THE INFLUENCE OF FINE SEDIMENT

INTRODUCED TO AN ARMORED BED

DOWNSTREAM FROM A DAM

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This work is dedicated to Dr. Gordon Goles of the University of Oregon,
who took the time one summer afternoon to open for me the door
to the world of geology.

As well this work is dedicated to Gunnar Lovblom,
who has stuck by me with his encouragement, laughter, and support
every step of the way.

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ABSTRACT

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Dam removal continues to emerge as a viable option in river management, yet little is known about the effects that a release of associated reservoir sediment may have on the riverine system downstream. An armored riverbed, commonly seen downstream from dams may have a complicating effect on the response of the channel to high inputs of fine sediment. It is hypothesized that an influx of fine sediment can affect the downstream bed by enhancing the transport of gravel fractions or in-filling the pore spaces in the surface gravel of the bed. When reservoir sediment is flushed downstream as part of a dam removal, the sediment is input to an armored bed condition. Upon the sudden input of fines, does the armored bed break or remain intact? If broken, then engineers must account for not only the reservoir sediment flushing downstream, but also the newly broken armor layer and associated substrate.

A sediment feed flume was used to examine the response of an armored bed to a sudden influx of sand. Four separate runs were conducted, each consisting of three phases: the first to obtain a dynamic equilibrium, the second to establish an armor layer, and the third phase to simulate a sudden flush of fine grained sediment, defined as less than or equal to 2 mm, onto an armored bed surface downstream from a dam. The four runs tested two sediment transport rates against two flow rates. Results show the armor layer being broken and mobilized during the third phase of each run. An increase in the total sediment transport rate is recorded and both sand and gravel are transported out of the flume. The remaining bed significantly fills in with sand regardless of flow rate or sediment feed rate. Distinctive patterns between Runs 1and 3 (lower flow rate) and between Runs 2 and 4 (higher flow rate) exist when the bed both armors and breaks. The results indicate that the flow rate has more control over the amount of sediment being mobilized and transported downstream while the sediment feed rate controls the level of sand deposition on the surface. Microtopography, imbrication, and clusters are observed to varying degrees in the armored bed, which may prove, with further research, to have a greater influence on the response of how the armor bed breaks.

CHAPTER I

INTRODUCTION

Dam removal has emerged as a viable option in river management. However, little has been quantified on the effects that dam removal may have on a downstream riverine system. Only within the last decade have the dynamics of sediment associated with dam removals begun to be addressed through quantitative research. Whereas the scientific community is beginning to gain an understanding of the many ecological, societal, and economic benefits and drawbacks related to dam removal, many questions pertaining to sediment issues still need to be answered. For a geomorphologist, the fundamental issue is understanding the morphodynamical response of a reservoir which is partially or completely filled in with sediment – the latter being more typical (Bromley, Cantelli, Wooster 2005; Wildman and MacBroom 2005). The possible impacts of erosion, transport, and deposition of reservoir sediment must be addressed in all dam removal studies (Randle 2003). If a dam is removed without addressing sediment related questions, then the removal has the potential to significantly impact the riverine system downstream of the dam site.

The removal of the Embrey Dam along the Rappahannock River at Fredericksburg, Virginia, serves as an example of a partially successful sediment management plan. Built in 1910 for hydroelectric purposes, the Embrey dam reservoir quickly filled in with sands, silts, and gravels. By the time the dam was slated for removal, February 23, 2004, the impounded sediment had grown to a volume of 405,728 cubic meters. The city of Fredericksburg enlisted the Army Corps of Engineers to oversee the dam removal project. This included not only dismantling the dam, but also developing a strategy to handle the vast quantity of impounded sediment and to monitor the sediment erosion, transport, and deposition following the dam removal. Preliminary studies concluded that the reservoir sediment contained no hazardous material (Friends of the Rappahannock, online). However, because of the unknown consequences associated with a sudden release of fine sediment on the downstream ecosystems, releasing such a large volume of sediment was out of the question. Hence, before the dam was removed, the Army Corps proposed to dredge 191,000 cubic meters of the sediment within close proximity to the dam, via suctioning water and sediment through 914 meters of pipe to a 32 hectares (13-acre) disposal pit (Dennen 2003). After the reservoir waters had been released, the anticipated remaining sediment would be left to natural river erosion. Due to inclement weather and deadline constraints, the Army Corps was not able to dredge the entire proposed amount of sediment. Upon dam removal, the amount of sediment released downstream far surpassed predicted quantities. The downstream effects of this unanticipated larger volume of fine sediment being flushed through the riverine system are still being documented in the field. It also serves as the inspiration for the research conducted in this thesis work.

Understanding how fine sediment will behave when flushed from behind a dam and into the river downstream is an essential component of planning a dam removal.

Through a series of laboratory flume experiments, this project evaluated the effects of introducing fine-grained sediment to an armored channel bed, thus simulating the flushing of fine sediment from behind a dam prior and subsequent to a dam removal. Through a physical model, the experiments allowed for a means to measure an armored bed's response to controlled inputs of sediment and water.

Specific research questions included:

- Does an influx of fine-grained sediment, defined as less than or equal to 2 mm in diameter, break and mobilize an armored bed just downstream from a dam, or does the armored bed remain intact?
- If the bed is broken, then:
  - How is the bed shear stress affected with the input of sand?
  - If the shear stress is affected, then how do these changes affect the transport capacity of the bed material?
  - How much gravel is mobilized?
  - From what region of the bed is the gravel mobilized?

If an armored bed were to break and be mobilized due to an influx of fine grained sediment, then the river system downstream not only would be affected by the surge of reservoir sediment, but also it would be inundated with a second surge of sediment – the armored river bed material and the underlying sediment suddenly exposed and mobilized. Through an understanding of how sands/reservoir sediment impact a bed surface below the dam, precautions and strategies can be taken to avoid or at least decrease the potential harmful effects of reservoir sediment surging downstream as a result of removing a dam.

CHAPTER II

LITERATURE REVIEW

Background of dams

Throughout the United States, over 76,000 dams (> 2 meters high) have been constructed on America's rivers (Pohl 2003). If all structures including those smaller than 2 meters high are counted, then there may be as many as 2 million dams (Graf 1999). Through time, dams have been built for a myriad of reasons, including: water supply for domestic and industrial use, irrigation, flood control, sediment control, water power (i.e. mills), hydroelectric power, navigation, recreation, waste disposal, and enhanced groundwater recharge (Heinz Center 2002; Brandt 2000). Due to the gradual structural deterioration of dams and reservoir infilling by sediment, the average lifespan ranges between 60-120 years (Doyle, Harbor, Stanley 2003; Poff and Hart 2002). Given this range, it is estimated that by the year 2020, 85% of America's dams will be near the end of their operational lives (FEMA 2003). Dam owners and governmental agencies are starting to re-explore options other than upgrading/repairing dams as the costs of repair are beginning to outweigh the costs and benefits of removal.

The concept of dismantling dams is not new to river managers and engineers (Pohl 2002). During the 20th century, over 400 dams were removed. However, dam removal appears to have been fairly uncommon prior to the 1970's (Pohl 2003). This could be due simply to the fact that dams were still operational, useful, and appreciated by society. By 2003, the pace of dam removal had picked up, as indicated by the removal of over 100 dams since 1999 (FEMA 2003). The recent acceleration of removals reflects problems associated with aging structures, growing social interests in restoring rivers and fish passage, new funding opportunities to support dam removal, national policies aimed at improving the safety of aging structures, and mitigating environmental impacts of these structures, i.e. Clean Water Act of 1977 and the Endangered Species Act of 1973 (Pohl 2003).

Many of the nation's dams currently are being evaluated for re-licensing by the Federal Energy Regulatory Commission (FERC). However, dam licenses are expiring in a significantly different regulatory and economic atmosphere than when they were originally granted (Doyle, Stanley, Harbor, Grant 2003). Society's values and attitudes, which were once pro-dam, are becoming more eco-friendly, leaning towards concerns for endangered species and river restoration. Thus, FERC and government agencies at the state and local levels now must not only consider safety issues of aging, non-operational dams, but also environmental issues (Pejchar and Warner 2001). As a result, as licenses begin to expire, many dams may not be considered for regulatory re-licensing, and the dam owner by order of FERC will have to remove the dam.

The Edwards Dam, along the Kennebec River in Maine, provides an example of FERC enforcing the removal of a dam due to environmental reasons - restoring passageways for anadromous fish species such as the Atlantic salmon and American shad. Rendered functionally obsolete, the Edwards Dam was viewed solely as an impediment to spawning fish. Within a year after the removal, large numbers of American eel, Atlantic and shortnose sturgeon, and striped bass were observed in upstream habitats that had been inaccessible to these species for more than 150 years (Hart et al. 2002). The 'successful' removal of the Edwards Dam and the reintroduction of once endangered spawning fish species to the upstream waters of the Kennebec River has inspired and motivated society to press for more dam removals nationwide.

The majority of dams that have been removed are relatively small structures, ≤ 5 meters height (Bushaw-Newton, Ashley, Velinsky 2005; Hart et al. 2002) with storage capacities less than 123,000 cubic meters (100 acre-feet) (Heinz Center 2002). No dam higher than 30 meters yet has been removed (Gregory, Li, Li 2002). The Edwards dam on the Kennebec River, Maine, at 7.6 meters (25 ft) tall, and 279.5 meters (917 ft) wide; and the Embrey Dam on the Rappahannock River, Virginia, at 6.7 meters (22 ft) tall, and 234.7 meters (770 ft) wide, are the largest structures thus far to be removed in 1999 and 2004 respectively (Maclin and Eckl 2004).

The Glines Canyon dam, along the Elwha River, Washington, at 64 meters (210 ft) tall with a storage capacity of 50,000,000 cubic meters (40, 500 acre-ft), and the Elwha dam, at 33 meters (108 ft) tall with a storage capacity of 10,000,000 cubic meters (8100 acre-ft) also along the Elwha River, Washington are slated for removal beginning 2008. The removal of these two dams will be the largest dam removal projects to date, setting the precedent for dam removal. The sheer volume of sediment, over four and a half million cubic meters, expected to course through the river system puts this dam removal, as Gordon Grant says, "in a class unto itself, for the most sediment that has been released in a dam removal to date is only on the order of a few tens of thousands cubic meters" (Downing 2004). When interviewed by Jim Downing (2004), Elizabeth Grossman, author of *Watershed: The Undamming of America,* stated 'people will definitely look to the Elwha project as evidence to whether a removal of this magnitude will really work'. Not only will the removals re-open passageways for spawning fish, but also provide an incredible opportunity for scientists to study the effects of how a river tries to digest a vast amount of reservoir sediment.

Impact of dams on river systems

To understand better the dynamics of how sediment is trapped behind a dam, which in turn will influence how it will behave when released downstream upon dam removal, one must first comprehend the impact a dam has on a river system. The shape, size and overall morphology of a river are influenced by the geology of the watershed/river channel, the climate, the water that flows through the channel, and the sediment transport regime (Grant, Schmidt, Lewis 2003). The nature of the watershed, and the place of a stream within its watershed, will have a dominant influence on water and sediment supply and on stream characteristics (Wilcock 2004). The region's geology can influence the sediment transport regime, including the frequency, volume, timing, and grain-size distribution of sediment transport (Grant et al. 2003). By altering the flow and sediment regime, the construction of dams on alluvial channels is likely to result in a number of hydrologic and morphological changes both upstream and downstream via erosion and deposition through space and time (Grant 2001; Diplas and Parker 1992; Williams and Wolman 1984). Changes downstream depend on the changes in flow regime and sediment transport capacity downstream from the dam; the erodibility of the downstream channel boundaries, as governed by the presence of vegetation and the grain-size distribution of the channel substrate; the presence of tributaries, hillslope mass movements, or other sources of sediment input to the main channel; and the amount and size distribution of sediment released from the reservoir (Wohl and Rathburn 2003).

Dams alter two critical elements of a geomorphic system: the ability of a river to transport sediment and the amount of sediment available for transport (Grant et al. 2003; Kondolf 1997). Physical changes to channels downstream of dams can range from bed degradation and narrowing, to changes in channel bed texture, i.e. armoring, to bed aggradation, bar construction, channel widening, to no measurable change at all (Fassnacht, McClure, Grant, Klingeman 2003).

Williams and Wolman (1984) surveyed 21 dams along 15 alluvial rivers and found that on most rivers the channel bed degrades in the reach immediately downstream from the dam. When flows released from dams have a greater transport capacity than the amount of sediment being supplied and the flows have sufficient ability to move most sediment size fractions in the downstream river bed, channel degradation will occur (Vericat, Batalla, Garcia 2006; Kondolf 1997). Stream channels will adjust to transport the sediment – or lack thereof – supplied to them with the available flow (Wilcock 2004). Energy in this clear water flowing over or through the dam is expended on erosion of the channel bed and banks below the dam until equilibrium is reached and the downstream bed material cannot be mobilized (Kondolf 1997). As degradation continues, progressive vertical and horizontal winnowing of the finer material from the surface forces the remaining surface material to pack together, concentrating the coarser size material on the surface, hence the average surface grain size increases (Williams and Wolman 1984).

When the bed surface coarsens and the bed shear stress is less than the critical shear stress needed to entrain the coarser particles of the bed surface but sufficient to move the finer grain material, an armored bed surface is created (figure 1). This armored bed surface is a common phenomenon seen downstream from dams (Vericat et al. 2006; Grant 2001; Brandt 2000; Kondolf 1997; Lamberti and Paris 1992; Richards and Clifford 1991; Parker and Sutherland 1990; Shen and Lu 1983). Streambed armoring strongly influences channel hydraulics, through mediation of the exchange of water between flow and bed; it defines the habitat for aquatic insects, salmonid spawning, and juvenile fish; and it determines the sediment available for transport (Wilcock and DeTemple 2005).

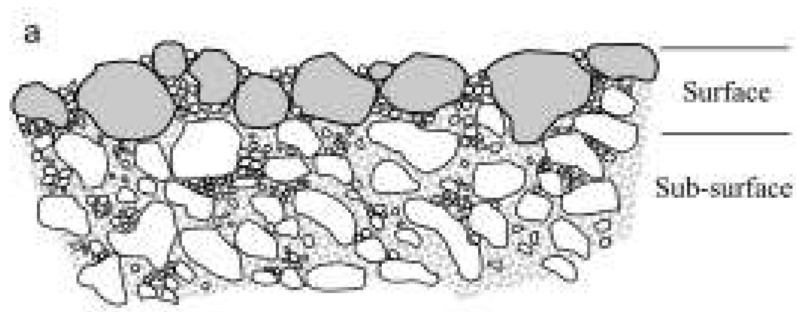


Figure 1. Schematic of armored bed surface. Note top surface coarsening.

Effects of dam removal

Dam removals have the potential to affect the physical, chemical, biological, and geomorphic components of a river ecosystem, and the responses of the varying components often will be intertwined (Bushaw-Newton et al 2002). For example, the sudden release downstream of impounded sediments can affect fish habitat as pools are in-filled with fine sediments (Rathburn and Wohl 2003; Wohl and Cenderelli 2000); alter water chemistry via sudden influxes of nutrients, affecting both flora and fauna (Stanley and Doyle 2002); and change channel morphology with the growth of new bed deposits, i.e. bed aggradation (Pizzuto 2002), which can disrupt navigation channels.

Depending on the impoundment trap efficiency, each dam along a river has the potential to trap and accumulate a portion of the natural suspended and bed load sediment, as well as trap pollutants (Wildman and MacBroom 2005; Grant et al. 2003; Brune 1953). Based on the geology of the watershed, some dams trap very little sediment if any at all, whereas others may trap a vast quantity (Wildman and MacBroom 2005). Upon breach or removal, the previously trapped coarse to fine-grained material is subject to re-suspension and transport downstream. Channel adjustment to increased sediment influx depends on the magnitude, frequency, duration and grain-size distribution of the sediment released, and on the downstream channel characteristics (Wohl and Rathburn 2003). Shifts in the patterns of sediment movement are a prominent and significant response to dam removal (Hart et al. 2002). Mobilization of potential pollutants, creation of downstream sediment loads and turbidity, downstream sediment deposition that buries the native substrate, and unstable incision of channels in the reservoir pool area are all documented effects of sediment being released during and post dam removal (Heinz Center 2002).

Looking at the geomorphology of the entire watershed upstream and downstream of a dam site, prior, during, and post removal is crucial to understanding how a river system will be affected upon removal. Pre-dam removal, the geology, climate patterns, and watershed use must be investigated, for these independent factors greatly influence the type and amount of sediment trapped behind a dam (Grant et al. 2003). A longitudinal profile of the river with the dam in place should be surveyed in order to allow planners to define a target bed elevation after removal (Bushaw-Newton, Ashley, Ashley, Velinsky 2005). Structures such as bridges, roads, and buildings that could be affected by changes in the sediment regime must be identified pre-removal (Bushaw-Newton Ashley, Velinsky 2005).

A chemical analysis of the impounded sediments should be conducted to test for contaminates, e.g. heavy metals, hazardous chemicals or nutrients from agricultural run-off. In the Midwest, dams were often built for milling of agricultural products, and the nutrients lost from farm fields are now stored behind dams (Stanley and Doyle 2002). In the Northeast, industry production is abundant upstream from many dams. The removal in 1973 of the Fort Edward Dam on the Hudson River provides valuable lessons regarding dam removal and the need for comprehensive pre-removal environmental assessment studies (Shuman 1995). Due to the lack of an environmental impact study, vast quantities of sediments contaminated with PCB (polychlorinated biphenyl) were released into the river system upon dam removal (Shuman 1995). The sediment severely polluted the system with toxic material, and it obstructed navigation channels. It has taken the state of New York and General Electric time and a lot of money to clean up the Hudson River. This catastrophe easily could have been avoided with a thorough pre-removal environmental impact study.

Assessing the responses of sediment on a river system post dam removal is a bit more complex, for each dam site has its own unique set of parameters controlling the response of sediment post removal (Landers 2004). Parallel responses from geomorphic models such as sediment waves induced by landslides, glacial outbursts, or disturbance of beaver dams (Butler and Malanson 2005) can provide a means of predicting sediment effects to dam removals (Doyle, Stanley, Harbor 2002). Likewise observing downstream patterns of sediment transport and deposition following controlled reservoir releases can be of benefit when predicting fluvial geomorphic responses (Wohl and Rathburn 2003; Wohl and Cenderelli 2000; Kondolf and Wilcock 1996).

Alongside information gained using geomorphic models, field observations are starting to measure channel responses to actual dam removals. While much of this fieldwork involves an integrative monitoring program to assess the physical, chemical, and biological responses to dam removal (Bushaw-Newton et al. 2002), part of the data being recorded looks at sediment behavior. For example, following the removal of a 2 meter high dam along the Manatawny Creek in southeastern Pennsylvania during the year 2000, increased sediment transport led to major changes in channel form in the former impoundment and downstream reaches (Bushaw-Newton et al. 2002).

Other field observations have shown the amount of time required to flush sediment through a system post removal can vary drastically. Following the removal of the Woolen Mills dam in Wisconsin, sediment flushing through the system took only six months, while sediment released from the removal of the Newaygo Dam in Michigan is expected to take 50-80 years (Bednarek 2001). After two dam removals in Wisconsin along the Koshkonong and Baraboo Rivers, at both sites a large amount of sediment was exported immediately from the reservoirs, but subsequent erosion of reservoir sediment, and thus subsequent downstream sedimentation, was strongly controlled by the rate and magnitude of channel development and evolution within the reservoir (Doyle et al. 2003).

Lastly, if a removal occurs during a period of low flow, the river may not have enough power or force to transport sediment downstream, aggravating turbidity; thus seasonal timing of a dam removal could affect sediment movement (Kondolf 1997).

Flume research associated with dam removal

Research using laboratory flumes, which are used for modeling river behavior (Parker and Wilcock 1993), has begun to quantify potential sediment responses to dam removal. Looking at the modes of transport, i.e. dispersion versus translation of sediment slugs or waves, Lisle et al. (2001) deduced that dispersion dominates the evolution of bed material waves in a gravel-bed channel. In another set of flume experiments, Lisle et al. (1997) showed that a sediment wave disperses both upstream and downstream with no translation on gravel-bed channels. These findings are significant because dispersive bed material waves create sediment impacts that decrease in severity both with time and distance downstream (Pizzuto 2002).

The National Center for Earth-surface Dynamics (NCED) associated with St. Anthony Falls Hydraulic Laboratory of the University of Minnesota has been conducting flume experiments to understand fluvial responses associated with dam removal. During the course of three separate experiments, NCED looked at the changes and the effects of basin geometry, sediment grain size, hydrology, and the rate of base level change on the morphodynamic response of a reservoir to a dam removal (Kelberer 2005). The first experiment included a set of ten runs with varying flow regimes in which Cantelli, Paola, and Parker (2004) studied the erosional response of a sandy deltaic front following a simulated dam removal. Their findings showed that after the sudden removal of a dam, the flow incised into the reservoir deposit, which induced erosional narrowing of reservoir sediment followed by a period of bank collapse and widening. They also observed vast amounts of sediment being transported downstream in a short span of time (Cantelli et al. 2004).

Realizing that the composition of reservoir sediment not only can be sandy, but also can be a mixture of sand interspersed with coarse sediment, a second set of experiments looked at how the interaction between coarse and fine layers of deltaic deposits influences channel evolution both upstream and downstream, and how it influences the release of sediment after dam removal (Bromley et al. 2005). The premise was to examine whether a deposit containing a mixture of both coarse and fine sediments would experience erosional narrowing followed by channel widening, as had been observed during the experiments of Cantelli et al. (2004). Results showed channel incision via a knick point migrating upstream, followed by channel widening, eventually transitioning back to a narrow channel (Bromley et al. 2005), however, the coarser material seemed to dampen the rate and amount of incising. Downstream from the dam site, fluctuations of aggradation and degradation were observed in response to channel width changes upstream. As sediment pulsated through the system, a sediment wedge developed immediately at the downstream end of the channel.

A third round of flume experiments at NCED created a scaled model of the Glines Canyon Dam, Washington, and its associated reservoir. Unlike the other two experiments that simulated a “blow and go” type of dam removal, this set of runs measured a river’s response when a dam is removed incrementally. Results showed that when dam removal began to one side, the first incision into the reservoir occurred near a reservoir sidewall, and an incised channel developed along that side of the reservoir wall. When the initial incision into the reservoir sediments occurred near the center of the reservoir, the channel moved freely back and forth across the width of the reservoir eroding, a larger quantity of deltaic deposits (Bromley et al. 2005). Hence, when removing a dam in stages, the placement of dam removal and channel initiation plays an important role in how the channel will erode upstream into the reservoir sediments, which in turn controls the amount of sediment eroded and transported downstream. In this set of runs, the percentage of total reservoir sediment transported downstream was proportional to the original delta volume eroded (Kelberer 2005).

The significance of these flume experiments is that a limited number of variables interact to produce a broadly similar response to dam removal, but the details of the channel response to dam removal may be sensitive to small changes in these controlling variables (Kelberer 2005). Comparing the three experiments, it is evident that the presence or lack of coarse sediment in reservoir material has a strong influence on the channel evolution both upstream and downstream from the dam site. If a dam is to be removed in stages, the rate of removal will be dependent on the channel geometry – be it dominant to the left, right, or center.

The stability versus instability of armored beds

In general, research on dam removal has focused on a broad, watershed scale perspective or has evaluated bulk sediment responses to dam removal. The research presented here focuses on the reach scale and how an armored bed responds to an influx of fines, specifically addressing the question of whether an armored bed breaks or does not break due to this influx of fines. Previously noted, the phenomenon of an armored bed is typically seen downstream from dams. This textural coarsening creates a rougher surface with greater intergranular friction angles, and thus slows down bed load transport rates (Buffington and Montgomery 1999; Parker, Dhamothoran, Stefan 1982). As a result, the bed surface requires more energy to mobilize, which alters the total contribution of subsurface sediment available for transport (Buffington and Montgomery 1999).

Channel adjustments to increased sediment influx depend on the magnitude, frequency, duration and grain-size distribution of the sediment added to the channel (Wohl and Rathburn 2003). Researching the process of initial entrainment of bed material in gravel-bed rivers, Richards and Clifford (1991) noted that a rapid increase in the bed load transport rate can occur when bed armor is broken and the finer material formerly protected by the armor layer is exposed to shear stresses well in excess of the normal threshold for these sizes. If the armored surface were to unravel in response to fines flushing through the system following a dam removal, then the subsurface sediments would be subject to mobilization and transport, thus increasing the total quantity of sediment moving downstream.

The key to understanding the impact of fines on an armored bed is through an understanding of sediment transport concepts (Wilcock, Kenworthy, Crowe 2001). Sediment transport is a function of flow strength, i.e. shear stress; sediment grain size and density; fluid properties, i.e. water density and water viscosity; and gravity. By altering any of these variables, in particular the supply of sediment in the size range of bed material, the change will alter the bed composition (Marion and Fraccarollo 1997) and thus the transport rates. When observing the increased input of sands onto a mobile gravel bed, previous flume studies have shown that with the increase of sand input, critical shear stresses for both the sand and gravel size fractions decrease, the transport capacity increases and the mobility of gravels increase (Curran and Wilcock 2005; Wilcock et al. 2001; Iseya and Ikeda 1987). In an attempt to identify, via flume experiments, the responses of mixed alluvial sand and gravel-bed channels to an increase in sand delivery into the system, Jackson and Bescheta (1984) observed that higher quantities of sand in transport precipitated stable gravel riffle bedforms to break apart, which in turn increased the amount of gravel in transport.

Looking more specifically at the behavior of a fixed armor layer in response to high peak flows during the course of a flood, Wilcock and DeTemple (2005) applied an inverse sediment transport model from Wilcock and Crowe (2003) to evaluate the persistence of an armor layer during high flows. The model results indicate that an armor layer does not break and is persistent during high flood flows. In contrast, field observations made during the years 2002 to 2004 along the Lower Ebro River of the Iberian Peninsula record the break up of an armor layer below the Flix Dam during peak flood conditions (2500 m^3/s) and the reestablishment of the armor layer during smaller floods (1000 m^3/s) (Vericat et al. 2006). Large and fine particles from both the surface and subsurface of the armored bed were entrained and transported downstream.

CHAPTER III

METHODS

Laboratory flume experiments are a method by which it is possible to observe and to measure an armored bed response to a sudden influx of fines. A sediment feed flume was used for these experiments because it directly answered the question pertaining to an armored bed response to a sudden input of fines (Curran and Wilcock 2005).

Sediment Dynamics Laboratory and flume

This project was conducted in the Sediment Dynamics Laboratory of the Colorado building on the Texas State University-San Marcos campus, in San Marcos, Texas. It used a small, tilting, sediment feed flume with the dimensions: 3.9 m (12.8 feet) length, 0.6 m (1.9 feet) height, and either 0.3 m (0.9 feet) or 0.6 m (1.9 feet) width depending on the experiment (figure 2). This study used a flume width of 0.3 m. The walls are made of clear plexiglass, which allows direct observation of the sediment transport (Curran and Wilcock 2005). While water recirculates through the system, sediment is fed by hand into the flume at the upstream end and collected in a screened collection box at the downstream end. Typically three people were involved during the experiment; one person feeding sediment into the flume at the upstream end, one person collecting sediment at the downstream end, and one person taking measurements at set timed intervals along the length of the flume.

Figure 2. The flume room. A small, tilting, sediment feed flume was used for the armor experiments. Sediment on floor is drying after a run.

Flume experiments

Four separate runs, each consisting of three phases, were performed. The first phase of each run allowed the bed to adjust to its equilibrium slope for the given flow and sediment feed rates. The sediment feed rates were chosen to maintain transport of all grain sizes at flows with shear stresses (τ^*) typical of gravel-bed rivers. The second phase of each run was performed to create an armored bed. During the third phase of each run, 100% sand only was fed into the channel simulating a flushing of fines onto a riverbed. For each run, discharge (Q) was held constant throughout the three phases, yet the slope, water depth, and bed surface were free to adjust. Sediment was fed at the same rate (Q_s) for the first and third run phases, and no sediment was fed when the armor formed during the second phase. The flow and sediment feed rates of each phase are given in detail in table 1.

Prior to each run the initial bed sediment (85% gravel, 15% sand) was mixed well by hand. This distribution ratio is typical of gravel-bed rivers with a moderate to low slope (Curran and Wilcock 2005; Andrews and Parker 1987). Using this mixture, the flume was filled to a thickness of 10 cm and pressed flat. Ten centimeters was used to match the weir height at the downstream edge of the flume, which was also ten centimeters. Having the bed height flush to the weir height allowed for a smooth overflow as water exited the flume. The sediment fed during phase one consisted of the same proportion of mixed sediment, (85% gravel, 15% sand) initially used to fill the flume. It too was mixed thoroughly by hand and by the same person to ensure consistency.

Table 1. Set up for flume experiments. Each run includes all three phases.

Run no.	**Discharge Q (m^3/s)**	**Sediment feed rate Q_s (g/ms)**
1	0.018	56 (5 minute interval)
2	0.02	56 (5 minute interval)
3	0.018	139 (2 minute interval)
4	0.02	139 (2 minute interval)

Phase 1: Equilibrium	Mixed sediment added (15% sand: 85% gravels)
Phase 2: Armor	No sediment added
Phase 3: Sand flushing	Fines introduced (100% sand added)

For each run, during phases one (equilibrium) and three (100% sand feed), 5000 grams of sediment was fed by hand consistently into the upstream end of the flume over a time frame of either two minute (139 $gm^{-1}s^{-1}$) or five-minute (56 $gm^{-1}s^{-1}$) intervals. During phase two (armor), no sediment was added. At the downstream end of the flume, for all three phases, both water and sediment passed over the edge of the flume and into a fine wire mesh collection box. The gage for the mesh screen was small enough to catch sand size sediment (0.1 mm – 2 mm) and gravels, yet large enough allowing water to pass through and to be pumped back to the upstream end. At the specified interval for a given run – two or five minutes - the sediment being collected downstream was entirely removed, weighed, and set aside. For example, if sediment was being added at the upstream end every five minutes, then sediment flowing over the edge of the flume was collected, removed and weighed over the same five-minute interval. The collected sediment from each phase was stored separately in large bins where it was later dried and sifted into its sand (less than or equal to 2 mm) and gravel components. The sand and gravel components then were weighed and recorded. Afterward, the sediment was remixed by hand to a composition of 85% gravel, 15% sand in preparation for the next run.

Dynamic equilibrium, indicated by a stable mean sediment transport rate equal to the feed rate (Curran and Wilcock 2005), was established when the amount of sediment being fed into the system, 5000 grams over the set time interval, equaled the amount of sediment exiting the system, 5000 grams over the same time interval as the feed rate. Equilibrium was verified by the sediment transport data collected (figure 3).

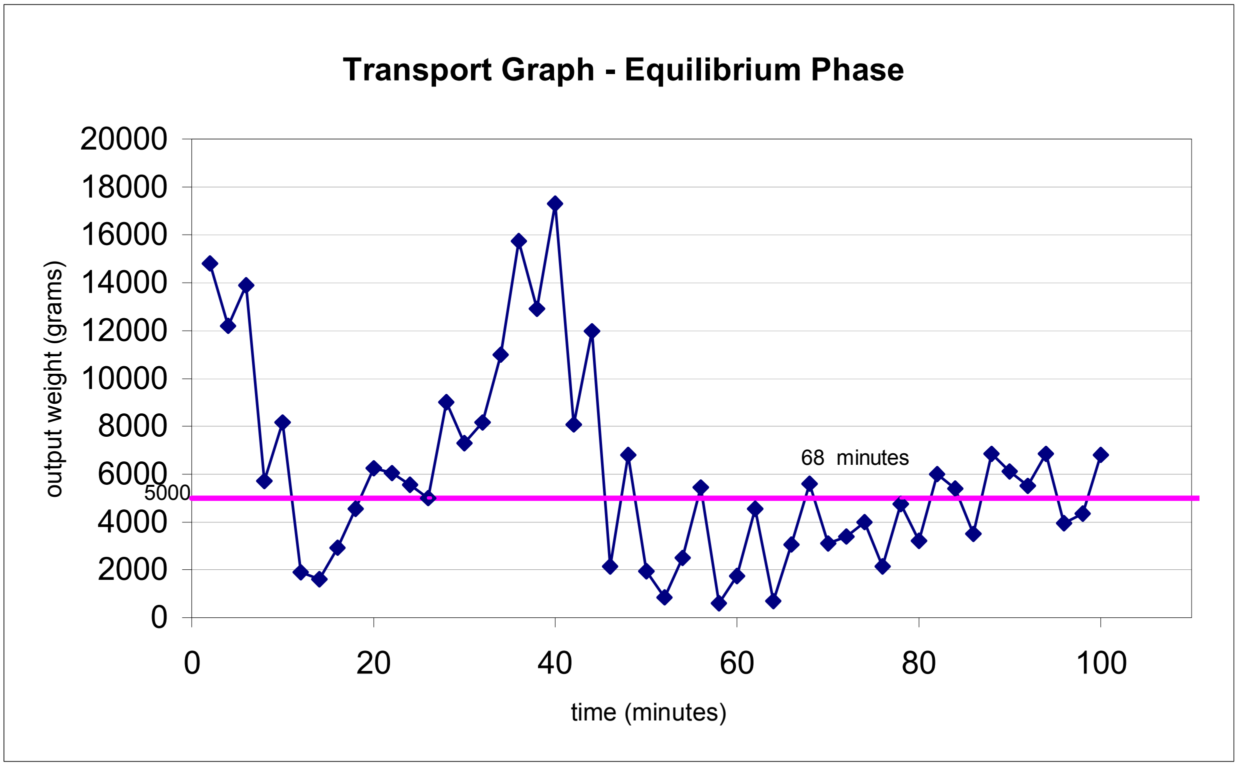


Figure 3. Transport graph – equilibrium. Sediment transport data recorded for equilibrium phase. Note horizontal reference line at 5000 grams. At 68 minutes, the bed begins to settle into dynamic equilibrium. By 80 minutes it begins to hover at dynamic equilibrium.

During phase two, an armored bed was achieved by cutting the sediment feed rate entirely, allowing only clear water to pass over the bed surface. The flow rate remained the same as in phase one. The armoring process was continued until the transport rate was reduced to one percent of the initial sediment feed rate of phase one, defining the point when an armored bed was created (Andrews and Parker 1987). For these runs, armor was declared when a total of 50 grams or less consistently exited the flume over a period of more than 60 minutes.

Once an armored bed had formed, sixty three gravels ranging in size from 5.6 mm to 45 mm were labeled with a red permanent marker “A”, “B”, or “C” for Run 3 and “1”, "2", or "3" for Run 4 (21 grains for each label). No grains were labeled for Runs 1 and 2. Each set of the sixty-three grains was divided equally into three sections. Twenty-one grains in the upstream section, defined as the length along the flume 0.0 meters to 1.0 meters, were labeled "A" or "1" depending on the run. Twenty-one grains in the mid section, defined by the length 1.0 meters to 2.5 meters, were labeled either "B" or "2" given the run number. Twenty-one grains from the downstream section, defined as the length 2.5 meters to 3.9 meters, were labeled "C" or "3" depending on the run (figure 4). Labeling the gravels in each specified section provided a means to determine if the armored bed was mobilized upon the sudden influx of sand during phase three, from what region (upstream, mid-stream, downstream) movement occurred, and over what distance.

To break and mobilize the armor layer, a sediment feed of 100% sand only (no gravel) was fed into the flume at the same sediment feed rate as was used for phase one of the same run. Sand was added until the bed was broken, sediment was moved and/or transported out of the flume, and the system reestablished a state of dynamic equilibrium.

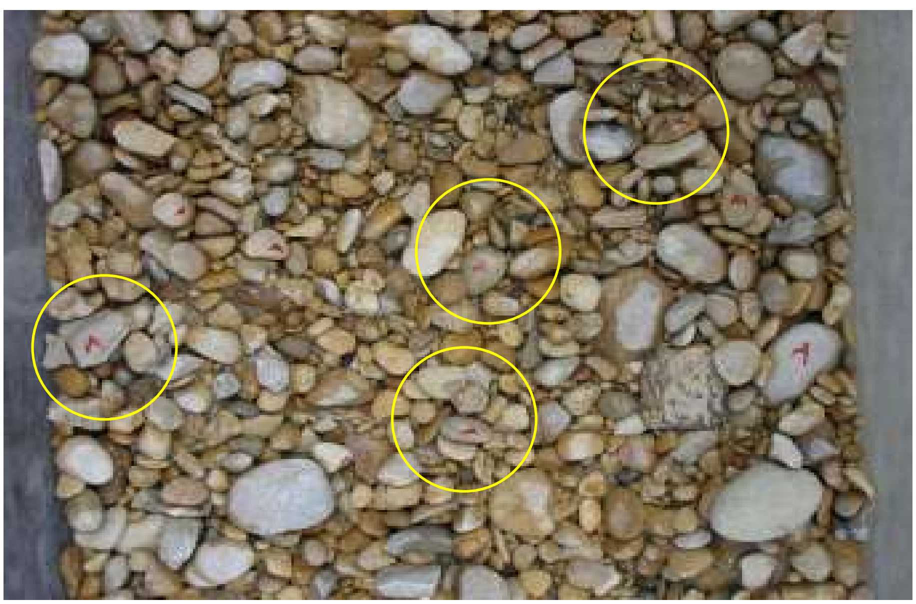


Figure 4. Tracer grains. (Upstream section) Examples outlined in yellow of randomly numbered gravels, "A", for Run 3 on armored bed before sand is added.

Measurements taken during each run included the elevations of the bed surface and the water surface, sediment transport rate, and surface velocity. The bed surface and water surface elevations were measured approximately every five minutes at 0.5 meter intervals along the length of the flume from the start of the upstream section, 0.0 meters, to the end of the downstream section, 3.9 meters. These elevation measurements, when corrected for the slope of the flume, provided flow depth, bed slope, and water surface slope (Curran and Wilcock 2005).

The sediment transport rate was measured at either five or two minute intervals: Runs 1 and 2 used five minute intervals; Runs 3 and 4 used two minute intervals. Over the specified time interval, the total sediment load exiting the flume was collected at the downstream end and weighed. This measurement was used to assess when the bed reached dynamic equilibrium and armored state, and to gauge when the armored bed had broken.

Surface velocities were recorded by timing a plastic float over 2 meters distance. Ten velocity measurements were taken during each phase. The high and low values were not used. The remaining eight values then were averaged to obtain a surface velocity. Mean flow velocities were calculated using the discharge, flume width, and mean flow depth.

Photographs using a 5.0 mega pixel digital Canon camera were taken at the end of each phase. The top bed surface and the sides of the bed were photographed as well any unusual bed forms or patterns that may have occurred during the run. The photographs were used to record visually each phase, to assess the percentage of sand to gravel ratio of the top surface, and to obtain the grain size distribution of the bed surface via grid by number method (Wilcock et al. 2001). The grid by number method incorporated a photograph of the bed surface that was projected onto a grid. One hundred grains were measured and recorded at each grid mark intersection. A reference gravel or penny, if a penny was in the photograph, was used for scale to measure the grid mark grains. Estimated lengths were made for partially hidden grains.

Post flume experiments

After each flume run, data collected included measurements of the final bed slope, the grain size distribution of both the bulk bed and bed surface, percentage of sand to gravel ratio on bed surface, and photographs of the final bed. The tracer grains from the armored bed were counted, measured, and their locations in the flume noted. The sediment transport material collected during each phase was dried, sieved, and weighed.

The final bed slope, relative to the flume bottom, was measured using a point gage. Avoiding any irregularities that may have developed next to the flume walls, the slope was measured down the middle of the bed from 0.0 meters to 3.9 meters every fifteen centimeters.

A visual assessment of the percentage amount of sand to gravel of the final bed surface was conducted. This ratio was assessed for the three sections, upstream, mid stream, and downstream.

Photographs of the final bed were taken using the same camera. Pictures included the entire length of the bed surface, the upstream, mid stream, and downstream sections of the bed surface, the side of the bed as seen through the clear flume walls, and any unusual/ interesting micro-bedforms that may have formed. Also, cross sectional pictures of the bed at upstream, mid stream, and downstream sections were taken during the bed excavation.

The final bed surface composition was measured via two methods: obtaining the grain size distribution by the Wolman pebble count (Wolman 1954) and the grid by number method (Wilcock et al. 2001). This allowed for evaluation of the texture of the bed and the bed surface composition. For the Wolman pebble count, one hundred, random grains were manually picked from the bed surface and measured using a gravelometer. The grain sizes in millimeters of the gravelometer included: 2, 2.8, 4, 5.6, 8, 11, 16, 22.6, 32, 45, 64, 90, 128, and 180, where 2 millimeters is very fine gravels and 180 millimeters is a large cobble. The cumulative frequency of each size was tabulated and then graphed on a grain size distribution curve (figure 5). From the curve the size classes D_{50} and D_{65} were found, where D_{50} or D_{65} represent the grain size that 50% or 65% respectively of clasts are equal to or smaller.

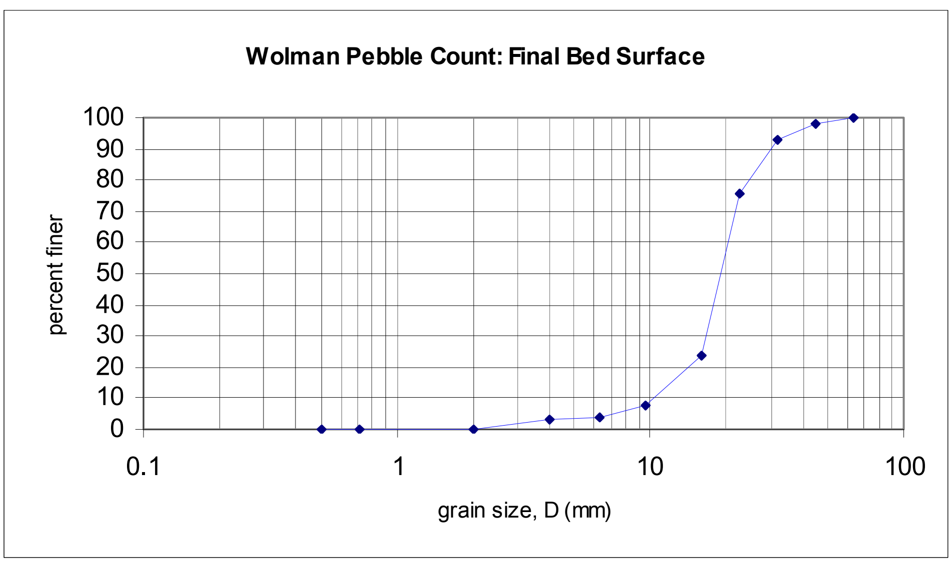


Figure 5. Wolman pebble count. Typical grain size distribution curve obtained from Wolman Pebble Count, where D represents the grain size in millimeters and percent finer represents the percentage of grains that are equal to or less than a given grain size.

To obtain the bulk bed composition, a sample from each section, upper, mid, and downstream was collected. Each sample was taken from the middle of each section, extended from the top of the bed surface to the bottom of the bed –roughly nine centimeters deep - across the width of the bed – thirty centimeters wide - and was ten centimeters long. The samples were then dried, sieved, and weighed. The cumulative weights were plotted on a grain size distribution curve.

As mentioned above, twenty-one gravels in the upstream section, twenty-one gravels in the mid section, and twenty-one gravels in the downstream section of the armored bed were labeled either “A, B, C” for Run 3 or “1, 2, 3” for Run 4. At the end of each run, the movement and non-movement of these gravels were recorded. Gravels that exited the flume were collected, separated into groups of A, B, C, and 1, 2, 3. The gravels of each group were counted and the size measured using the gravelometer. Likewise gravels that remained in place were counted and the size measured. The gravels that moved downstream but did not exit the flume were collected, counted, and measured; and the section to which the gravel moved was recorded.

The sediment transport material that had been collected for each phase – equilibrium, armor, and addition of sand – was separately dried and sieved into sand and gravel. The piles of sand and gravel were then weighed and recorded, and the percentage of sand to gravel ratio was then calculated. These data were compared to the original sediment mixture to determine if any changes in the percentage of sand to gravel ratio had occurred.

CHAPTER IV

RESULTS

Equilibrium – Phase one

A dynamic equilibrium was reached for all runs. This allowed the channel to develop a consistent base level without imposing a channel bed or roughness on the system. On average it took 142 minutes to reach and maintain a dynamic equilibrium. Flow depth remained nearly constant at 0.07 meters for all four runs. The bed slope reached a constant of 0.03. Mean flow velocity hovered at 0.9 m/s. Results from the Wolman Pebble Count showed a median surface grain size D_{50s} of 9.86 mm and a surface D_{65s} equal to 11.67 mm. Note that 's' refers to the bed surface material en masse. This notation will be used henceforward. The percent of sand on the bed surface ranged from three to seven percent. The amount of total sediment transport material, which included both sand and gravel collected at the downstream end of the flume, averaged 196,305 grams. See table 6 (appendix) for a complete summary of experimental measurements.

Armor – Phase two

An armored bed was achieved after transport of sand and gravel dropped to less than one percent of the original feed rate for over sixty minutes. The armoring process took the longest of the three phases. On average the process took 358 minutes to reach an armored bed. Sediment transport material exiting the flume clearly began to diminish with time. The armored bed was confirmed via the sediment transport graph (figure 6).

During the armoring process Tait, Willets, and Maizels (1992) observed a series of sediment flushes as the larger surface grains, which lost stability due to of the winnowing of finer sediment, were entrained. Once the protective surface armor was broken, the finer substrate material was exposed, entrained and transported downstream creating a flush of sediment exiting the flume. These flushes of sediment during armoring were measured in all four runs. Figure 6 illustrates well the series of sediment pulses observed during armoring phase of Run 3.

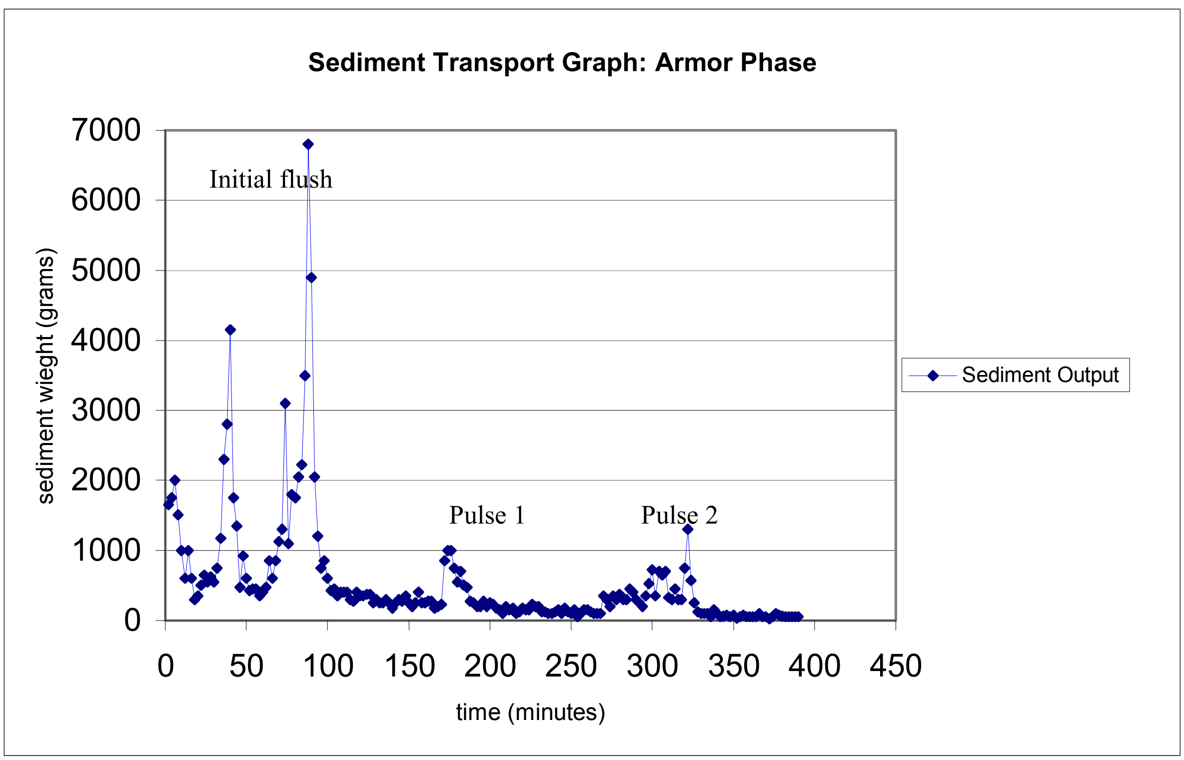


Figure 6. Sediment transport graph for armor phase: Run 3. Note sediment pulse 1 and 2 during run, which indicate large clasts being mobilized, thus exposing underlying smaller material for transport. Sediment output is less than 1% sediment feed (50 grams) from minute 325 to end of run. An armored bed is reached at time 390 minutes.

The flow depth for Runs 1 and 3 (lower discharge rate) hovered between 0.065 meters to 0.07 meters, remaining fairly consistent with its equilibrium flow depth. The flow depth for Runs 2 and 4 (higher discharge rate) increased and leveled out at 0.08 meters. The bed slope for Runs 1 and 3 dropped from 0.03 to 0.02, while the bed slope for Runs 2 and 4 changed very little from the equilibrium slope, 0.03. During all four experiments, the bed surface began to coarsen upon armoring (figure 7). Using the grid by number method, results showed D_{50s} as 9.85 mm for Runs 1 and 2, 7.3 mm for Run 3 and 13.74 mm for Run 4. D_{65s} spanned grain sizes between 8.2 mm and 15.70 mm. Grain size distribution for bulk material was not recorded so as to avoid disturbing the bed between phases two and three of the experiments. The percentage of surface sand decreased to between 1% and 3% of the bed surface.

Vertical sorting of fines downward into the bed, causing pore spaces in the subsurface to infill with sand, was observed through the clear plexi-glass wall (figure 8). As the fines either sifted down into the bed or were transported out of the system, a coarse veneer of gravels (figure 9), formed on the bed surface. Similar to what Parker and Sutherland (1990) observed during their flume experiments, the veneer of coarser material typically reached a thickness equal to the size of the larger clast, 21.6 mm – 32 mm. The surface veneer was coarser than the substrate, and contained grains representing all grain sizes of the bed, although in different relative proportions than the subsurface.

Figure 7. Top view of armored bed surface. Imbrication of gravels is beginning to form. Note penny (18 mm) for scale.

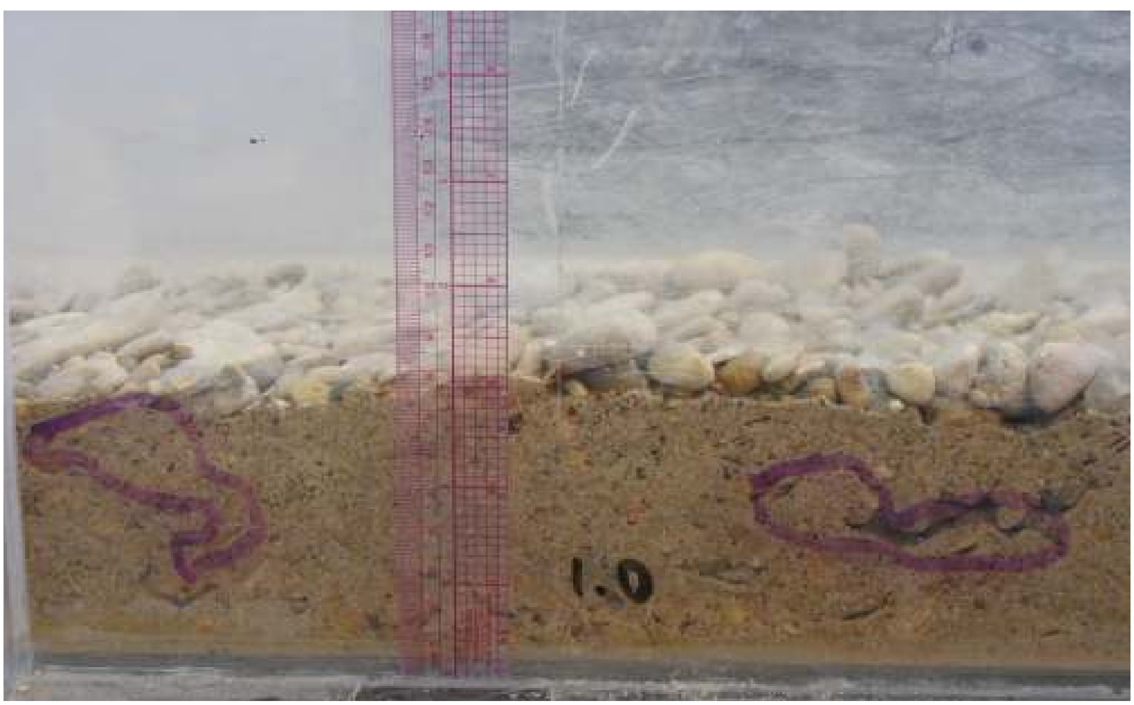


Figure 8. Winnowing of fines into armored bed. Amorphous purple shapes once outlined pore spaces in bed during equilibrium phase and at onset of armor phase. Majority of space has filled in with fines.

Figure 9. Side view of armored bed. Note coarse veneer of top surface.

Influx of sand – Phase three

Once the bed was armored, the third phase of the experiment was set to observe how the bed would react to an influx of fines. A 100% sand feed was begun with sand being fed into the flume at the same rate that sediment was fed during phase one. Consistently for each of the four runs, the armor was broken upon the influx of fines and gravels were mobilized and transported downstream. Within the first five to ten minutes a flush of both sand and gravels were exiting the flume. The surge of sediment lasted anywhere from 42 minutes as seen in Run 3 (figure 10a) to 65 minutes for Run 2, refer to (figure 10b). With time, the sediment flush leveled off and the system established a new 'quasi-equilibrium' in which gravels and sand still were being mobilized and transported, but at a steadier rate and lower quantity.

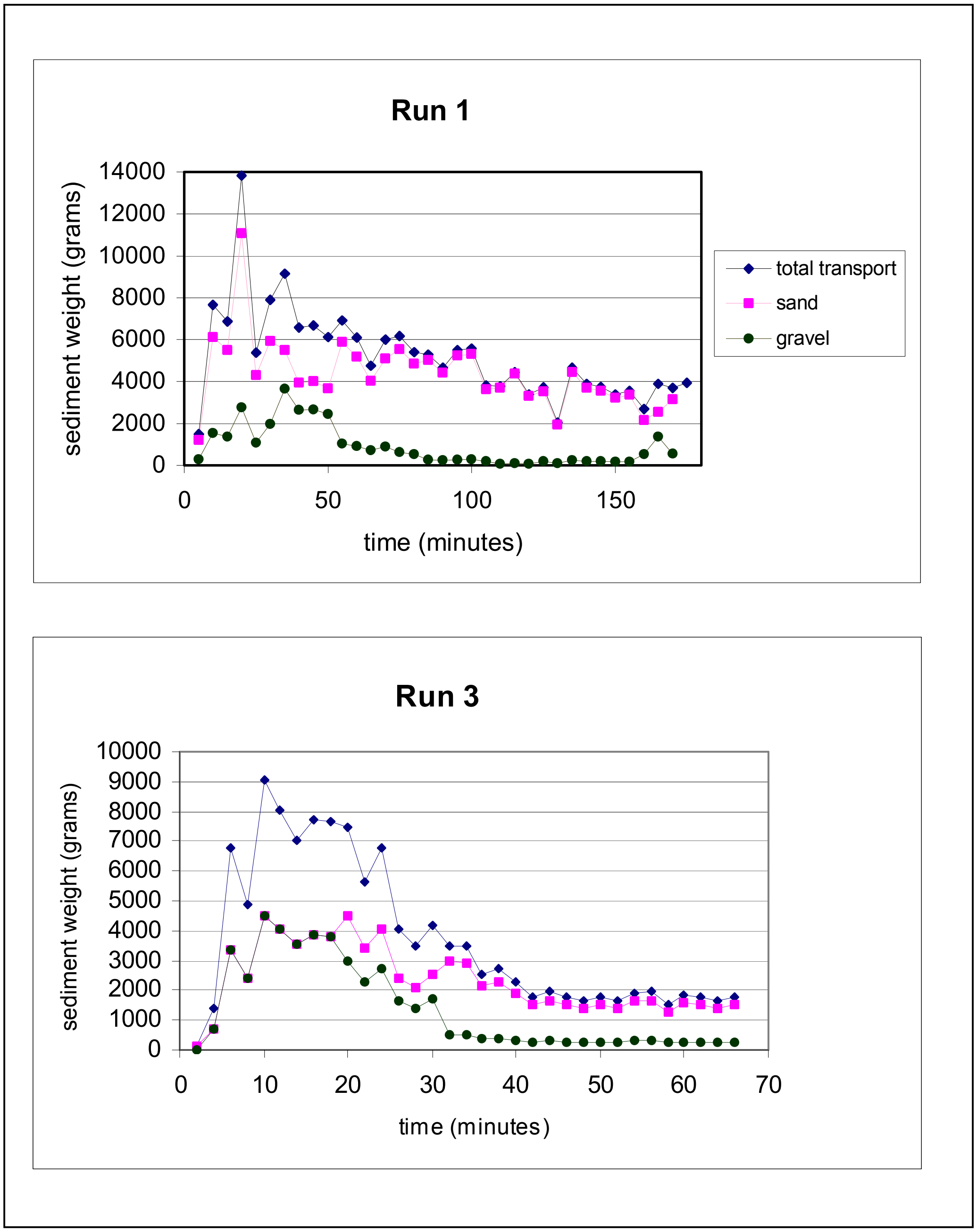


Figure 10a. Sediment transport graph: Runs 1 and 3. Both gravel and sand are being transported from armored bed as result of 100% sand influx. Note initial 'flashy' surge of gravels which then shifts to a more steady, even output. Legend from Run 1 graph applies to Run 3.

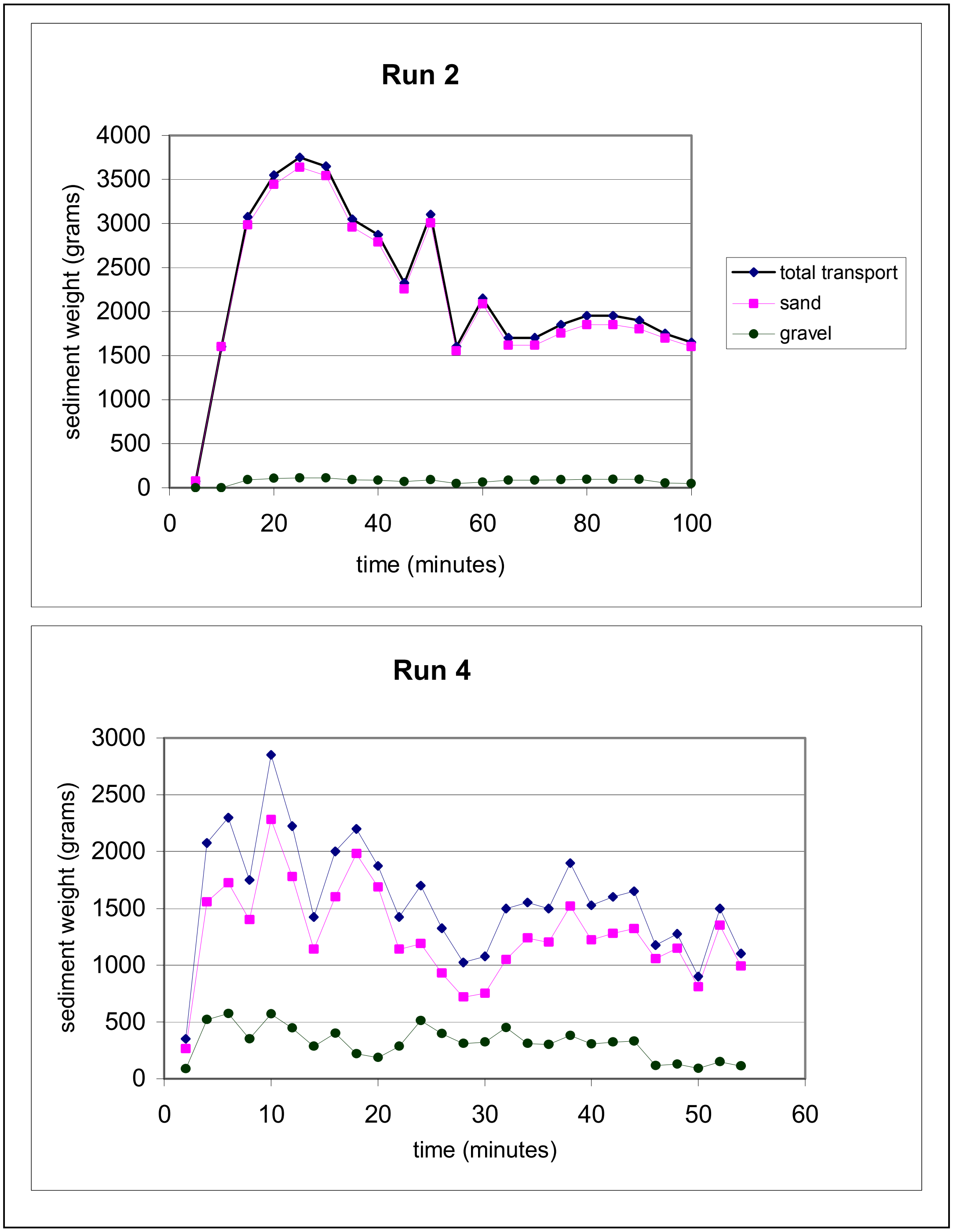


Figure 10b. Sediment transport graph: Runs 2 and 4. Gravel is being mobilized and transported out of the flume upon addition of sand, yet it is being transported at a more consistent, lower rate over time. Legend from Run 2 graph applies to Run 4.

Runs 1 and 3 (the lower discharge rate) mobilized and transported the largest amount of sediment and the greatest percentage of gravels upon the influx of fines. Runs 2 and 4 (the higher discharge rate) reacted differently to the influx of sand. They mobilized and transported sediment out of the flume, but the total output was less quantity and had a higher percentage of sand than in Runs 1 and 3. The gravel output fluctuated steadily through the entire run of Runs 2 and 4. In contrast, for Runs 1and 3, the gravel output was initially very high, but then leveled off with time. Refer to table 2 for sediment output quantities and table 3 for sediment output percentages.

Table 2. Sediment output quantities. Note higher total sediment and gravel output for Runs 1 and 3.

Run no.	Total sediment output (kilograms)	Gravel output (kilograms)	Sand output (kilograms)
1	183	31	152
2	45	2	44
3	122	45	77
4	55	11	43

Table 3. Sediment output percentages. Summary of total percent of sand and gravel outputs at the end of phase three, sand input. Note the higher percentages of gravel output for Runs 1 and 3 versus the higher sand output for Runs 2 and 4.

Run no.	Percent gravel output	Percent sand output	Percent gravel in final bed	Percent sand in final bed	Percent sand on final bed surface
1	27%	73%	78%	22%	35%
2	2%	98%	70%	30%	40%
3	21%	79%	72%	28%	65%
4	12%	88%	69%	31%	90%

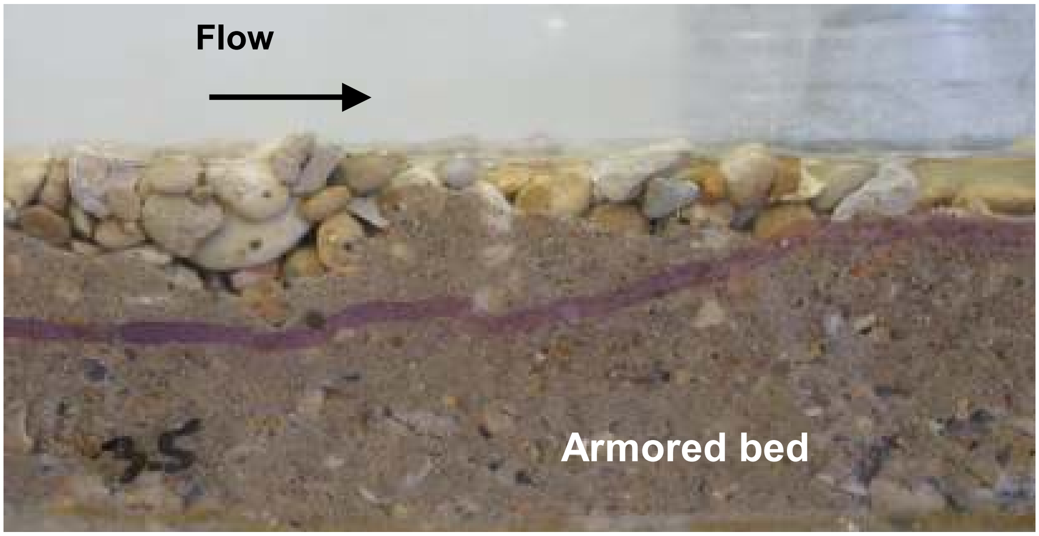
Sand content increased both in the bed and on the surface for all runs. Thus the surface of each sediment bed was smoothed with sand. Under the higher sediment feed rate, Runs 3 and 4, the concentration of sand on the bed surface was the greatest, creating a ‘sandy’ pavement (figure 11). Still prevalent on this sandy pavement were isolated patches of gravel cluster formations.

Figure 11. Final pavement: Runs 3 and 4. Bed surface has been smothered by sand, creating a sandy surface. The same feed interval of 2 minutes was used, yet the discharge was different for each run. Run 4 experiences a greater concentration of sand. Cluster formations protrude through both beds. Examples are outlined in yellow.

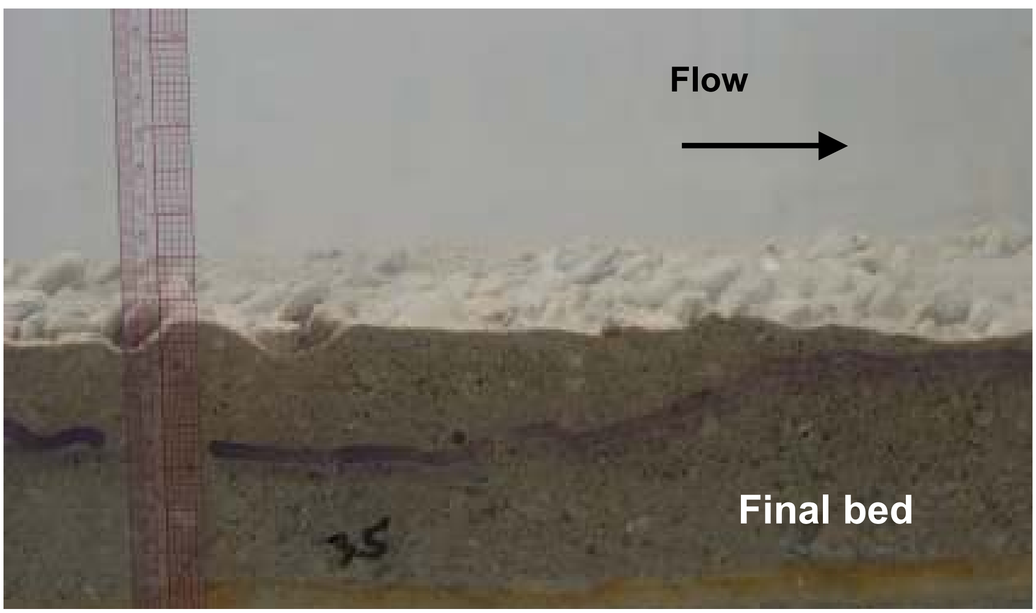
During Runs 1 and 2, the bed surface experienced an increase of sand, but observations showed the sand to be distributed unevenly across the bed. Sand filled in troughs and/or depressions in the bed topography, such that the overall bed surface remained fairly coarse with patches of sand (figure 12).

Figure 12. Final pavement: Runs 1 and 2. Less sand is being added to the system when using a five-minute feed interval. The bed still experiences some smothering of sand, yet it is patchy. A coarse surface dominates. Examples of sandy patches are circled in yellow.

Sand infilling of the bed occurred for all runs (figure 13). The overall composition of the bulk sediment changed from the original 15% sand to 22-31 % sand. This result is significant because the change in bed composition due to an increase in sand considerably influences the ability of the same flow rate to transport gravel sediment (Wilcock et al. 2001).



a.



b.

Figure 13. Final bed infill: side view. Both photograph a, armor bed, and b, final bed, were taken at 3.5 meters of Run 3. Note the amount of armored bed pore space that has been filled in with sand upon the influx fines.

The degree of sand infilling of both surface and subsurface sediments was observed to increase with distance downstream, with the highest concentration of sand measured in the downstream section (figure 14). During Runs 2 and 4 (higher discharge) the overall amount of sand infilling was greater than in Runs 1 and 3 (lower discharge). The percentage of gravels in the bulk bed decreased for all runs from 85% gravel in the original bed to 69-78% gravel in the final bulk bed sediment (see previous table 3).

Figure 14. Final bed infill: cross-section. Bed cross-section view at 3.5 meters of bed showing sand infill of pore spaces after 100% sand input. Penny is 18 mm; pen is 150 mm.

The bed slope for Runs 1and 3 increased slightly, indicating bed aggradation at the upstream end. Whereas the bed slope decreased for Runs 2 and 4 indicating degradation took place upstream resulting with subsequent aggradation at the downstream end, thus leveling the overall bed. In a unidirectional transport system, slope decreases as sediment is eroded from the upstream in a downstream direction (Curran and Wilcock 2005).

The surface grain size D_{50s} and D_{65s} increased during all runs. During all the runs, the bed coarsened until the D_{50s} reached a consistent grain size around 19.5 mm, and the D_{65s} consistently stayed close to 21.5 mm. Both D_{50b} and D_{65b} decreased significantly from equilibrium grain size D_{50b} and D_{65b} values, where D_{50b} (equilibrium) dropped from 11.8 mm to a range of 5.1 mm – 10.27 mm (final bed) and D_{65b} (equilibrium) dropped from 15.2 mm to a range of 8.03mm – 12.73 mm (final bed). As a result, the bed became sandier. The bulk grain size from the armor phase could not be measured as the bed surface was not disturbed between phases two and three of the runs. The bulk grain size was measured for only the initial equilibrium bed and the final bed material. Nonetheless, the change of bulk grain size from beginning to end illustrates changes in the overall bed composition.

Shear stresses

The bed shear stress, or the total boundary shear stress, τ, is the force exerted by the water flow on an area of the bed. It is the factor that measures the power of the flow to dislodge the sediment (Henderson 1966). Shear stress was calculated using the DuBoy's equation and measured values of flow depth and bed slope,

$$\tau = \rho g h S$$

where ρ (kg/m^3) is fluid density of water, g is the acceleration of gravity (m^2/s), h is the flow depth (m), S is the bed slope, and τ is the total shear stress (Pa). The shear stress was adjusted to compensate for the unavoidable hydraulic side effects of a smooth walled flume (Chiew and Parker 1994; Vanoni and Brooks 1957). The sidewall corrected shear stress values are used in further analysis.

As the level of sand on the bed surface increased during the third phase of 100% sand input, the shear stresses for Runs 1 and 3 increased slightly from 17.8 Pa (armor phase) to 18.1 Pa (sand phase) and 11.9 Pa (armor phase) to 12.4 Pa (sand phase) respectively. This increase is minor and it is reasonable to consider shear stress to be fairly constant. The shear stress for Runs 2 and 4, however, decreased considerably from 26.7 Pa (armor phase) to 13.4 Pa (sand phase) for Run 2 and 22.3 Pa (armor phase) to 15.0 Pa (sand phase) for Run 4 (figure 15).

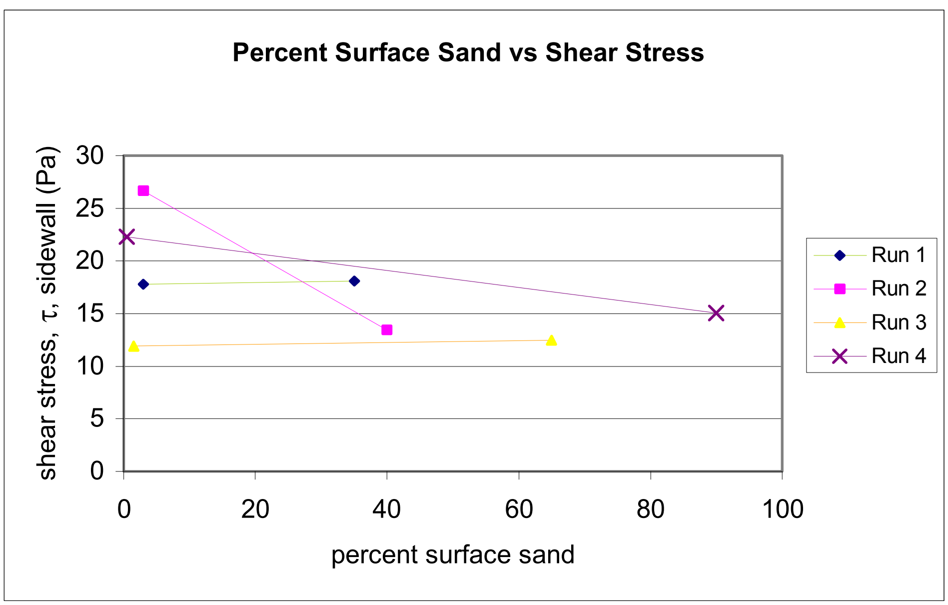


Figure 15. Shear stress versus percent surface sand.

Sediment is mobilized when the shear stress acting on the bed can be expressed as a dimensionless number, τ*, which is a ratio of the fluid shear stress exerted on the bed to the resisting force (Oldmeadow and Church 2006). The dimensionless shear stress is defined by the equation

$$\tau * = \frac{\tau}{(s-1)\rho g D_{50}}$$

where τ is the boundary shear stress; s, which is assumed to be 2.65 g/cm^3, is the ratio of sediment density, ρ_s, to water density, ρ; g is gravity; and D_{50} is sediment surface grain size (mm). When sand was added to the armored bed, τ* decreased considerably (figure 16).

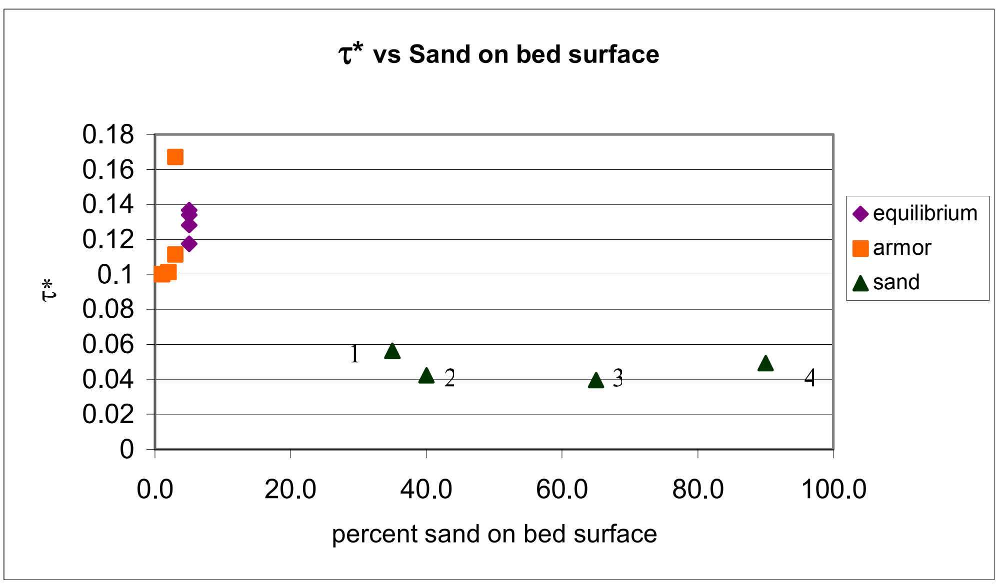


Figure 16. Dimensionless shear stress versus percent surface sand. Note the decrease in stress upon the introduction of sand onto the armored bed. Run numbers for sand phase are noted.

The critical Shields number, τ_c*, is the nondimensional form of critical shear stress. It is the critical value of τ* defining the threshold of sediment transport (Wilcock et al. 2001; Meyer-Peter and Mueller 1948). The Shields number is a representation of the forces imposed on a grain in comparison with the force necessary to mobilize it (Oldmeadow and Church 2006). It defines the stress at the initial moment in which a bed grain begins to move. In a mixed sediment system, this exact moment of initial entrainment can be virtually impossible to identify. Hence, the non-dimensionalized reference shear stress, τ_r*, is used to estimate τ_c*. This reference shear stress is a shear stress that produces a small, constant, and agreed-upon reference transport rate (Wilcock 1998). Although τ_r*, is slightly larger than τ_c*, it is close enough to serve as the surrogate to critical shear stress. Upon the influx of sand to the armored bed, the reference shear stresses decreased dramatically from the values reached for the equilibrium and armor phases (figure 17). This result is significant because a lower reference shear stress indicates that less force is required to mobilize grains in the bed while maintaining the same transport rate. The transport capacity of the system therefore increases and bed material, which typically requires higher shear stresses to initiate movement, can be mobilized and transported downstream.

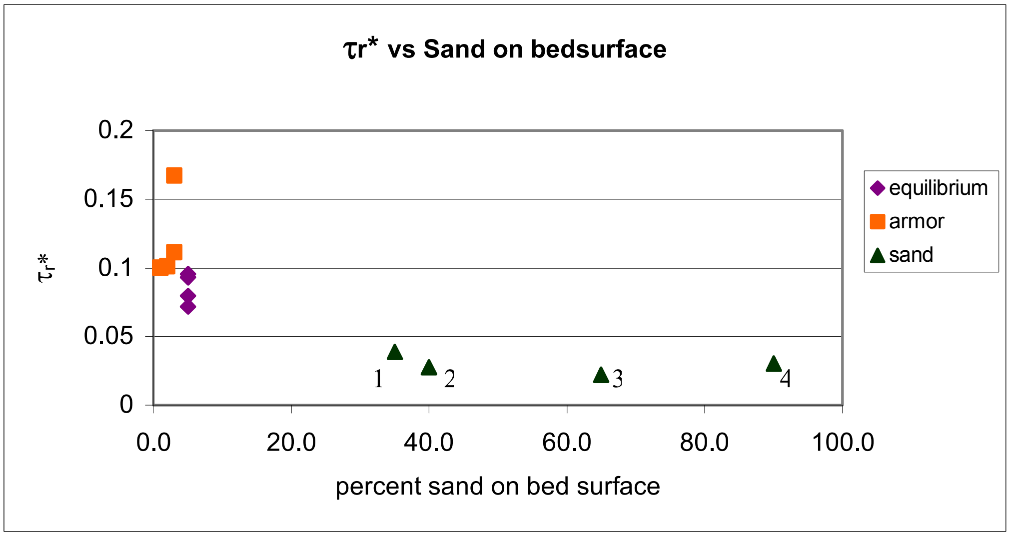


Figure 17. Reference shear stress versus percent surface sand. Note drop in stress for Runs 1 through 4 upon the addition of sand. Run numbers for sand phase are noted.

Tracer grains

As previously mentioned in the methods chapter, Runs 3 and 4 each had 63 grains of the armored bed labeled either 'A', 'B', and 'C' (Run 3) or '1', '2', and '3' (Run 4). This allowed for an analysis of grain movement, if any, from the armored surfaces. Table 4 provides a full accounting of tracer grain movement. The original grain size distribution of tracer grains spanned 11 mm – 32 mm for both runs. Run 3 (table 4a), with a lower discharge (Q=0.018 m^3/s), experienced the most movement of tracer grains. Only three out of twenty-one grains remained in the upstream section, eight out twenty-one remained in the mid section, and seven out of twenty-one remained in the downstream section. All other tracer grains either moved downstream one and/or two sections or completely exited the flume. Run 4 (table 4b), with the higher discharge(Q=0.02 m^3/s), eight out of twenty-one grains remained in the upstream section, and ten out of twenty-one grains remained in each the mid and downstream sections. As in Run 3, all other tracer grains either moved one and/or two sections downstream or exited the flume. For both runs, the most common grain size to remain in place was 22.6 mm and the most common grain size to exit the flume was 16 mm.

Table 4. Accounting of tracer grains. a) Run 3 and b) Run 4. Grain movement occurred in all sections. Upstream and downstream movement was more common than midstream. Smaller grain sizes (11 mm, 16 mm) were highly mobile and tended to be evacuated from the flume. Medium to larger grains (22.6 mm, 32 mm) moved one section downstream or remained stationary.

4a. Run 3

Original GSD of tracer grains (mm)		
A (U/S)	**B (MID)**	**C (D/S)**
2 x 11	3 x 11	1 x 11
8 x 16	8 x 16	7 x 16
8 x 22.6	8 x 22.6	7 x 22.6
3 x 32	2 x 32	6 x 32
total: 21	total: 21	total: 21
Grains (mm) that remained in original position		
A	**B**	**C**
0 x 11	0 x 11	0 x 11
0 x 16	3 x 16	1 x 16
2 x 22.6	3 x 22.6	3 x 22.6
1 x 32	2 x 32	3 x 32
total: 3	total: 8	total: 7
Grains (mm) that moved downstream		
A to Mid	**A to D/S**	**B to D/S**
0 x 11	0 x 11	1 x 11
1 x 16	0 x 16	0 x 16
1 x 22.6	2 x 22.6	1 x 22.6
0 x 32	1 x 32	0 x 32
Grains (mm) that evacuated the flume		
A	**B**	**C**
2 x 11	2 x 11	1 x 11
7 x 16	5 x 16	6 x 16
3 x 22.6	4 x 22.6	4 x 22.6
1 x 32	0 x 32	3 x 32

4b. Run 4

Original GSD of tracer grains (mm)		
1 (U/S)	**2 (MID)**	**3 (D/S)**
2 x 11	6 x 11	4 x 11
10 x 16	7 x 16	10 x 16
7 x 22.6	6 x 22.6	4 x 22.6
2 x 32	2 x 32	3 x 32
total: 21	total: 21	total: 21
Grains (mm) that remained in original position		
1	**2**	**3**
1 x 11	1 x 11	0 x 11
1 x 16	3 x 16	3 x 16
4 x 22.6	4 x 22.6	4 x 22.6
2 x 32	2 x 32	3 x 32
total: 8	total: 10	total: 10
Grains (mm) that moved downstream		
1 to Mid	**1 to D/S**	**2 to D/S**
0 x 11	0 x 11	1 x 11
1 x 16	1 x 16	1 x 16
2 x 22.6	0 x 22.6	1 x 22.6
0 x 32	0 x 32	0 x 32
Grains (mm) that evacuated the flume		
1	**2**	**3**
1 x 11	4 x 11	4 x 11
7 x 16	3 x 16	7 x 16
1 x 22.6	1 x 22.6	0 x 22.6
0 x 32	0 x 32	0 x 32

CHAPTER V

DISCUSSION

Understanding how fine sediment will behave when flushed from behind a dam and into the river system downstream is an essential component of planning a dam removal. Results from this work have shown that an input of sand onto an armored bed will mobilize and transport downstream both gravels and sand from the bed. As sand infiltrates and covers the bed, the bed composition shifts to a sandier mixture. Changes in the proportion of either the sand or gravel will affect the transport rate of the other (Wilcock 2004). In a mobile, bi-modal sediment system, increasing the amount of sand in either the sediment supply or the bed will cause an increase in the mobility of the gravel fraction (Curran and Wilcock 2005; Wilcock 2004; Wilcock, et al. 2001; Iseya and Ikeda 1987; Jackson and Bescheta 1984) by reducing the reference shear stress, and therefore, increasing the total sediment load that can be transported (Curran and Wilcock 2005). With an immobile armored bed, as sands are introduced into the system, the armored bed is broken, and the gravel fraction becomes mobile and is transported downstream, thus increasing the overall sediment load. The increase of gravel mobility from both a mobile and immobile bed is attributed to a drop in the reference shear stress caused by the input of sand. The amount of force typically required to transport larger grains is lowered throughout the system, which in turn increases the overall transport capacity of the system. Hence, an abundance of bed material including larger grains will be entrained at lower shear stresses, while the transport rate, which is dependent on the shear force exerted by the flow, remains high. It is interesting that an input of sand onto a mobile bed or immobile bed yields similar sediment responses.

The distinctive pairing between Runs 1 and 3 (lower flow rate) and Runs 2 and 4 (higher flow rate) that emerges with the bed's reaction to the input of fines is an intriguing result. Each pair is held at the same flow rate against two different sediment feed rates. If the addition of sand helps to mobilize gravel as seen with Curran and Wilcock (2005), Wilcock (2004), Wilcock, et al. (2001), Iseya and Ikeda (1987), Jackson and Bescheta (1984), and this research, then it is reasonable to hypothesize that the runs with a higher sand feed rate, which are Runs 3 and 4, would mobilize the most gravels. This is not the case. Runs 3 and 4 do not mobilize the most gravel nor generate the most gravel output. Runs 1 and 3, with the lower discharge and variant feed rates mobilize, and generate much more gravel output than Runs 2 and 4. This is not to say that the addition of sand holds no bearing on the outcome, for clearly it does, but the results indicate that the discharge rate is a more dominant controlling factor than previously thought.

The discharge rate can cause the system to break and mobilize the armor bed as seen with research on the breakup and reestablishment of armor layers below the Flix dam along the Lower Ebro River (Vericat et al. 2006). However, the input of sand makes it easier for an armored bed to break, and once the bed is mobilized, the sand further increases gravel mobility. What is not yet fully investigated is the amount of control the discharge rate has over the formation of the armor layer, i.e. a loosely packed armored bed or a tightly packed armored bed, which in turn may control the changes in shear stresses in the system that account for the increase in sediment mobility and transport downstream. Vertical sorting of sediment during the armoring process is the result of interactions between flow magnitude and duration, sediment grain size distribution, sediment supply, and the initial bed surface conditions (Hassan, Egozi, Parker 2006). If discharge plays a significant role in the armoring process, then a higher discharge may produce an armored bed with tightly interlocked grains, thus making the bed more difficult to break apart. Likewise, a lower discharge may create an armored bed that is more loosely packed, requiring less force to break, thus exposing more bed material for transport, which can increase the total sediment yield.

The control of discharge over the formation of the armored bed can be investigated through the tracer grains for any correlation between the number and distance of grains that moved to the discharge. Recall the same feed rate was applied to both runs, but different discharges were used. Run 3 with the lower discharge moved 71% of the numbered grains either downstream or completely out of the flume. As well, 5 of the 11 tracer grains 32 mm in size moved. In contrast, Run 4 transported downstream 60% of the tracer grains. All of the 32 mm sized tracer grains remained stationary. A reasonable but incorrect assumption would have been that Run 4 with a higher discharge, would move at least as many of the same grain sizes as the lower discharge. This is not the case, as there are fewer grains being exposed for transport in Run 4 where a tightly interlocked armor layer formed under the higher discharge. Also in Run 4, the bed was quickly covered with sand, which may have inhibited mobilization of the larger grains in the armor. In contrast, the bed for Run 3 consisted of a looser packed armor layer, which was more easily broken. Once the armor grains were mobilized, the underlying substrate was exposed and entrained. It is possible that loose bed material allowed the larger 32 mm size tracer grains, to be mobilized and transported downstream.

In all four runs, once the armor bed was broken, the system shifted from an immobile armored bed to a mobile bed in which both sand and gravel transported through the system. Eventually the bed was smothered with sand and the gravel fraction transport slowed down, but did not cease. Unlike the sediment-starved system below the Flix dam along the Lower Ebro River, the bed did not re-establish an armor layer after being broken. Instead it transgressed into a 'quasi-equilibrium' where the amount of sand being fed at the upstream end equaled the total amount of sand mixed with a few gravels exiting at the downstream end.

Two new questions arise from this project and discussion that are worthy of further investigation. The first pertains to the influence of discharge on the formation of the armor bed and thus the breakup of the armor bed. What are the driving forces that control the formation of an armored bed? Do these forces influence how the armored bed is broken and mobilized? The second question concerns finding the right balance between the amount of sand to flush onto an armored bed coupled with an accurate estimate of discharge used to flush the sand. In Runs 3 and 4 a high sediment feed of sand quickly smothered the bed, whereas in Runs 1 and 3 the lower discharge transported more sediment downstream. These results indicate that in order to minimize the impacts of sediment on the downstream river morphology during a dam removal, the optimum combination would be a low sediment feed rate coupled with a high discharge rate.

CHAPTER VI

CONCLUSION

As the option for dam removal gains popularity, scientists and decision-makers will be faced with many challenges pertaining to the uncertainties of the sediment effects from removing a dam. The cost of repairing and/or upgrading aging dams will continue to increase. Hence, dam removal will probably become an increasingly common facet of river management (Doyle et al. 2003).

While abundant research has been done on how rivers are affected by dam construction, only a few dam removals have been conducted with rigorous pre- and post-removal monitoring and/or analysis (Grant 2001). As a result, there are only a small number of peer-reviewed studies available on completed dam removals (Bednarek 2001). Presently no standardized method is available for analyzing sediment transport relating to dam removal, nor are the available algorithms considered to be absolutely dependable (Lorang and Aggett 2005; Pizzuto 2002).

The purpose of this study was to gain more clarity on how a channel may respond to a sudden change in sediment supply. In particular it examined the behavior of an armored bed in response to an influx of fine-grained sediment. Gravel-bed rivers typically show a coarse grained surface, known as the armor layer (Hassan et al. 2006), just downstream from dams. This surface is the result of kinematic sorting (Wilcock et al. 2001), which is a continuous selective transport, horizontal winnowing of fines, and bed degradation until a veneer of coarse material forms which prevents further sediment transport (Hassan et al. 2006). Questions addressed with this research included: upon the sudden input of fine-grained material, i.e. sands, what happens to the armor layer? Is the layer forced to break, thus mobilizing sediment for transport? How is the bed shear stress affected with the input of sand? How do these changes in shear stress affect the transport capacity of the bed material? If the armored bed is broken, then how far does the sediment travel downstream?

To answer these questions, a tilting, sediment feed flume was used to simulate the sudden flushing of fines onto an armored bed. Four runs were conducted using two different flow rates against two different sediment feed rates. The water discharge, and the sediment feed composition and feed rate were specified, while the bed slope, bed surface, and flow depth were free to adjust (Curran and Wilcock 2005). When sediment was fed into the flume, the system responded by adjusting the bed surface composition, the flow depth and slope to carry the imposed load (Wilcock and DeTemple 2005).

Results showed that the armor layer was broken with each run and both gravels and sand were mobilized and transported downstream. This was measured as the flush of gravels exiting the flume, and the movement of tracer grains. The reference shear stress, a surrogate to critical shear stress, dropped significantly when sand was added to the system, thus increasing the transport capacity of the gravel fraction. Applying this result to the field, this increase of gravel and sand transport could impact navigation channels and engineering structures downstream, and clog tributaries and fish spawning passageways. Upon the break-up of the armor layer, the bed not only infilled with sand but also the surface was smothered with sand. This result could have detrimental effects on downstream flora and fauna as habitat is inundated and buried with sand.

A distinctive pairing between Runs 1 and 3 (lower flow rate) and Runs 2 and 4 (higher flow rate) emerged through the bed's response to the input of fines. The bed's response varies with the discharge rate, indicating that discharge may have a more dominant controlling role in armored bed formation and break-up than previously thought. How the bed armors itself and thus breaks apart lends to a new set of questions that are worthy of exploration especially when trying to minimize the amount of detrimental sediment effects downstream by controlling the level of discharge and sand flushing onto an armored bed during dam removal.

Before the larger dams such as the Glines Canyon and Elwha dams in Washington State start to come down, more laboratory work and fieldwork needs to be done to enhance and contribute to the current state of knowledge. Looking at lessons learned from dam removal projects such as the Embry Dam along the Rappahannock River, Virginia, or the Edwards Dam along the Kennebec River, Maine, along with further flume experiments analyzing the effects of fine grained sediment on downstream bed morphology will only increase the knowledge and understanding of the effects dam removals have on a riverine system.

APPENDIX

Table 5. Summary of armor experiments.

Armoring Run #	**1**			**2**		
Run Date	11/3/2006	11/8/2005	1/9/2006	1/30/2006	1/30/2006	2/6/2006
Total Time, minutes	670			760		
Valve setting	L8R0	L8R0	L8R0	L10R0	L9R0	L9R0
Q (m^3/s)	0.0194	0.0194	0.0194	0.0207	0.0200	0.0200
q (m^2/s)	0.0647	0.0647	0.0647	0.0690	0.0667	0.0667
Flume S	0.00507	0.00507	0.00507	0.032508	0.032508	0.0313431
Feed Rate (g/ms)	56	0	56	56	0	56
Time interval (min)	5	5	5	5	5	5
Sediment output (g)	140600	53805	182695	126735	82295	45250
Phase	equilibrium	armor	sand	equilibrium	armor	sand
Phase time (min)	0-255	0-240	0-175	0-120	0-540	0-100
S_w	0.0399	0.029	0.0288	0.0358	0.0358	0.0145
S_b	0.03250	0.02650	0.02900	0.03430	0.03470	0.01760
S_E	0.03546	0.02762	0.02894	0.03469	0.03532	0.01577
R (m)	0.0364	0.0369	0.0356	0.0359	0.0392	0.0396
h (m)	0.0708	0.0728	0.0678	0.0689	0.0820	0.0839
U (m/s) U=Q/A	0.913	0.888	0.954	1.001	0.841	0.822
Us (m/s)	1.828	1.828	1.828	1.784	1.784	1.784
F	1.096	1.051	1.170	1.218	0.938	0.907
U_*	0.150	0.138	0.139	0.152	0.167	0.120
f	0.236	0.200	0.169	0.187	0.321	0.154
Manning's n (h)	0.018	0.016	0.015	0.016	0.021	0.015
Manning's n (R)	0.006	0.006	0.006	0.005	0.006	0.007
$\tau=\rho ghS$ (Pa)	24.63	19.72	19.25	23.45	28.41	12.98
$\tau=\rho gRS$ (Pa)	12.67	10.01	10.11	12.22	13.57	6.13
τ_o (Pa) sidewall	21.38	17.79	18.10	21.85	26.67	13.41
% sand-bulk	15	n/a	22.0	15	n/a	30.0
% gravel-bulk	85	n/a	78.0	85	n/a	70.0
D_{65} (mm) - bulk	15.20	n/a	8.03	15.2	n/a	12.03
D_{50} (mm) - bulk	11.8	n/a	5.1	11.8	n/a	10.27
% sand-surface	7	3	35.0	5	3	40.0
% gravel-surface	93	97	65.0	95	97	60.0
D_{65} (mm) - surface	11.67	11.85	21.75	11.67	11.85	21.51
D_{50} (mm) - surface	9.86	9.85	19.82	9.86	9.85	19.56

Table 5 – Continued. Summary of armor experiments.

Armoring Run #	**3**			**4**		
Run Date	2/23/2006	3/6/2006	3/8/2006	6/21/2006	6/28/2006	6/29/2006
Total Time, minutes	560			414		
Valve setting	L8R0	L8R0	L8R0	L10R0	L9R0	L9R0
Q (m^3/s)	0.0194	0.0194	0.0194	0.0207	0.0200	0.0200
q (m^2/s)	0.0647	0.0647	0.0647	0.0690	0.0667	0.0667
Flume S	0.01881	0.01881	0.01881	0.027299	0.015602	0.015602
Feed Rate (g/ms)	139	0	139	139	0	139
Time interval (min)	2	2	2	2	2	2
Sediment output (g)	216010	107410	121700	301875	35295	54575
Phase	equilibrium	armor	sand	equilibrium	armor	sand
Phase time (min)	0-93	0-402	0-65	0-100	0-250	0-64
S_w	0.0314	0.021	0.0209	0.0286	0.0164	0.018
S_b	0.03150	0.02020	0.02300	0.02940	0.02930	0.02470
S_E	0.03146	0.02040	0.02293	0.02918	0.02212	0.02302
R (m)	0.0477	0.0350	0.0335	0.0361	0.0391	0.0354
h (m)	0.07	0.0658	0.0604	0.0696	0.0818	0.0671
U (m/s) U=Q/A	0.924	0.983	1.071	0.991	0.844	0.994
Us (m/s)	1.443	1.443	1.443	1.773	1.773	1.773
F	1.115	1.223	1.391	1.200	0.942	1.225
U_*	0.147	0.114	0.117	0.142	0.153	0.128
f	0.203	0.109	0.095	0.162	0.200	0.123
Manning's n (h)	0.016	0.012	0.011	0.016	0.017	0.013
Manning's n (R)	0.011	0.005	0.005	0.006	0.006	0.005
$\tau=\rho ghS$ (Pa)	21.61	13.17	13.59	19.92	17.75	15.16
$\tau=\rho gRS$ (Pa)	14.73	7.01	7.53	10.33	8.49	8.00
τ_o (Pa) sidewall	20.44	11.92	12.44	18.78	22.30	15.05
% sand-bulk	15	n/a	28.0	15	n/a	31.0
% gravel-bulk	85	n/a	72.0	85	n/a	69.0
D_{65} (mm) - bulk	15.2	n/a	10.9	15.20	n/a	12.73
D_{50} (mm) - bulk	11.8	n/a	9.4	11.80	n/a	9.8
% sand-surface	3	2	65.0	5	1	90.0
% gravel-surface	97	98	35.0	95	99	10.0
D_{65} (mm) - surface	11.67	8.2	21.29	11.67	15.70	21.52
D_{50} (mm) - surface	9.86	7.3	19.4	9.86	13.74	18.8

Table 6. Definition of terms. Armor summary table.

Armoring Run #	Name of experiment
Run Date	Date of experiment
Total Time, minutes	Total experiment time
Valve setting	Left valve setting: Right valve setting
Q (m^3/s)	Flow rate, discharge
q (m^2/s)	Discharge per unit width (q=Q/A)
Flume S	Slope of flume, measured from bottom of flume to floor
Feed Rate (g/ms)	Amount of sediment being added at specific time interval
Time interval (min)	Length of interval sediment is being added
Sediment output (g)	Amount of sediment to exit flume during phase
Phase	Specific phase during run
Phase time (min)	Total time for each phase
S_w	Slope of water
S_b	Slope of bed
S_E	Slope of energy
R (m)	Hydraulic radius
h (m)	Flow depth
U (m/s) U=Q/A	Velocity
Us (m/s)	Surface velocity
F	Froude #
U_*	Shear velocity
f	Friction factor
Manning's n (h)	Manning's n based on flow depth, h
Manning's n (R)	Manning's n based on hydraulic radius, R
$\tau=\rho ghS$ (Pa)	Shear Stress based on flow depth, h
$\tau=\rho gRS$ (Pa)	Shear Stress based on hydraulic radius, R
τ_o (Pa) sidewall	Shear stress corrected for sidewall
% sand-bulk	Percent sand within bed
% gravel-bulk	Percent gravel within bed
D_{65} (mm) - bulk	D_{65} within bed
D_{50} (mm) - bulk	D_{50} within bed
% sand-surface	Percent sand on bed surface
% gravel-surface	Percent gravel on bed surface
D_{65} (mm) - surface	D_{65} on bed surface
D_{50} (mm) - surface	D_{50} on bed surface

Note: D_x denotes the grain size for which *x* percent of bed material is finer. For example, D_{50} bulk or D_{50} surface indicates the median grain size in which 50% of the bulk bed material or bed surface material is finer. Similarly, D_{65} bulk or D_{65} surface denotes the grain size in which 65% of the bed material (bulk or surface) is finer.

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VITA

Mary Katharin Pritchard was born in Richmond, Virginia, to Dr. George E. Pritchard and Mrs. Barbara Pinnell Pritchard. The founding blocks of her education began at St. Catherine's School, Richmond, Virginia. Upon graduating from St. Catherine's in June 1988, she began her undergraduate degree at Denver University, Denver, Colorado. During the winter of her sophomore year, she decided to take some time off from her academic education. Fully confident she would return when ready to the academic world, she shifted gears and stepped into the school of life where she worked and traveled extensively the United States. In 1993 she enrolled at the University of Oregon in Eugene, Oregon where she fell in love with the science of geology. Her third year at U of O, she travelled abroad to study geology and a little bit of surfing at Curtin University in Perth, Western Australia.

After graduating from the University of Oregon in 1997 with a Bachelor of Science in Geology, she moved back to Richmond, Virginia. She began working in 1999 as a research assistant for Dr. Eugene Maurakis, head scientist of the Science Museum of Virginia. As research assistant she provided geologic interpretation on historic river drainage basins of mainland Greece.

She began the Geography graduate program at Texas State University-San Marcos, Texas, in 2003. During her time as a graduate student, she was the head

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