered isolated from their surroundings. Site analysis of mine works needs to go beyond site-specific information and relate to the regional context of the greater environment. Understanding design approach can turn features perceived by the public as being undesirable (mines and pits) into something perceived as being desirable.

1. Introduction

Aggregate resources (sand, gravel, and crushed stone) rank first in order of amount and value of the global extracted mineral resources [1]. Nearly every community, whether industrialized or agrarian, is dependent on aggregate resources to build and maintain their infrastructure.

Geology controls where aggregate occurs. Although aggregate tends to be widely distributed, there are large areas where it is absent. Geologic conditions also control the type and properties of the potential aggregate resource. For example, glacial deposits yield different types of gravel than marine terraces, and volcanic rocks have different properties than intrusive rocks. The properties of the aggregate determine the environmental impacts that might result from mining the resource, as well as the amount of processing and the amount of waste material generated.

Aggregate is a low-unit value, high bulk commodity. Consequently, excavation of aggregate near the point of use, which is commonly at population centers, is most economical. In these areas, conflicting land use, regulations, and citizen opposition further restrict the development of aggregate. In some areas, the options for places to develop aggregate resources are extremely limited.

Unfortunately, aggregate resources necessary to meet societal needs cannot be developed without causing environmental impacts. At one time, aggregate and other resources could be mined with little regard as to how that mining might impact the environment. Fortunately, that situation has changed in many parts of the world, and responsible operators must reckon with the environmental impacts created by aggregate mining.

When options for extracting aggregate are limited, identification of areas for extraction that are free from potentially serious environmental problems may not be possible. We may be forced to develop aggregate resources in areas that we otherwise might choose to avoid. That we understand what potential environmental impacts exist, and know how to mitigate or avoid those impacts is of utmost importance.

2. Environmental impacts from aggregate mining

2.1 DEFINITION OF ENVIRONMENTAL IMPACT

Although the scientific literature is replete with discussions about impacts from metallic and coal mining, far fewer reports describe details of environmental impacts from aggregate mining. (Some of those reports are included in symposium volumes or other comprehensive collections of individual papers, many of which are referred to in this paper.) Therefore, before beginning a discussion of environmental impacts of aggregate mining, it is beneficial to define what is meant by environmental impact. Kelk [2], defined environmental degradation or pollution as follows:

> the alteration of the environment by man through the introduction of materials which represent potential or real hazards to human health, disruption to living resources and ecological systems, [or] impairment to structures or amenity * * *

For use in this paper, Kelk's term "introduction of materials" is expanded from "introduction of materials or activities" to include aggregate mining. It is important to note that the definition includes humans, other living resources, ecological systems, and structures.

2.2 GENERAL TYPES OF IMPACTS FROM AGGREGATE MINING

We cannot obtain aggregate resources without causing some environmental disturbance. Some of the disturbance is caused directly by the mining or processing activities. The most obvious environmental impact of aggregate mining is the conversion of land use, most likely from undeveloped or agricultural land use, to a hole in the ground. This major impact may be accompanied by loss of habitat, noise, dust, vibrations, chemical spills, erosion, sedimentation, changes to the visual scene, and dereliction of the mined site. (Some references that generally describe these impacts include Barksdale [3]; Kelk [2], Smith and Collis [4], Lüttig [5], and Bobrowski [6].)

Mining may cause secondary impacts or a ripple effect. Some are obvious, such as transporting aggregate from the plant to the market frequently results in heavy traffic. Some are less obvious, such as mining in some environments may cause stream erosion. Erosion may cause loss of shade along stream banks, which, in turn, may cause loss of fish habitat.

Societal pressures can exacerbate the environmental impacts of aggregate development. In areas of high population density, resource availability, combined with conflicting land use, severely limits areas where aggregate can be developed, thus forcing large numbers of aggregate operations to be concentrated into relatively small areas. Doing so can compound impacts and transform what might be an innocuous nuisance under other circumstances into severe consequences. In other areas, the rush to build or update infrastructure may encourage relaxed controls. Under looser controls, aggregate operators may fail to follow responsible operational practices, which can result in severe environmental consequences.

2.3 NATURE OF ENVIRONMENTAL IMPACTS

One way to assess an environmental impact is to characterize its nature. The nature of an impact can be referred to by using a number of terms that include range, timing, duration, ability to predict, and ability to control. In this paper, these terms are expressed in relative values.

2.3.1 *Range of Impact*

The range of the impact refers to how large the area is that is impacted by the aggregate operation. Impacts, such as conversion of land use, are commonly (although not always) restricted to the site. Impacts, such as noise and dust, are commonly limited to the near-site area. Impacts, such as erosion, sedimentation, and changes to the visual scene, may be widespread.

2.3.2 *Timing of Impact*

The timing of the impact refers to how rapidly the impact develops. Impacts, such as conversion of land use, take place immediately. Other impacts, such as erosion, may not begin to be noticed until many years after aggregate extraction begins.

2.3.3 *Duration of Impact*

The duration of the impact refers to how long the impact lasts. The impacts associated with noise commonly last only as long as the equipment generating the noise is being operated. The impacts associated with conversion of land use commonly last until the operation is reclaimed, at which time yet another conversion of land use will occur. Other impacts, such as erosion, may last for an extended period of time

2.3.4 *Ability to Predict Impact*

The ability to predict the impact refers to how easily one can anticipate that the impact will occur and how easily one can predict the range, timing, and duration of the impact.

Predicting the range, timing and duration that results from conversion of land use is relatively easy; predicting those factors for subsequent erosion is more difficult.

2.3.5 *Ability to Control Impact*

The ability to control the impact refers to how easily one can avoid, minimize, or mitigate an impact. Impacts, such as dust, commonly can be avoided or minimized by using modern careful production techniques and modern technology. Impacts like erosion may be difficult to control.

The above terms often are interrelated. For example, an impact that is widespread is likely to have a long duration. Similarly, an impact that is difficult to predict is likely to be difficult to control.

3. Discussion of Impacts

Aggregate mining is divided into three distinct phases - site preparation, aggregate excavation, and aggregate processing. Each phase of mining is typified by specific activities, with each activity having the potential to create specific types of environmental impacts. This section of the report describes the impacts that result from the three phases of mining, and offers measures that can be taken to mitigate the impacts.

3.1 IMPACTS FROM SITE PREPARATION

Site preparation commonly starts with stripping a sufficient amount of overburden to access the resource. The method used depends on the type and thickness of material to be removed. Soil and partially weathered rock can be pushed aside with a bulldozer and removed with conventional loaders and haul trucks. Harder, more-consolidated material may require drilling and blasting. Organic soil commonly is separated from the overburden and stockpiled for reclamation activities. Overburden may also be used to construct berms, stockpiled, or sold. When pre-production stripping is complete, berms, haul roads, settlement ponds, processing and maintenance facilities, and other plant infrastructure are constructed by using standard building techniques.

The land use immediately preceding mining might not be the original land use. Civilizations in many parts of the world have created enormous impacts on the landscape. What we are witnessing today is only the most current nature of the landscape. The land use at any particular site may have changed many times owing to forces of nature and of our predecessors.

3.1.1 Conversion of Land Use

The most obvious environmental impact of aggregate mining is the conversion of land use, most likely from undeveloped or agricultural lands, to an aggregate operation. The impact to the site commonly is quite dramatic because open-pit mining, which is the common method of winning aggregate resources, is dramatically different from other types of land use. The mine site, however is a designed facility, and the impact is, therefore, predictable and controllable.

One method to minimize the impact of conversion of land use is to develop the best resources available. For example, quarrying a thin, flat-lying limestone bed with thick overburden will likely create more environmental impacts than quarrying a thick granitic intrusive body with thin overburden. To obtain the same amount of material, the limestone quarry will have to move more overburden, be larger in area, and result in more spoil piles than the granite quarry. Of course, the limestone might have certain properties that the granitic rock does not possess and might be developed instead of the granite for that reason.

Another means of minimizing environmental impacts is through the development of superquarries. A single huge operation at an environmentally acceptable site may be preferable to many smaller quarries at scattered locations. The concept is dependent on cheap, high-volume transport and on benefits to the local economy through revenues earned from export of aggregate [2].

Accompanying conversion of land use is a change to the visual scene (viewshed) either from the site or from locations remote from the site. The change, which can be either temporary or permanent, is a very subjective topic; what is acceptable to some people is objectionable to others. The nature of this impact depends on the topographic setting, natural ground cover and type of operations. The change to the visual scene for quarries commonly is an issue because most quarries have a very long duration. The extended duration of quarries may result in unpleasant visual impacts and semi-permanent nuisances to the local environment.

The change to the visual scene can be mitigated through sequential reclamation, buffering, and screening (including berms, tree plantings, fencing, or other landscaping techniques). Overburden and soil can be stockpiled in out of the way places. The area impacted can be predicted by using standard off-the-shelf geographic information systems with line-of-site calculation capabilities.

With most aggregate operations, conversion of land use to mining is commonly temporary. After mining has been completed, the land can be reclaimed and converted to yet another land use. In many instances, the second use is equal to or more acceptable than the original use.

3.1.2 Destruction of Habitat

Site preparation results in destruction of habitat in the actual mined area. Unless relocated, vegetation and wildlife that is not mobile is destroyed. Mobile wildlife may leave the site for other areas. Some areas of aggregate serve as habitat for rare or endangered species. In addition to habitat, aggregate mining may impact archeological sites, and in some instances, the geologic deposit may be a rare feature itself. For example, Gonggrijp [7] described how the only esker system in The Netherlands has had an extensive part of it mined for aggregate. Mining aggregate might be acceptable in some of these areas but should be conducted only after meeting all permitting requirements and then only with extreme prudence.

Habitat destruction cannot be eliminated, but can be controlled by regulations and, in some situations, by relocating selected animals or plants. In some cases, the site can be reclaimed to look similar to the original habitat after mining has ceased.

3.1.3 Erosion

The potential for erosion from site preparation occurs in moderate to steep areas where aggregate mining results in the removal of vegetation, soil cover, and changing the natural land surface slopes. Except in rare geographic settings, common engineering practices can limit erosion.

3.1.4 Landslides

Aggregate operations in, or near, the toe or head of an existing landslide deposit can remobilize the slide. Even in areas where natural factors are not conducive to slope failure, aggregate mining can cause landslides. Goswami [8] investigated landslides in Gauhati, northeastern India, and attributed the failure to aggregate mining that had disrupted the natural equilibrium of the hill slopes and their natural drainage conditions.

Aggregate operations should avoid areas of known landslides and areas with slope, aspect, and geologic conditions that are favorable for mass movement.

3.1.5 Sedimentation

Earth moving associated with site preparation may increase sedimentation in nearby streams. Sedimentation commonly can be controlled with techniques employed in normal construction, such as with catchment basins or erosion barriers.

3.1.6 Stream Flow

Aggregate mining may create impervious land that prevents infiltration, remove vegetation that normally retards runoff, or otherwise change runoff patterns. The resultant faster, higher peak runoff can result in higher peak stream flow.

Retaining the runoff in infiltration basins can mitigate the impact.

3.1.7 Ground water

Under some geologic and climatic conditions, removing vegetation and soil from the land surface can reduce evapotranspiration and ultimately increase ground water. Changes in ground-water quality in areas of sand and gravel mining [9] are attributed to the removal of soil that had been acting as a protective layer, filtering, or otherwise reducing contaminants to the ground water. The level of impact ranges depends on a number of factors, which include the thickness of material removed, the surface area involved, the total volume of the aquifer, and recharge to the aquifer.

Impacts can be mitigated by controlling recharge in aggregate operations, or by locating resource extraction areas outside of recharge areas.

3.2 IMPACTS FROM AGGREGATE EXTRACTION

A variety of methods can be used to excavate aggregate. The methods to excavate aggregate depend, in large part, on the geologic environment. Sand and gravel is commonly mined from pits or dredged from water bodies. Crushed stone is mined from quarries and requires drilling and blasting prior to excavation. The impacts are different for each type of excavation.

3.2.1 Dry Pit

In this paper, if sand and gravel mining does not penetrate the water table, then it is referred to as a "dry pit." The aggregate is dry and can be extracted by using conventional earth-moving equipment, such as bulldozers, front loaders, track hoes, and scraper graders. The equipment chosen commonly depends on the lay of the land and on operator preference.

The impacts from excavating aggregate from a dry pit are commonly easy to predict, observe, and control with standard engineering practices. Dust and noise (discussed below) are the most common impacts. Runoff patterns may be changed.

3.2.2 Wet Pit Mined Dry

In this paper if sand and gravel mining extends to a depth that penetrates the water table, then it is referred to as a "wet pit." In some geologic settings, wet pits can be made dry by dewatering the pit. This is done by collecting the groundwater in drains in the floor of the pit and pumping the water out of the pit. Construction of slurry walls or other barriers to ground-water flow around the pit may be required. After ground-water drains from the deposit, sand and gravel can be extracted by using the dry mining techniques described above.

Two potential impacts of great significance result from dry mining of sand and gravel from the saturated zone (beneath the water table) - the effect of dewatering the pit and the potential for pit capture during floods (if the pit occupies an active floodplain). Dewatering commonly lowers the water table in the vicinity of the pit and may affect the flow of nearby streams. In some geologic settings, the streamflow will decrease. In others, drained water that is returned to streams can increase streamflow. The extent of the impact depends on the type of deposit (floodplain, stream terrace, alluvial fan, marine terrace, glaciofluvial, etc.), hydraulic properties of the aggregate deposit, the thickness of water table penetrated, where the drained water is discharged, and whether or not slurry walls are used.

The impacts from dewatering a pit can be monitored by use of observation wells. In highly permeable deposits, the use slurry walls might be necessary to isolate the pit from the water table. Water removed through dewatering can be returned to nearby streams.

Cut-offs and avulsions of a stream during floods may result in capture of a wet pit located on an active floodplain. Pit capture can result in changes in channel position and can substantially alter the spatial distribution of energy and force of the stream or river [10]. The ability to predict flooding and capture of the pit largely depends on how well the hydrology and history of the adjacent stream are known.

Levees may protect floodplain pits from flooding and stream capture.

3.2.3 Wet Pit Mined Wet

In some situations where the sand and gravel pits penetrate the water table, the pit may not be able to be drained, or the operator may prefer to extract the material by using wet mining techniques. Material may be excavated by using draglines, clamshells, bucket and ladder, or hydraulic dredges.

The greatest potential impact of mining a wet pit is if the pit is located on an active floodplain. Cut-offs and avulsions of a stream during floods may result in capture of the pit, thus resulting in the impacts described above in Section 3.2.2. Again, the ability to predict flooding and capture of the pit largely depends on how well the hydrology and history of the adjacent stream are known.

Depending on the geologic and climatic conditions, the pit can act as a recharge area or a discharge area. In humid areas, precipitation can collect in the pit and recharge the ground water. In semiarid or arid climates, evaporation from water in pits can lower the water table. Monitoring wells installed around the pit and stream gauges can be used to observe effects on the water table. Levees may protect floodplain pits from flooding and stream capture.

3.2.4 In-Stream Mining

Sand and gravel can be excavated directly from stream channels or from embayments dredged off of the main channel by using draglines, clamshells, bucket and ladder, or hydraulic dredges. During times other than flooding, aggregate can be skimmed from bars in the channel or from active floodplains by using the dry mining techniques described above.

Depending on the geologic setting, in-stream mining has the potential to create very serious environmental impacts. Impacts may be particularly serious if the stream being mined is an eroding, as opposed to an aggrading stream. Mossa and Autin [11], Kondolf [12], Florsheim *et al.* [13], as well as many other authors, have described the dramatic changes to river systems where in-stream mining is being improperly managed. Impacts can be a result of extracting too much material at one site, or the combined result of many small but intensive operations [14].

The principal cause of impacts from in-stream mining is the removal of more material than the system can replenish. The major impact of removal of gravel from the stream is a change in the cross section of the stream. This, in turn, has many secondary impacts. Upstream incision can result from increased gradient, and downstream incision can result from decreased sediment load. The stream may change its course, thus causing bank erosion. Erosion may cause the removal of vegetation and overburden and the undercutting of structures. In-stream mining can also result in channel bed armoring, increases in sediment load, lowering of alluvial water tables, and stagnant low flows. All these impacts can result in major changes to aquatic and riparian habitat.

Removal of gravel from aggrading streams may not cause adverse environmental impacts. Some eroding streams underlain with large gravel layers deposited under conditions other than those prevailing at the current time may support gravel extraction with no serious environmental impacts. Jiongxin [15] described such a situation on the Hanjiang River in China where downcutting stopped when coarse bed material was reached. Similar situations exist where coarse gravels of glacial origin underlie modern stream deposits.

The best method of mitigation of the impacts of in-stream mining is prevention of the impacts. Kondolf [16] suggested a number of strategies to manage in-stream mining of aggregate. One method is to define a minimum elevation for the thalweg (the deepest part of the channel) along the river and to restrict mining to the area above this line. Another method is to estimate the annual bedload and to restrict extraction to that value or some percentage of it. Difficulties may exist, however, in realistically determining the annual bedload.

Although riverbed incision is generally assumed to be irreversible, evidence of exceptions exist. In streams that suffer from the effects of in-stream mining, the first step for mitigation is to reduce or stop the excavation. Piégay and Peiry [17] described how the Giffre River in the northern part of the French Alps rehabilitated itself following extensive extraction of gravel from the river channel. This restoration is largely due to the fact that after the amount of material allowed to be extracted from the channel was reduced, the bedload supply greatly exceeded extraction.

3.2.5 Dry Quarry

Rock quarries that do not penetrate the water table or where discharge from the water table is offset by evaporation or is otherwise insignificant are referred to as dry quarries. To produce aggregate, the rock is first drilled and blasted. The types of drills or explosives vary because of the diversity of rock types and formations used as aggregate. Blasting commonly breaks the rock into pieces suitable for crushing. If the rubble is too large, then secondary breaking may be required. The blasted material is dry and can be extracted by using conventional earth-moving equipment, such as bulldozers, front loaders, track hoes, and scraper graders. The equipment chosen commonly depends on the lay of the land and on operator preference.

The main impacts from quarrying are the affects of blasting. Poorly designed or poorly controlled blasts may cause rocks to be projected long distances from the blast site (fly rock), which is a serious hazard. Poorly designed or poorly controlled blasting can fracture the surrounding rock, thus altering the ground-water flow paths. This ill effect of blasting, if it occurs, is difficult to observe or predict. Blasting may cause ground shaking for some distance from the quarry. Ground shaking can be monitored with seismic equipment and can be limited by reducing the size of the blast or by employing time-delay blasting techniques.

The technology of rock blasting has evolved substantially, and when blasting is properly conducted, its environmental impacts should be negligible. Blasting, however receives numerous complaints from neighbors. Blasting or other noise may also frighten certain types of wildlife, although buffer areas and areas of undeveloped reserves commonly serve as habitat for some wildlife. One way to manage complaints is through education, outreach, and prompt response to complaints.

3.2.6 Wet Quarry Mined Dry

Rock quarries commonly penetrate the water table. Where this occurs, the quarries commonly are kept dry by pumping of the water. The rock is then mined by using the procedures followed in a dry quarry.

The impacts of extracting aggregate from a wet quarry mined dry are similar to those for a dry quarry (Section 3.2.5). Depending on geologic conditions, dewatering the quarry may lower the water table that surrounds the quarry. The impact of dewatering on the water table can observed with monitoring wells.

3.3 IMPACTS FROM AGGREGATE PROCESSING

Aggregate processing consists of loading rock or sand and gravel, transporting the material to the plant, crushing, screening, washing, stockpiling, and loadout. Material commonly is transported from the mining face to the plant either by conveyor or truck. If the material consists of boulders or blasted rock, then it commonly goes through a primary crusher. A conveyor then moves it to a surge pile. A gate at the bottom of the surge pile releases material at a constant feed rate to an area where it is screened and sorted by size. Depending on the type of material being processed, and on the final product, the material may be washed. After screening, sorting, and washing, if necessary, the material is moved by conveyor to stockpiles. Upon sale, the final product is loaded on trucks, railcars, or barges for transport to the final destination. For this paper, processing also includes the repair and maintenance of equipment.

Dust, noise, and a change to the visual scene are all common impacts associated with any type of earth-moving activity, which includes aggregate processing. Dust can be from a point source, such as drilling or processing equipment or as fugitive dust from blasting or haul roads. A recent concern, primarily for worker safety, is the issue of dust that contains dangerous amounts of crystalline silica or carcinogenic particulates. The impacts from dust commonly can be mitigated by use of dust suppression techniques, which includes water, dust suppression chemicals, covers on conveyors, or the use of vacuum systems and bag houses. Workers are protected from dust through the use of enclosed, air-conditioned cabs on equipment and, where necessary, the use of respirators. Worker safety commonly includes regular health screening.

Noise is generated from blasting, excavating equipment, crushing and processing equipment, and trucks. The impacts of noise can be mitigated through the use of berms, locating noisy equipment (such as crushers) away from populated areas, limiting blast sizes, use of conveyors instead of trucks for in-pit movement of materials, and limiting the hours of operation. Workers are protected from noise through the use of enclosed, air-conditioned cabs on equipment and, where necessary, the use of hearing protectors. Worker safety commonly includes regular health screening.

Maintenance of equipment may result in the accidental release of fuel, solvents, or other chemicals. Accidental spillage can be controlled by limiting the amount or type of chemicals on hand and by careful operating and safety training and procedures.

4. Reclamation

Reclamation commonly is considered to be the start of the end of environmental impacts from mining. The development of mining provides an economic base and use of a natural resource to improve the quality of human life. Equally important, properly reclaimed land can also improve the quality of life. Wisely shaping mined out land requires a design plan and product that responds to a site's physiography, ecology, function, artistic form, and public perception.

Examining selected sites for their landscape design suggested nine approaches for mining reclamation. The oldest design approach around is nature itself. Humans may sometimes do more damage going into an area in the attempt to repair it. Given enough geologic time, a small site scale, and stable adjacent ecosystems, disturbed areas recover without mankind's input. Visual screens and buffer zones conceal the facility in a camouflage approach. Typically, earth berms, fences, and plantings are used to disguise the mining facility. A restoration design approach attempts to restore the land to its original landscape character. Rehabilitation targets social or economic benefits by reusing the site for public amenities, most often in urban centers with large populations. A mitigation approach attempts to protect the environment and to return mined areas to use with scientific input. Recognizing the limited supply of mineral resources and encouraging recycling efforts are steps in a renewable resource approach. An educative design approach effectively communicates mining information through outreach, land stewardship, and community service. Mine sites used for art show a celebration of beauty and experience-abstract geology. The last design approach combines art and science in a human/nature ecosystem termed "integration."

Site analysis of mine works needs to go beyond site-specific information and relate to the regional context of the greater landscape. Understanding design approach can turn undesirable features (mines and pits) into something perceived as desirable by the public.

In her study of landfill and sewage treatment, Engler [18] discussed eight approaches to designing waste landscapes. Mining generates a disturbed landscape that many consider waste until reclaimed, and Engler's terminology appears to be adaptable to reclaimed mine sites with minor reinterpretation (table 1).

Table 1. Design approaches to reclaiming mine sites

ENGLER'S LIST	AUTHORS' LIST	DESCRIPTION
	Natural	Allow nature to reclaim site with no, or minimal, human influence.
Camouflage	Camouflage	Conceal a mining facility with visual screens and buffers.
Restoration	Restoration	Return land to its approximate original condition.
Recycling	Rehabilitation	Use site for public amenities.
Mitigation	Mitigation	Repair mined-out site that has experienced extensive damage from human or natural causes.
Sustainable	Renewable resource	Use site to recycle man-made or natural resources.
Educative	Education	Communicate resource information through outreach.
Celebrative	Art	Treat site as work of beauty and unique experience.
Integrative	Integration	Combination of approaches integrating art and science.

One approach that Engler did not mention is nature itself. Although a combination of the above approaches is most often applied, examination of the specific categories with examples is still useful.

4.1 NATURAL

Wait long enough and no matter how great the disturbance, nature works to regenerate with or without the benefit of man. Some areas devastated from fire, landslide, volcanic eruption, or quarrying manage to recover well without human intervention. Therefore, a conscious natural design approach may be one of hands off. For example, the moist climate, dense vegetation, and remoteness of areas like Alaska are likely places for some mined-out pits to be passively reclaimed by nature. Heavy equipment brought in to recontour these old sites may do far more damage to the existing ground cover and surface soil than the benefit gained.

In other areas, long-term natural recovery may not bring about the specific changes people find desirable. Few, if any, people living near Appalachian coal mining sites would want to wait 30 years for hardwood seedlings to sprout. Studying nature's ability to heal is one way scientists and designers can learn new techniques for reclamation by taking maximum advantage of natural geological and biological processes.

Natural seedfall for restoration of cottonwood (*Populus* sp.) and willow (*Salix* sp.) was tested in a sand and gravel pit near Fort Collins, Colorado, U.S.A. Controlled flooding was used to simulate historic spring flooding conditions along the Poudre River to establish vegetation [19]. With additional timed floodings, clearing of undesirable exotic saltcedar (*Tamarix chinensis*) seedlings was successful. The pit is an example of seminative riparian vegetation being used to reclaim a site with little human involvement and cost.

4.2 CAMOUFLAGE

Camouflage uses visual screens and buffer zones to conceal the mining or mined out facility and to provide barriers to sound, dust, and noise. Austin [20] calls using landscape skills "merely to provide a cosmetic touch to an otherwise ravaged landscape, an exercise akin to putting lipstick on a pig." This may have been true in the past when reclamation took a backseat to exploration, but in some instances, a minimal approach is justified. In the past, an immediate response by the industry was to use fences, earth berms, and plantings (small-scale features) to disguise the activity from residential areas. The design solution was frequently associated just with the site perimeter. Camouflage commonly made use of linear, uniform rows of quick-growing plant species. Wide buffer zones were frequently abandoned in the interest of cost. Today, progressive aggregate companies recognize the value of including landscape architects early in the planning stage. For example, a long-term approach to camouflage may involve the use of quick-growing plants as part of a matrix that contains the slower growing native species matched to grow in the overburden and spoil material. Another consideration is the profound effect vegetation has on water control (infiltration and erosion).

4.3 RESTORATION

Returning the land exactly to its original condition is a restorative approach. Mining is considered to be a temporary activity that leaves a disturbed area that many think should be returned to pre-mining biological conditions. Restoration to the original condition is seldom possible because we do not currently have the level of information and skill required to return ecosystems exactly to their original structure. In addition, the new land is environmentally unstable, and exotic species invade disturbed sites. Many native organisms do not return or fill the same ecological niche. Instead of returning an area to its original condition, a more-realistic approach is to approximate the new habitat as closely as possible to its original function and to recapture the landscape character.

4.4 REHABILITATION

A rehabilitative approach reclaims mined-out land for public amenities with social or economic benefits. Beginning in 1904, Butchart Gardens in British Columbia, Canada, reclaimed 50 acres of an exhausted limestone quarry to a premier botanical garden. The city hall of Hagen, Germany, is located on the site of an inactive quarry [21]. Many of the natural rock outcroppings are left for visual impact, and quarry rock is used on the interior and exterior of the building. Golf courses have been built over abandoned quarries near many U.S. cities. Construction of townhouses, shopping centers, or industrial parks are other examples of a rehabilitative approach.

Near Mombassa, on the coast of Kenya, an abandoned quarry illustrates a more-comprehensive rehabilitation plan. Once barren land with almost no underground water, it is covered with grass and trees. Rene Haller, a Swiss agronomist, introduced agriforestry, animal farming (including cattle, sheep, oryx, tilapia, and crocodiles), and tourism to the wasted landscape [22].

4.5 MITIGATION

Some mined areas have undergone major negative environmental changes after mining ceased. A mitigation approach uses scientific input to protect the environment and to return these mined areas to beneficial uses. For example, dumping of contaminated debris from the U.S. Department of Defense and Atomic Energy Commission sites into the Weldon Spring Quarry (near St. Louis, Missouri, U.S.A.) went on for nearly 30 years [23]. Ground-water contamination was spreading towards well fields that supplied homes and industries throughout the area. A quarry cleanup of the bulk waste began in 1989 under the U.S. Environmental Protection Agency (EPA) Superfund Program and the State of Missouri. High-quality clay soil is required to construct the permanent disposal facility and to make it impervious to water. Nearly 2 million cubic yards of clay was excavated from more than 200 acres of land in the nearby Weldon Spring Conservation Area. In this case, the cleanup of one mine site requires the construction of another.

Nature can also degrade mined lands. During a 35-year period, Cooley Gravel Co. extracted more than 26 million tons of aggregate from a site along the South Platte River, Colorado, U.S.A. Floods in 1965 and 1973 breached levees and changed river channels, which caused catastrophic impact on the land. Cooley reclaimed the land and donated 425 acres to the city of Littleton. The design made use of native seed mixes, incorporated trails, fishing along the South Platte River, and educational tours at the Carson Nature Center. Today, together with adjacent land dedicated by Littleton, South Platte Park is one of the largest wildlife parks within city limits in the United States.

4.6 RENEWABLE RESOURCE

Mined-out land can be a source of or a place to process renewable resources. One of the most dramatic effects that man has had on the ecosystem relates to loss of wetlands. The reclamation of gravel mining pits at the Farm (Boulder Valley, Colorado, USA) to wetlands is replacing renewable resources. During the period from 1780 to 1990, Colorado lost about half of its wetlands [24]. The Farm design incorporates oxbow lakes and more than 39,000 plants native to prairie wetlands in a hundred-acre site [25].

For some experts, a sustainable relationship with the earth will only come about by controlling growth, reducing our consumption of goods, and preserving diverse landscapes. A tremendous amount of demolition debris is buried in landfills and becomes a wasted resource. Some mined-out areas are contributing to the reuse effort by serving as locations for recycling of concrete, macadam, glass, and other resources. Recognizing the limited supply of mineral resources and encouraging recycling efforts are beneficial steps toward sustainability. England and Wales have established planning guidelines that include reducing the proportion of stone removed from land from the current 83 percent to 68 percent by 2006 [26].

4.7 EDUCATION

In the educative approach, one tries to effectively communicate mining information through outreach so that citizens can make informed choices about future land use. Europeans tend to be ahead of the United States in this regard, perhaps, owing in part to their limited available land. They also focus on aesthetics as much as the functional after use. For example, scientists in the United Kingdom have understood the importance of gravel pits for bird habitat since the 1930's and 40's.

An example of educational outreach is in Albuquerque, New Mexico, U.S.A., where Western Mobile replaced the grass lawn at its corporate headquarters with a xeriscape garden. The ground cover, parking lot, pavement, signage, and building make use of aggregate and, together with the garden, help educate and promote their products. The garden requires about 10 to 20 percent of the water previously needed and is open to the public.

4.8 ART

An artistic approach is one where the site is celebrated as a work of beauty and unique experiences. Engler [18] categorized the approach as celebrative; people become fully aware of the connection between the production of an item and their everyday lives. One pioneer in the earthworks-as-art movement was Robert Smithson. Smithson proposed "Art can become a resource that mediates between the ecologist and the industrialist" [27]. Sites examined for their artistic design approach include Parc des Buttes-Chaumont, Aexoni Quarry, and Smithson's *Broken Circle.*

The public Parc des Buttes-Chaumont in Paris (*c.*1864-69) was built upon old quarried limestone and gypsum pits, abandoned gallows, sanitary sewage dump, and a mass grave. After the reclamation, Parisians could stroll "aimlessly while observing the city's changing physical and social structure" and appreciate "artistic urban accomplishments" [28].

A sculpted quarry at Aexoni, Greece, celebrates music and dance while acknowledging the natural landscape. The quarry expresses the Greek philosophy of the unity of all things. Although it provides a stage for performing arts and exhibitions, the sculptured quarry illustrates the artistic and rehabilitative approaches. Regional plant species were planted, and sculptural forms relate to adjacent rock formations. The floor plane and backdrop of the stage design are an impression of excavation-a cave [29].

In 1971, Smithson used a sand pit and body of water to create a circular jetty and canal entitled *Broken Circle.* The project was planned in The Netherlands as part of an international art exhibition. The symmetrical landform is about 140 feet in diameter and suggests yin and yang, thus inviting human passage. The earthwork also evokes images of dikes and polders that are the backbone of the Dutch landscape.

4.9 INTEGRATION

The combination of art and science in a "human-nature ecosystem where work and leisure coexist" is an integrated approach [18].

Quarry Cove, on the Oregon coast, U.S.A., is a quarry that has been converted into a man-made tidal zone fed and nourished by wave action [30]. Quarry Cove, which was developed by the Bureau of Land Management, provides a variety of wildlife habitats and is expected to have species diversity comparable to a natural tidal pool within 5 to 10 years. Visitors (the site is wheel-chair accessible) can view nature taking its course as marine life invades the area. The cove is an exciting example of an exhausted site becoming a "natural" biological laboratory with community outreach.

On a larger architectural scale is a design by sculptor Michael Heizer. Entitled *Effigy Tumuli,* the project is sited on land disturbed by coal mining. The reclamation plan celebrates the region's history of Indian burial mounds with earth shapes or tumuli; water strider, frog, turtle, snake, and catfish [31]. Located on a sandstone bluff above the Illinois River, the 150-acre outdoor project was a cooperative team effort by Ottawa Silica Company, a nonprofit organization, and State and Federal Governments [32]. The artist minimized expensive earth moving by studying the existing mine-site topography for hidden forms. The project included the treatment of millions of gallons of acid water, neutralizing acid spoil, and seeding with wildflower and grass. Although this instance concerns a coal mine, pit and quarry reclamation can be tailored to include landform sculptures, as demonstrated Section 4.8.

5. Environmental Ethics

There is an economic cost to limiting environmental impacts while developing aggregate resources. Economic costs can be in the form of increased costs for land acquisition, equipment, processing, or transportation. In some areas, the economic costs may add an overwhelming burden to the cost of developing the resource. If so, then compromises between the cost of extracting aggregate and the environmental impacts of extraction might have to be made.

What constitutes an overwhelming burden is relative. In part, it depends on the wealth of an area and the ability of the citizenry in the area to pay the added costs. Less economically developed areas have less economic wealth to prevent or address environmental impacts. In some cases, the incentive to address environmental issues may be lacking. In less economically developed areas, a few environmental impacts might appear to be a small price to pay for what can be gained through developing aggregate resources to build an infrastructure.

This report can help guide compromises between the economics of extracting aggregate and the environmental impacts of extraction. It should be clear from reading the environmental impacts described above that some impacts are restricted to the site, short term, easy to predict, and easy to control. These commonly would be the best impacts to consider for compromise. Impacts that affect health and safety or impacts that are long lasting and far-reaching would be unlikely candidates for compromise.

Economically developed areas commonly have funding available to address environmental issues. Even so, citizens in some economically developed areas may feel that the best way to avoid environmental impacts is to avoid development of resources within their jurisdiction. This philosophy is many hundreds of years old. Pliney the Elder, a Roman naturalist who died at the eruption of Vesuvius during A.D. 79, wrote that Roman citizens felt mining, although an appropriate activity for conquered lands, was not an appropriate activity in the homeland [33].

The question of ethics arises when one recognizes that aggregate resources have to be developed somewhere. When a wealthy area excludes development of aggregate resources within its jurisdiction, it is depending on obtaining resources from some other area. If the area providing the aggregate is significantly less wealthy, then it likely will have less capability to address environmental issues. To add to the burden, per capita consumption of aggregate commonly increases with wealth. The wealthy area may demand more aggregate from a poor area than the poor area demands for its own needs. Not only must the citizens in the less economically developed area suffer their own environmental problems, but they also must suffer the environmental impacts for those in the more wealthy area. The overall affect may be one of not preventing environmental impacts, but of exacerbating and relocating them.

Sometimes, areas without large wealth (or even wealthy areas) may want to be suppliers of resources. If an area has large supplies of high-quality aggregate resources, then it may be able to develop superquarries or other types of aggregate operations and export those resources to areas that are unwilling or unable to develop their own resources. It is, however, important to include environmental safeguards, and pass the cost of those safeguards on to the consumer.

6. Summary

Most environmental impacts associated with aggregate mining are benign. Extracting aggregate seldom produces acidic mine drainage or other toxic affects commonly associated with mining of metallic or energy resources. Other environmental health hazards are rare. Most of the impacts that are likely to occur are short lived, easy to predict, and easy to observe. By employing responsible operational practices and using available technology, most impacts can be controlled, mitigated, or kept at tolerable levels and can be restricted to the immediate vicinity of the aggregate operation.

There are, however, a number of situations in which mining aggregate can lead to serious environmental impacts. The rush to build quickly and cheaply with whatever materials come to hand can result in severe environmental consequences. Mining in areas of high population density can force large numbers of aggregate operations to be concentrated into relatively small areas and can exacerbate the environmental impacts of aggregate development. Societal pressures may encourage relaxed controls, and aggregate operators may fail to follow responsible operational practices.

Some geologic environments, such as active stream channels and landslide-prone areas, are dynamic and respond rapidly to outside stimuli, which include aggregate mining. Mining thin deposits or deposits that contain large amounts of unsuitable material results in the generation of large mined areas and large amounts of waste material. Some areas and (or) ecosystems serve as habitat for rare or endangered species, and any activity in these areas may be detrimental. Similarly, some geomorphic features are themselves rare examples of geologic phenomena. Mining aggregate might be acceptable but should be conducted only after careful consideration and then only with extreme prudence.

Important operational conditions that affect environmental impacts are the location and type of the mine, mining techniques, processing techniques, the type and effectiveness of regulations, and the enlightenment of the operator.

Planners are using landscape architects to help enhance the native character of reclaimed sites by fitting the built landscape into the natural design of the surrounding area. By discovering the true landscape and understanding it, reclamation planning and design can concentrate on ecology and development, research and technology, culture and nature, science, and art. The data may not say what choices to make, but they can help with wise options.

Perhaps the most effective means to minimize the impact of conversion of land use is to develop the best resources available and to implement a second land use that is compatible with nature and acceptable to the public.

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