QUALITATIVE AND QUANTITATIVE EXPERIMENTS USING THE EM4 PHYSICAL RIVER MODEL

Timothy Edward Keenan, B.S.

An Abstract Presented to the Graduate Faculty of
Saint Louis University in Partial Fulfillment
of the Requirements for the Degree of
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ABSTRACT

Work with experimental fluvial models is an important part of understanding processes that operate in natural systems. Much work has been done with geomorphological physical models over the past century, and much progress has been made in understanding the formation and evolution of various landforms. Experimental models also have a great value in educational endeavors, as interactive learning is an essential part of geoscience education.

This work seeks to understand processes operating in the formation and modification of bedforms in fluvial systems using a mobile bed stream table. The EM4 stream model has already shown great promise as an educational tool in the qualitative observation of fluvial processes. It is the goal of this research to obtain a greater understanding of the EM4 and lay the groundwork for future geomorphological research using this equipment.

Several sets of experiments were conducted on the EM4 by modifying both the longitudinal and latitudinal gradients of the stream table and simulating base level change. These experiments were conducted in an effort to evaluate the experimental stream's response to induced perturbations in light of previous research with both specific field sites and other experimental physical models. Results from the "Base Level Change" experiments on the EM4 are consistent with previous research investigating the effects of base level change. Although certain parameters were difficult to constrain on the EM4, overall trends and geometrical relationships within the fluvial system were consistent between experiments.

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COMMITTEE IN CHARGE OF CANDIDACY:

Assistant Professor Ana Londoño;
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Associate Professor John Encarnación

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DEDICATION

This work is dedicated to my parents, William and Deborah Keenan, and my wife, Katherine Keenan. Their unwavering love, support, guidance, generosity, and humility have given me the tools and drive to succeed, while providing me with a higher standard with which to live my life. All of my best qualities, I owe to them.

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CHAPTER 1: INTROCUCTION

Experimental Geomorphology

<u>Use of Physical Geomorphological Models</u>

Development of experimental models to study landscape evolution has a long history. Some of the earliest documented work with experimental models can be traced back to the early 20th century. Tarr and von Engeln (1908) and Ellis (1912) were a few of the early pioneers to explore the use of laboratory physical models in classroom education. The focus of this initial research was aimed at providing students with a visual, three-dimensional representation of natural features in a laboratory setting. When weather conditions did not permit the study of natural landscapes in the field and the use of topographic maps was employed to study geomorphological features, Tarr and von Engeln noted the “inability of the average undergraduate beginner to see in the map what is really there” (1908; 74). They found that the use of these laboratory scaled models helped to “increase the interest of the student; to lead to a better understanding and appreciation of maps, and to make the meaning of maps and map work more real and instructive; and to supply a better basis for constructive imagination upon which to interpret the problems of the map” (1908; 74). Both Tarr and von Engeln and Ellis went to great lengths to develop these models to efficiently illustrate the natural interactions between water and sediment (and their resulting landforms) for the benefit of these early 20th century agriculture and physical geography students.

Use of physical models was not only used for classroom educational purposes. Howe (1901) and others developed geomorphological physical models with a more traditional research approach in mind; developing and testing hypotheses for a greater understanding of the development and evolution of land surface features.

Work in experimental physical modeling of streams is important because it provides insight into the development and evolution of streams, the mechanisms governing their flow patterns and planforms, the formation and migration of bedforms, and fluvial landform generation and modification. Physical models of streams offer several advantages over observing processes occurring in natural systems; two significant advantages are the compressed time scale (which allows processes that may occur over thousands of years to be observed over the course of minutes to days) and the manageable size of the models (which allows settings such as the Mississippi River basin to be simulated in a relatively small laboratory space) (Schumm, Mosley, and Weaver, 1987; Paola, Straub, Mohrig, and Reinhardt, 2009). Use of experimental models also enables the observation of a streams response to changes in singular controlled parameters such as discharge, sediment flux, gradient, lateral tectonic tilt and local base level in order to better understand a system's sensitivity to such changes (Koss, Ethridge, and Schumm, 1994).

Although much progress has been made in the knowledge of geomorphological processes and their governing variables, motivations behind the early work conducted by Tarr, von Engeln, Ellis, Howe, and others continue to hold true in today's work with experimental geomorphological models. The importance of the use of physical models in understanding surficial processes is clear; experimental models continue to provide students with an appreciation for and the means of observing natural processes in a laboratory setting. They also enable researchers to test hypotheses (developed both in the field and in the model) and record quantifiable data.

Types and Limitations of Physical Models

Chorley and Haggett (1967) broadly categorized physical geomorphic models into three types: unscaled reality models, scale models, and analog models. The concept of unscaled reality models can hardly be considered a model, in the true sense, considering that it merely refers to the act of studying a natural area. Such "unscaled reality models" will not be discussed here.

Scaled models attempt to replicate a natural setting; downscaling various parameters to enable experimental study in a laboratory setting. In perfectly scaled models, the relationship of the parameters involved (forces, physical properties, border conditions etc.) is maintained (Schumm et al., 1987). As one may guess, there are many difficulties associated with attempting to achieve perfect scaling. Many of these difficulties possibly stem from a lack of understanding of all of the involved variables in natural systems. Recognizing this hurdle, some approaches in scale modeling have chosen to scale one variable (typically the Froude number) and adjust all other variables until model verification is obtained (Hooke, 1968). After model verification (features produced in the model represent those in the prototype), results from scaled models may offer the advantage of being "reliably extrapolated to the prototype" (Hooke, 1968).

The aim of analogue models is to, "reproduce only some aspects of the structure or a web of relationships" demonstrated in natural systems (Chorley and Haggett, 1967; 68). According to Chorley and Haggett (1967), these models often involve changes in the type of media used in the model. For example, Lewis and Miller (1955) used kaolin clay as a substitute for glacial ice when studying the deformation of a valley glacier. Likewise, Graveleau, Hurtrez, Dominguez, and Malavieille (2011) developed a sediment mix of silica powder, glass microbeads, plastic powder, and graphite that they used to study erosional landscapes. Although, through the use of such media substitutions, many geomorphological features can be reproduced in the lab, Chorley and Haggett (1967) warn of the great potential for "noise", or the creation of features in the models that are highly uncharacteristic of natural systems.

Bridging the gap between scale models and analog models, Hooke (1968; 392) developed the idea of "similarity of process" in which the following conditions in the models must be met;

> (1) that gross scaling relationships be met; (2) that the model reproduce some morphologic characteristic of the prototype; and (3) that the process which produced this characteristic in the laboratory can logically be assumed to have the same effect on the prototype.

Although a model prototype is mentioned in Hooke's approach, analog models do not necessarily need a specific real world location or natural system in mind when developing the model. The main goal in experiments using analog models is to enable the study of general principles governing morphology, and the subsequent development of hypotheses that can be applied to and tested in a wide range of natural systems. Analog models "may reproduce some significant aspect of the form and function of a natural phenomenon, but the forces, materials, and processes may be quite dissimilar to those in nature." (Schumm et al., 1987; 3). For geomorphologists, a physical analog modeling approach can be very useful. Discussing scale models (in which there is a prototype for which the model is based) Hooke (1968; 392) states, "This approach is clearly impractical for many geomorphic problems. Geomorphologists are seldom interested in a particular system, but are instead concerned with general principles applicable to a population of systems." Analog models allow for the study of general relationships and underlying principles present in a system that may otherwise be missed. Analog models also allow several other practical advantages such as the simplicity of the models and setting up experiments, and the relatively low cost and space requirements of these models (Peakall, Ashworth, and Best, 1996).

Many experimental geomorphological studies have been conducted over the past century (Schumm and Khan, 1972; Tal and Paola, 2007; Smith, 1998; Metivier and Meunier, 2003; Braudrick, Dietrich, Leverich, and Sklar, 2009; Lague, Crave, and Davy, 2003; Schumm, 1993). Much of this work conducted before the mid 1980's is summarized well in "Experimental Geomorphology" (Schumm et al., 1987). Work with physical geomorphological models since the 1980s is reviewed by Paola et al. (2009). These two sources include a summary of experiments on erosional landscapes, depositional systems and landforms (alluvial fans and deltas), rivers, and deep water processes. One limitation on experimental geomorphology using scaled models that resonates throughout both publications is the difficulty in scaling all relevant variables of an experiment so that the laboratory model replicates the natural prototype. Paola et al. (2009) therefore urges a change from traditional modeling techniques using a "classical dynamic scaling" approach (scale models) to a more analytical approach (using analog models). A point is made that attempting to scale the model with the goal of mimicking a "real life" setting is unrealistic, given the vast amount of parameters (both known and unknown) involved in the process. Using the analytical approach, we can simplify the process, allowing researchers to focus more on understanding the general processes and mechanisms at work rather than attempting to exactly recreate and replicate a natural system or some real world prototype. Although it is important that the models be generally representative of processes occurring in natural systems, it is not necessary for the models to mimic small scale processes (Paola et al., 2009). In addition, Paola et al. (2009) state that although most of the experiments referenced are far from being properly scaled, they still illustrate the essential geomorphological features and processes at work in natural systems. Much can be learned from unrealistically scaled physical models in geomorphology (Paola et al., 2009).

Scientific Question Addressed

This research seeks to understand and document fluvial processes under controlled variables using a laboratory-sized, mobile bed stream model. A laboratory setting allows for specific variables to be controlled and modified in an effort to better understand the responsive changes in fluvial systems to these modified parameters. Common to most fluvial models is the ability to modify sediment type, size and distribution, water velocity and discharge, and sediment flux; with our particular equipment, it is possible to simulate base level change (by lowering the water level at the local basin) and both longitudinal and latitudinal tilting in addition to modifying the previously mentioned parameters. In two of the experiments, we attempt to determine the extent upstream to which stream modification occurs, and if changes can be detected after base level modifications or latitudinal tilting.

The objectives of this work include not only attempting to quantify the experimental stream's response to induced changes, but also to evaluate methods of documenting morphological changes of the developed channel. Close Range Photogrammetry (CRP) will be examined as an alternative to more traditional physical measuring techniques used for documenting morphological change in these experiments.

CHAPTER 2: METHODOLOGY/METHODS

The EM4 Stream Model

The EM4 stream model is a mobile bed, laboratory scale physical model that was designed and manufactured by Little River Research and Design in Carbondale, Illinois. The experimental work in this research uses the EM4 stream model to simulate processes and landforms generated in fluvial systems. This mobile bed model is one of three existing models of its kind. Current research flumes range in size from the small, bench-top flumes to the 110m x 3.7m flume located in the O.H. Hinsdale Wave Research Laboratory. Appendix A contains figures detailing the various parts of the EM4. The stream table at St. Louis University (S.L.U.) is of intermediate size (1.5m x 4m) (Figure A1). The table is made of aluminum and has a 15 cm tall wall bordering the edges to retain the sediment. The table is designed to recirculate its' water supply. Water is introduced on the upper end of the table (Figure A2), and drains out of the lower end of the table via a cylindrical drain with adjustable height (Figures A3 and A4). Two water reservoirs are located beneath the table on the upper and lower ends of the table (Figure A5) and are connected to each other via a 3" plastic hose. A pump draws water from the upper reservoir and introduces flow to the upper end of the table. The water that drains out of the lower end of the table is emptied into the lower reservoir and is subsequently recirculated. Modifying the height of the drain cylinder allows us to simulate base level (local or ultimate) rise and fall.

In addition to local base level modifications, this equipment also allows users to modify the surface gradient vertically and horizontally through a series of gear systems which tilt the table surface (Figures A6 and A7).

The mobile bed is simulated by using a cohesionless sediment that is made from ground melamine plastic that has a specific gravity of 1.5. Three different, color coded, sediment sizes are represented on the stream table (Figure A8) with average diameters of 0.7 (brown and black grains), 1.0 (white grains), and 1.4 mm (yellow grains). This sediment was included in the purchase of the EM4 system.

The EM4 also has two sprinkler systems attached near the upper end of the table (Figure A9). These allow for adjustment of water table elevation in the upper reaches of the table.

All of the main discharge and sprinkler discharge controls and pumps are located on a mobile cart (Figure A10). Additional accessories on this mobile cart include a dye injection system which allows the water on the table to be falsely colored in order to better illustrate the active channels.

Measuring Techniques

There are several methods for documenting and measuring morphological change in these fluvial experiments. These can be broadly categorized as either remote sensing, in which data are gathered without physical contact or disturbance, or in-situ measurements, where measurements are made by physical contact with the experimental setup.

Two of the most widely used methods in remote sensing include photogrammetry and LiDAR. Close Range Photogrammetry (CRP) and ground based LiDAR (terrestrial laser scanning or TLS) are two remote sensing techniques that have been tested on the EM4 at Saint Louis University. These two remote sensing techniques have three significant advantages over physical measurements: they are non-invasive, they allow relatively rapid and precise measuring, and they easily allow complete records of experiments to be archived for later use. Repeat surveys using these techniques allow researchers to quantify changes over time. Remote sensing data is commonly displayed as a three-dimensional data set which allows any number of quantifiable measurements to be made. With a defined spatial resolution, data are collected as points in three-dimensional space. Each point has a relative spatial location to all other points in the data set. Current applications of CRP and TLS are wide ranging and include mass wasting studies, civil and structural engineering applications, neo-tectonic and erosional studies, use in monitoring vegetation, and archaeological studies (Matthews, 2008). Recent applications also include the use of CRP for grain size analysis on laboratory flume experiments (Gardner and Ashmore, 2011).

Close range photogrammetry is a photographic remote sensing technique that uses two or more photographs of the same object to create a three-dimensional point cloud. Attempts were also made at using this technique to document the changes that occurred during experimental work.

Terrestrial LiDAR (which uses time of flight data to determine the location of points in space) was also tested several times to document fluvial experiments on the stream table, but was not a good technique for the scope of our work. Although very high precision can be achieved using this technique, approximately one hour was needed to collect one set of the necessary LiDAR data. This temporal scale was too large to capture the changes occurring in our dynamically changing fluvial experiments.

Another simpler, but perhaps just as effective, technique for documenting change in the stream table experiments is in-situ, physical, surface elevation measurements. In our case, these measurements are taken at specific points in both latitudinal and longitudinal profiles in and across the stream channel. Depending on the lateral spacing between the points measured, fairly detailed stream profiles can be produced which show the topography of the stream bed and banks. These measurements can be made easily using a ruler and a level. The low cost and limited number of materials required for these types of measurements makes it a cost effective method for documenting topographic changes in experimental stream channels.

For our experimental purposes, we used a combination of standard 12" wooden rulers with centimeter markers and a laser level to obtain relative elevation measurements, and retractable tape measures to conduct horizontal distance measurements.

Determining Error in CRP Measurements

Difficulties arise in attempting to determine the precision of close range photogrammetry in the stream table experiments. In order to validate the measurements obtained through CRP, other independent measuring methods must be used to compare the results from the two techniques. Initially, we attempted to measure specific features created in a channel on the stream table using both CRP and in-situ measuring devices. It was soon realized that in using the equipment available (calipers, rulers, and other in-situ measuring devices) to physically measure a feature in the channel, there is an inevitable disturbance of the object measured. The cohesionless nature of the sediment used on the table makes it very difficult to physically measure any feature without some degree of disturbance. Therefore, another method needed to be developed to validate the CRP measurements.

A simple experiment was designed to test the vertical precision of our close range photogrammetry setup using objects that could be precisely measured without disturbing the dimensions of the measured object. To set up the experiment, the camera was mounted onto the rack above the stream table (Figure 1). The sediment was removed from an area of the table and a series of numbered wooden blocks were arranged on the table surface. Zinc plated, flat washers were placed on the wooden blocks. The photogrammetry targets were positioned around this array and two stereo photos were taken for photogrammetric processing.

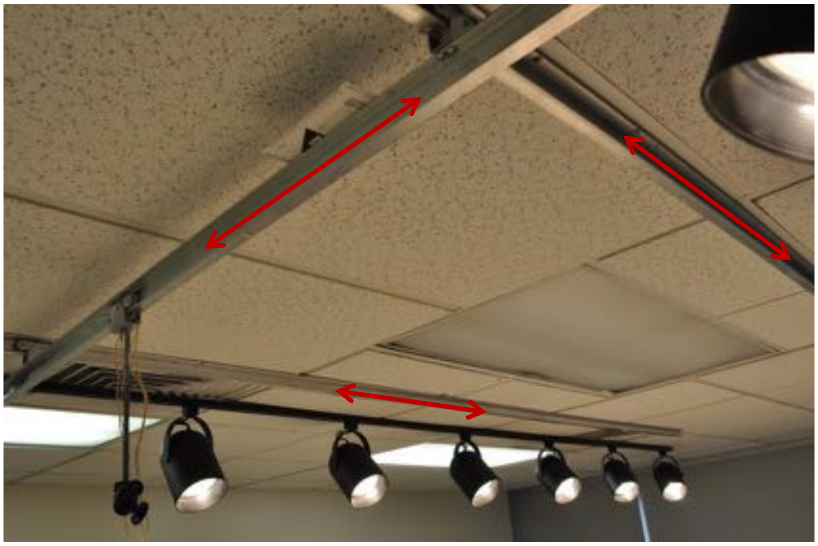

Figure 1: CRP camera mounting system - Image showing the ceiling mounted rack from which photographs for photogrammetry processing were taken.

A dense surface model (DSM) was created at a 0.5 mm sampling interval. Initial results of this experiment failed to accurately place 3D points. One cause of these issues was the reflective and non-textured surfaces of the zinc plated washers, the washers were covered with a thin layer of blue painter's tape, on which random patterns were drawn with a ballpoint pen. The experiment was repeated and much better results were achieved and the second DSM was more representative of the scene captured in the photographs.

Within the DSM, several washers were chosen at random. Two points were selected; one on the washer's surface, close to the edge of the washer, and one on the wooden block upon which that specific washer was placed. The vertical distance between these two points was assumed to represent the thickness of that washer, at that specific point. This thickness was compared to the thickness of that washer as measured by digital calipers. Comparison of the independent measurements showed that the two results were very similar. For example, the thickness of one of the washers measured by CRP showed a thickness of 1.263 mm. Measuring the same washer using digital calipers, yielded a thickness of 1.25 mm.

As demonstrated by the simple experiment above, photogrammetry can be used to generate very precise data and shows promise for the detailed documentation of morphological change on EM4 steam experiments.

Determining/Estimating Error in In-Situ Measurements

In-situ measurements during experiments were made by several undergraduate students and were simultaneously recorded by myself as they were taken. Some degree of variability is expected within each student's measurements as well as between different students. Two obvious sources of variability are the location at which each student reads the measurement from (the top, bottom, or middle of the laser mark) and whether each student holds the ruler perfectly level (perpendicular to the horizontal plane established by the rotating laser level) when measurements are read. In an effort to determine the measuring error for our in-situ measurements, which used a combination of rulers and laser and bubble levels, a simple experiment was designed.

Materials used for this experiment were a felt tipped pen, unmarked bamboo skewers, a rotating laser level, and a standard surveyor's rod level. To set up the experiment, the rotating laser level was placed on a flat surface and leveled. For each measurement, a bamboo skewer was placed along the rod level (to ensure the vertical orientation of the skewer). The skewer and attached level was then placed vertically on the surface just adjacent to the laser level. Several undergraduate students were recruited to use the felt pen to mark the skewer where they perceived the laser impact. Each student repeated the process fifteen times.

Digital calipers (model #3145 manufactured and calibrated by Control Company) were then used to measure the distance between one end of the skewer and the middle of the mark created by the felt tipped pen. The caliper measured results are reported in the table below.

Table 1: In-Situ Measuring Error

	Student 1	Student 2	Student 3	Student 4
Average (cm)	11.780	11.769	11.785	11.757
Standard Deviation (cm)	0.053	0.059	0.075	0.059

As Table 1 demonstrates, the standard deviations calculated from these measurements were very small. Since the smallest reported difference in measurements during stream table experiments was typically 0.1 cm, the measuring error calculated from these standard deviations is considered to be acceptable and shouldn't significantly affect measured results from the experiments.

General Setup of Experiments

Several different types of experiments were conducted on the stream table. In all experiments, pump discharge was kept constant (6 liters per minute). Variables that were modified were: longitudinal tilt of the table surface, latitudinal tilt of the table surface, base level elevation, and various techniques in an attempt to modify the inter-granular sediment properties (packing and moisture content). All of the experiments conducted went through a similar process to setup the experiment.

Sediment Preparation

The sediment was first wetted with a hose and well mixed using a large plastic shovel to ensure an even distribution of sediment sizes throughout the table. The sediment was then pushed back to 116 cm from the back, inside edge of the table. This step was done to enable uninhibited longitudinal growth of the fan delta and also in an effort to minimize the amount of sediment that could be transported through the table drain. Previous problems were encountered when large sediment loads were allowed to drain into the lower reservoir. We found that pump performance and water discharge onto the table were affected due to filter clogging in the lower reservoir. A 2” by 4” wooden plank was placed down the center of the table to establish the location of the proto-channel, and to keep this channel clear of sediment during the following preparation techniques. To make a consistently thick sediment bed, the sediment was leveled across the area it covered using a 2”x4” wooden board that was cut to the width of the table. Sediment was cleared out at the top of the table near the water input in an effort to avoid later problems such as the development of a disappearing stream (the occurrence of disappearing streams on the EM4 will be discussed briefly in Chapter 5).

After this moist, evenly thick, bed of sediment was prepared on the stream table’s surface, a series of 1” thick wooden boards were placed on top of the sediment bed. The sediment was then packed by stomping on these boards. After the sediment was packed, the “proto-channel plank” was removed. Any sediment that was present in this proto-channel was removed, and the proto-channel was widened to 4cm to initiate the experiment (Figure 2). Throughout the course of the experiments, no sediment was manually added to the channel. All sediment introduced into the channel was from bank erosion.

Base Level (Stand Pipe height)

In most experiments, the initial stand pipe height was set so that when the lower basin of the stream table was filled, the water level would just reach the lower edge of the sediment bed (Figure 2). This height varied depending on the longitudinal gradient of the table surface. Base level elevation (stand pipe height) for each experiment will be discussed in later sections which detail the individual experimental parameters.

Figure 2: EM4 Setup - Image demonstrating the basin water level relative to the prepared sediment bed as well as showing the final setup of the table before experimentation begins.

The setup described in the above sections was common in all experiments. There was some variance as to locations where measurements were taken in some of the experiments. These will be discussed individually in their respective sections.

General Methodology of In-Situ Measurements

Several different types of in-situ measurements were made including; channel aggradation (or sediment bed thickness), width of channel, and sinuosity. For sediment aggradation measurements, a rotary laser level was placed on a table top surface adjacent to the stream table. This was used to establish a horizontal reference plane. Rulers with attached rod levels we used to measure the vertical distance between the sediment surface in the channel, and the horizontal plane established by the laser level.

Channel width measurements were made with a retractable tape measure. Width was estimated by standing on the sides of the stream table in an elevated position, and holding the tape measure across the channel. For our purposes, width of the channel was considered to include any regions on the stream table where the stream had reworked its' sediment. These were not always regions where the channel was currently active, but instead essentially reflects the width of the stream's floodplain. These measurements were made perpendicular to the length of the table (or perpendicular to the original, straight proto-channel).

Sinuosity of the channel was measured using a flexible length of cord. Several different types of material were used for this cord. The cord was placed in the active channel so that it was allowed to move freely within the water. Sinuosity is determined to be the ratio of the length of this cord to the straight line distance down the table length (i.e. stream length : valley length). The materials used to measure sinuosity and problems encountered with these measurements are later discussed in Chapter 6.

General Methodology of CRP Measurements

For Close Range Photogrammetry, a camera was attached to a ceiling mounted rack above the EM4. The rack is constructed of a standard rolling track system, commonly used for sliding doors (Figure 1).

Two tracks are mounted onto the ceiling above opposite sides of the table, running parallel to the long axis of the table. A crosspiece rail connects the two and is able to slide up and down the length of the table. The camera is mounted to a roller attachment on the crosspiece rail, allowing full range of movement, both latitudinal and longitudinal, over the stream table. The camera utilized in these experiments was a 12.3 megapixel Nikon D90 SLR digital camera with a 20mm fixed focal length lens.

Photogrammetric techniques require a minimum of two stereo photos (of the same scene) to obtain the three-dimensional position of objects in the photographs. PhotoModeller Scanner™ was the software used to process the photo pairs in order to obtain a DSM (dense surface model). The program uses triangulation techniques to determine the relative location of features contained within the photos; each solved location is assigned a point and, depending on the user defined sample spacing (resolution), the program generates an array of points known as a point cloud.

In order to properly solve for the relative location of points in the photographs, PhotoModeller Scanner™ requires the use of coded targets (Figure 3). These strips of targets are placed in the scene of interest before photographs are taken. By determining the offset of these target points between the photo pairs, the program solves for the location of all other features in the photos.

Figure 3: CRP coded targets – Image showing the unique coded targets used when taking photographs for CRP.

Although photogrammetric techniques were tested as a method for recording morphological change during experiments, it was not the final method selected for data collection. This technique and its' limitations will be discussed in further detail in Chapter 6.

CHAPTER 3: EXPERIMENTS CONDUCTED

"Static" Channel

Background and Motivation

Two sets of experiments were run on the table in an effort to determine the natural variability of the stream model. In both sets of experiments, pump discharge and sediment preparations methods were identical. For the first set of experiments, table gradient was set to 2.27°, and 3.98° for the second set. The standpipe (base level height) was adjusted so that the basin's water level just reached the edge of the sediment bed. See Figure 1.

Several parameters were measured in these experiments: width and depth of the channel and sinuosity. The motivation for conducting these experiments was to observe, measure, and determine the variability in channel morphology. A concerted effort was made to keep all parameters and settings identical in the experiments. The idea behind changing the table gradient was to determine if one gradient produced a larger or smaller standard deviation in the measured variables (if one gradient was better for producing repeatable results).

Methodology of Measurements

For these experiments, measurements were taken every 15 minutes for 90 minutes. Longitudinal gradient was set to 2.27° for the first set of experiments and 3.98° for the second set. Two strings were strung across the width of the stream table and were used as beginning and ending markers for where measurements were taken. The strings were placed 154cm apart. Parameters measured in this set of experiments were sediment aggradation, width of the floodplain and sinuosity of the channel. A string that was marked at 14cm intervals was used to measure the stream's sinuosity (refer back to "In-Situ Measuring Techniques" for details). The exact location of these measurements, with respect to their location on the table, varied at each time interval due to the slight variations in channel position and sinuosity. Depth and width measurements were taken at these markers in the string. The location of these measurements with respect to "valley length" was also noted. Two aggradation measurements were taken at each interval down the length of the channel and were averaged to obtain an approximate average aggradation measurement of the channel at each specified location. All aggradation measurements were corrected for the longitudinal tilt of the table so that the numbers reflect only the absolute thickness of sediment deposited at the specified location.

Upon completion of these sets of experiments, sinuosity was not considered in analyzing the data due to issues in the measuring techniques. These are discussed in the Chapter 6.

Base Level Change

Background and Motivation

Schumm (1993; 280) defines base level as, "the level base with respect to which normal sub-aerial erosion proceeds." In the real world, ultimate base level is normally thought to be sea-level, although as Lane (1955; 4) notes: "There are often certain local levels which, geologically speaking, temporarily are elevations toward which streams tend to cut their beds." Base level change occurs periodically and is recorded in the geologic record; often induced by tectonism or glaciation cycles.

Numerous studies on the effects of base level change on fluvial system and depositional dynamics have been conducted in the past. Data for these studies has been extracted from both experimental physical models (Wood, Ethridge, and Schumm, 1993; Koss et al., 1994; Schumm, 1993) and specific field sites (Lane, 1955; Sloss, 1991). There is some argument among researchers as to the magnitude of the effects that a base level change can have on fluvial systems and deltaic deposits, however there is a consensus that these systems do respond to such a change. Using real world examples such as the Salton Sea in California, Lane (1955) asserts that the effect of a base level change on a stream's profile, lowers or raises the elevation of the stream profile, but the grade of the stream's bed eventually returns to its' original value (Figure 4).

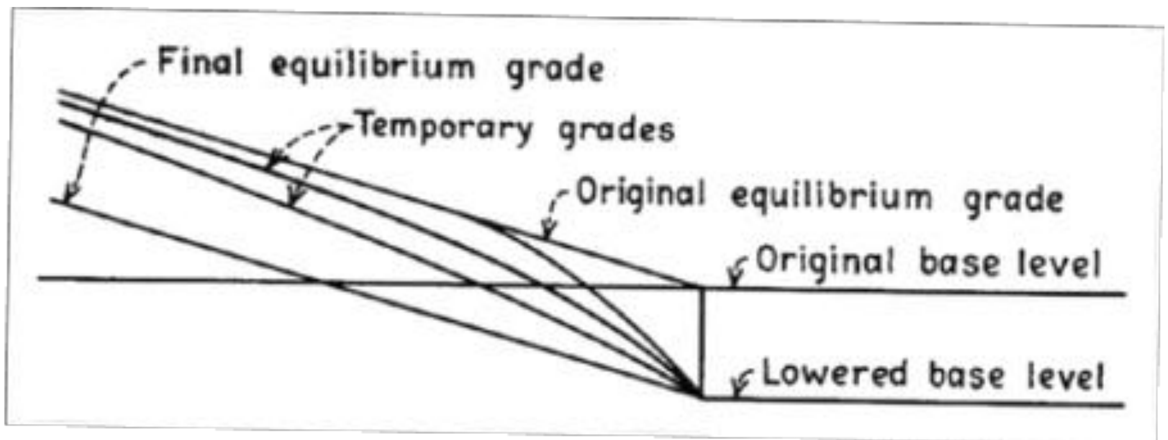

Figure 4: Lane's channel response to base level change. This figure illustrates Lane's hypothesis on the response of a channel to a baselevel change. Notice the similarities in the "temporary grades" profiles with the profiles shown in Figure 5. Figure from Lane (1955; 15).

In contrast, studies conducted by Leopold and Bull (1979) indicate that a base level change will only affect the local elevation of a stream's profile. Experimental work conducted by Germanowski and presented in Schumm (1993), supports Leopold and Bull's claim (Figure 5).

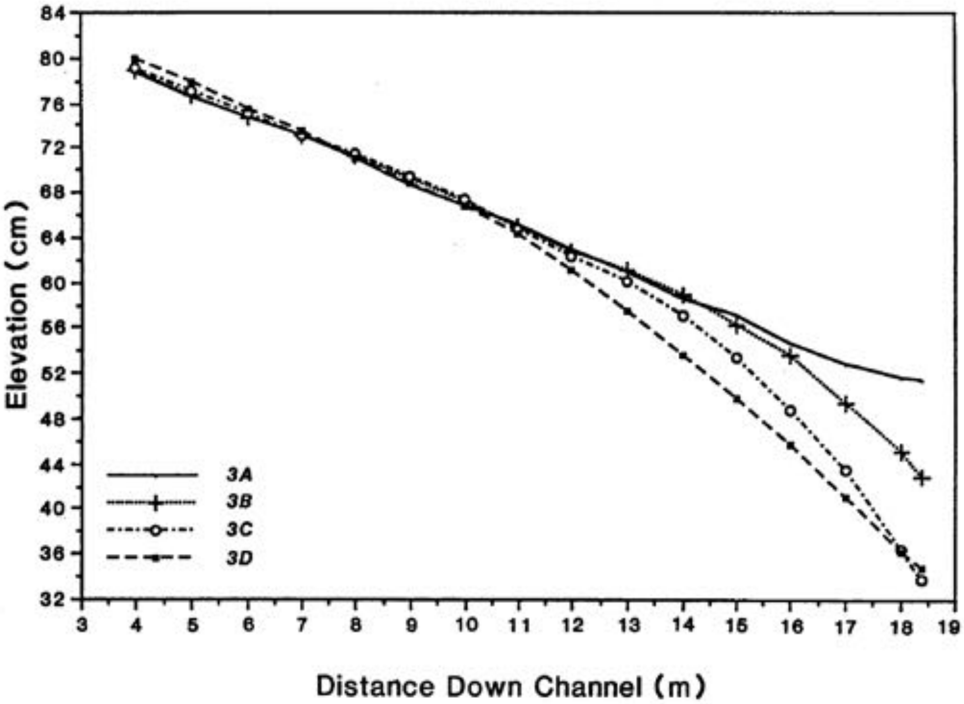

Figure 5: Germanowski's channel response to base level change. This figure demonstrates the response of an experimental channel to a base level change in work done by Germanowski. In this experiment, base level was lowered. The order of data, in terms of increasing time after the base level lowering, is 3A, 3B, 3C, and 3D. Figure from Schumm, 1993; 287.

Schumm (1993) summarizes several studies (including Lane, 1955 and Leopold and Bull, 1979) investigating the effect of base level change, and identifies specific variables that can affect a stream's response to such a change. These variables include; rate, direction, magnitude, and duration of base level change, lithology and other geologic controls, and various geomorphic controls (Schumm, 1993). Operating under the assumption that on the stream table setup, all of the possible controlling variables mentioned by Schumm (1993) remain constant between experiments, we attempt to evaluate the stream's response to an instantaneous base level drop. Local base level on the stream table is considered to be equal to the water level in the table's basin, which is defined by the height of the adjustable standpipe.

The first objective of our base level change experiment was to evaluate how the experimental stream in the model responds to a sudden change in base level. Additionally, this experiment was aimed at evaluating the previous hypotheses of a channel's response to base level change developed by the aforementioned researchers.

Methodology of Measurements

For these experiments, the stream was allowed to develop for 50 minutes before measurements were taken. Longitudinal gradient was set to 1.3° and initial standpipe height (base level) was set at 5cm elevated above the table surface. At 60 minutes after the start of the experiment, the standpipe was lowered to 1.5cm to simulate a rapid base level drop. Measurements were taken at 50, 55, 65, 70, 75, 80, 85, and 90 minutes after starting flow on the stream table (labeled in the figures as -10, -5, 5, 10, 15, 25, and 30). Two strings were strung across the width of the stream table and were used as beginning and ending markers for where measurements were taken (Figure 6).

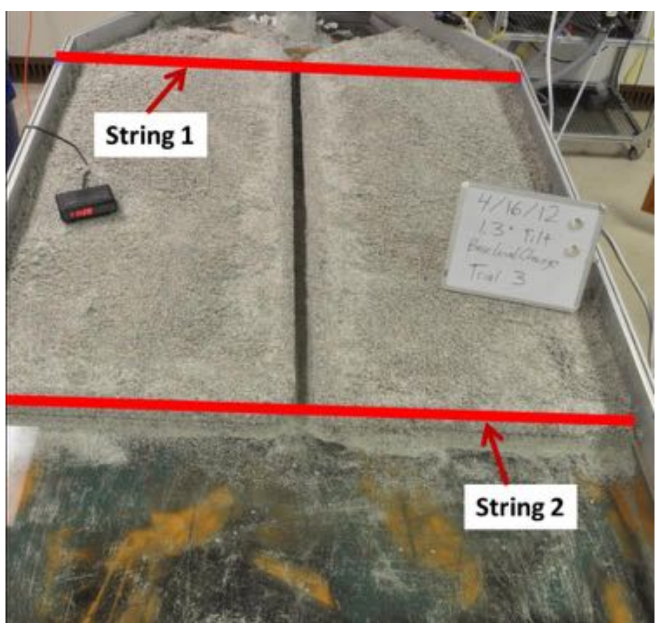

Figure 6: Measured interval on the EM4 – Picture showing the location of the two strings that were spanning the width of the EM4. During experiments, measurements were taken in the channel between these two locations.

The strings were placed 154cm apart and measurements were taken every 10cm (exception was the last interval from 140cm to 154cm) at the specified time intervals. Parameters measured in this set of experiments were sediment aggradation and width of the floodplain. Two aggradation measurements were taken at each 14cm interval down the length of the stream table and were averaged to obtain an approximate average aggradation measurement of the channel at each specified location. Each aggradation measurement was corrected for the longitudinal tilt of the table so that the numbers reflect only the absolute thickness of sediment deposited at the specified location.

Lateral Tilt Experiments

Background and Motivation

Experiments were run to observe channel response to changes in the lateral tilt of the stream table's surface. Our aim was to better understand the depositional dynamics and channel avulsion of the experimental stream using the provided sediment; can we observe a change in the relative position of the experimental channel and the deposition of sediment within the channel after inducing a lateral tilt? Lateral tilting of the table can be thought of as analogous to differential tectonic uplift. Our initial hypothesis was that the stream would abandon its bars on the uplifted side of the channel and incise into the banks on the lowered side of the channel.

Methodology of Measurements

For these experiments, the stream was allowed to develop for 40 minutes before measurements were taken. At 60 minutes after the start of the experiment, the table was tilted laterally 2.2°. Measurements were taken at 40, 50, 65, 75 and 85 minutes after starting flow on the stream table (labeled in the figures as -20, -10, 5, 15, and 25). Two strings were strung across the width of the stream table and were used as beginning and ending markers for where measurements were taken (Figure 6). The strings were placed 154cm apart and measurements were taken every 14cm at the specified time intervals. Parameters measured in this set of experiments were sediment aggradation and width and lateral position (relative to the stream table) of the active channel. Aggradation measurements were taken every 2cm across the width of the channel at each 14cm interval down the length of the stream table. Each measurement was corrected for both the longitudinal and latitudinal tilt of the table so that the numbers reflect only the absolute thickness of sediment deposited at the specified location.

CHAPTER 4: EXPERIMENTAL RESULTS AND INTERPRETATION

General Morphology of Experimental Channels Developed in the EM4

Before discussing the results of the experiment, it is appropriate to first note the general morphology of the types of experimental channels developed on the EM4. The channels developed on this stream table can be generally classified as braided streams. The high availability and cohesionless nature of this sediment causes the channel to be highly dynamic. Typically there is a dominant channel that occasionally braids into smaller channels which are separated by bars. The bars which separate the braided channels are highly mobile and cause the position of the channels to migrate often. These bars are constantly being formed and breached as the channel avulses. Although the channel can be generally classified as braided, it was usually clear that there was one dominant channel (Figure 7).

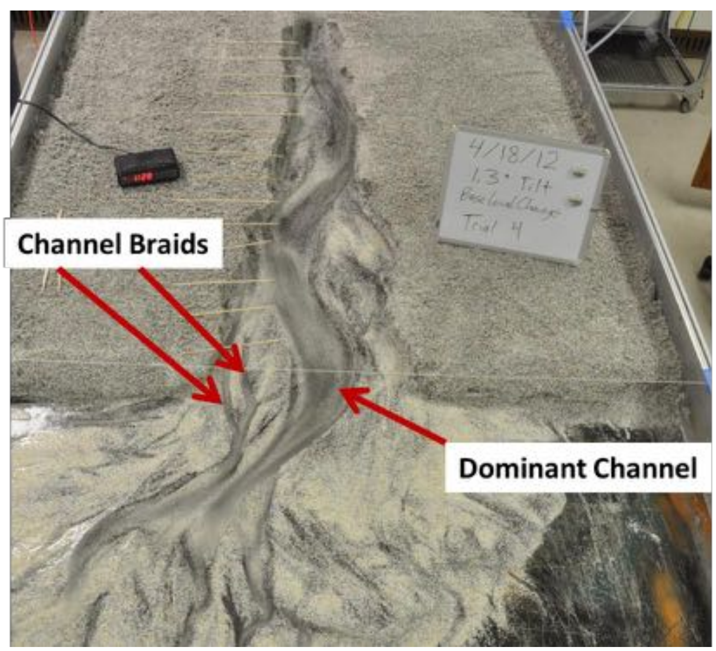

Figure 7: Braided Channels on the EM4 – This image illustrates a typical experimental stream developed on the EM4. Channel braiding is occurring although, usually one channel remains dominant.

The formation of deltaic deposits occurred on the table when the channel encountered the "base pool" near the lower end of the table. The location of this base pool was determined by the height of the stand pipe. Channel avulsion more frequently occurred on the delta deposits causing migration of delta lobes and modification of the delta's planform. This typically was the most dynamically changing location for the experimental channels (Figure 8).

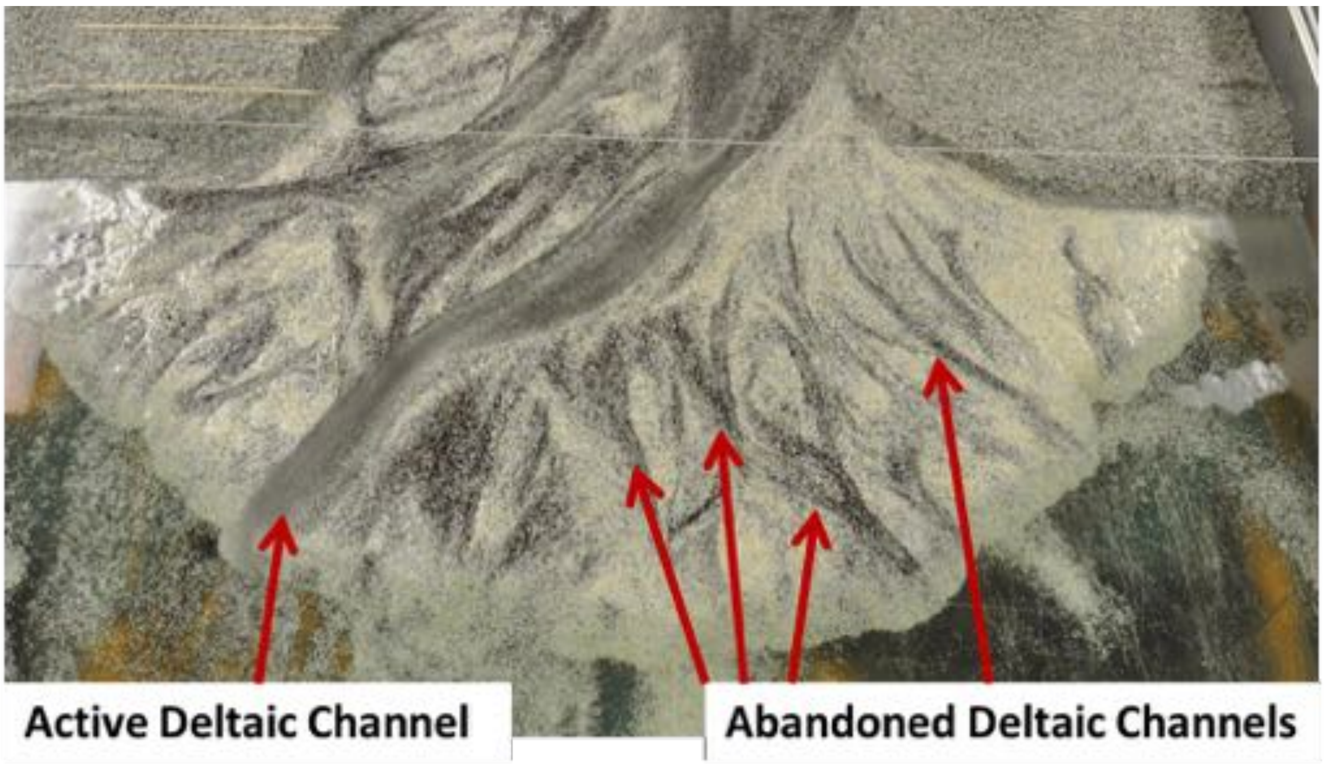

Figure 8: EM4's Delta – Image showing a delta developed on the EM4. The deltas are always the most dynamically evolving locations in the experiment. Notice the many recently abandoned deltaic channels in the figure.

Complete videotaping of selected experiments was conducted to collect more qualitative observations. This was done recognizing the fact that not all information regarding the evolution of the experimental channels could be collected using the qualitative measuring techniques that were used during the experiments. One video of both the "Base Level Change" experiments and the "Lateral Tilt" experiments are available at the request of the reader (see Appendix E).

Similarity exists among some observations in the experiments. At the beginning of the experiments, early bank erosion can be observed in the upper reaches of the channel. By the time five minutes have elapsed, delta deposition starts to occur. Although most of the channel is occupied by water in these early stages of channel evolution, small meandering of the stream is present. The meanders and bars are highly dynamic and constantly changing; avulsion frequently occurs as the bars are formed and breached. As the experiment progresses and the floodplain widens, avulsion occurs more frequently downstream while channel position in the upper reaches retains some stability. As the meanders change position, their previous locations can often be seen as meander scrolls, highlighted in the experimental stream by the presence of the darker (finer) sediment. Occasionally, the presence of a bar in the channel causes the water to split into two channels, causing the stream to change from meandering to a braided stream.

Bank failure seems to be the main mechanism for floodplain widening. The width of the floodplain remains fairly constant in the juvenile stages of stream development, but as time elapses, the floodplain becomes wider down channel.

At the stream's mouth, the delta grows by the continued deposition of sediments in lobe deposits. The position of these deposits changes frequently in the early stages of the experiments. Due to the dynamic nature of the experimental system and avulsion in the delta channels we can often observe multiple channels present in the delta, depositing multiple lobes simultaneously Avulsion in the lobate delta deposits continues to occur in the later stages of the experiment, although it is less frequent..

Abandoned terraces can be seen in the later stages of channel development. These terraces are left exposed as the channel either incises further into the sediment bed or avulses.

The terraces are eventually destroyed as the stream reworks the sediment during avulsion or lateral migration. Longer lived terraces tend to be present in the upper reaches of the stream.

Channel avulsion is one process that can be observed in the videos that quantitative measurements conducted during the experiment could not capture. Analysis of the videos shows that channel avulsion in the experimental channels can occur in four different ways; by bank collapse and massive sediment input, by bank erosion, by bar migration, and by stream capture. Avulsion by bank collapse can be observed in the first five minutes of the “Base Level 1” video as well as at 22:30 of the “Lateral Tilt 1” video. In these cases, bank collapse (due to the destabilization of the banks from undercutting) effectively chokes the channel with sediment and forces the channel to avulse or meander around the newly introduced sediment package. Avulsion by bank erosion can be observed at the 17:45 mark of the “Base Level 1” video. In this case, a meander near the end of the channel is causing the channel to deposit mainly on the left side of the delta. As the outside of the meander (cutbank) continues to erode the bank, it eventually breaks through the edge of the bank and exposes the channel to a lower elevation exit onto the delta, causing avulsion to occur.

Between the 24:00 and 25:00 mark of the “Lateral Tilt 1” video, avulsion by bar migration can be observed. In this event, downstream migration of a bar eventually blocks the active channel path and induced avulsion. In the “Lateral Tilt 2” video, between the 8:00 and 10:00 mark, we can see a good example of stream capture causing avulsion. Headward erosion of a secondary channel eventually meets the main channel and captures its' flow. After this capture, the main channel abandons its’ former downstream reach and flow is diverted to the secondary channel.

“Static” Channel Experiments

Experiments run with the 3.98° longitudinal gradient were not successful in generating a self-sustaining channel. Several attempts were made with this steeper tilt, but in all of the attempts, the channel was not able to carry the sediment load, and subsequently transformed into a disappearing stream. The suspected cause of these failures is discussed in more detail later in Chapter 5. The remainder of this section will be dedicated to discussing results from the experiments run with a 2.27° gradient.

Several plots were made from the data collected in these experiments in an effort to characterize the variability and behavior of the experimental channel. Results from these plots are shown in Appendix B, C, and D.

Appendix B contains figures plotting aggradation against width of the floodplain. Each figure is for one specific time and the series in each figure represent different experiments. Seven separate experiments are compared at elapsed times of 15 (B1), 30 (B2), 45 (B3), 60 (B4), 75 (B5), and 90 (B6) minutes. All of the plots illustrate a positive correlation between aggradation and floodplain width. This result is expected; as the channel widens its floodplain, it erodes bank material which is subsequently deposited within the channel. Overall, the slopes of the best fit lines in all of the figures are similar. Variation in the slopes of the best fit lines may be attributed to a number of variables. Any variation in slope is essentially telling us that the sediment being eroded from the banks at one location, is not necessarily being immediately deposited in the adjacent channel. The bank erosion on one location in the channel may affect the aggradation further downstream in the channel. It is difficult to tease out the finer details of sediment transport using this data, however we can see a highly correlative relationship between these two variables. Additionally, we see that the correlation increases significantly after the 15 minute interval. After this time, the R^2 values of the best fit lines seem to increase dramatically.

In general, the correlation between aggradation and valley width seem to increase over time. Examining Figure B4 we notice that the data from experiment 8 is more scattered and the R^2 value of the best fit line is relatively low. Upon further investigation of the data, it was found that at this 60 minute time interval for experiment 8, the experiment was experiencing seepage and had developed a disappearing stream (see Chapter 5 for details). The two data points which seem to disrupt the correlation, have anomalously high aggradation values and occurred just upstream of where the channel disappeared and was converted to groundwater flow. We interpret the values and relative position of these data points to indicate that at these locations, the stream lost its ability to transport the sediment and subsequently dropped its sediment load. This resulted in higher measured aggradation at these points, without widening of the channel.

Overall, the R^2 values from the best fit lines in the figures contained in Appendix B, illustrate that correlation between valley width and aggradation increases as more time passes in the experiment. The R^2 values have a significant increase between 15 and 30 minutes after the start of the experiment, and then appear to stabilize after 30 minutes. This suggests that the parameters of valley width and aggradation seem to reach a state of equilibrium (with regard to an aggradation and width relationship) after 30 minutes of elapsed time in the experiment.

Aggradation against distance down valley (from the initial measuring point) is plotted in the following figure (Figure 9). The different series represent data averaged from all experiments at the specified elapsed times of 15, 30, 45, 60, 75, and 90 minutes after the start of the experiment. Best fit lines were added to the data series. The height of the curve represents the thickness of sediment deposition down the valley (left to right in the figure). With the exception of T15 (which has a polynomial best fit line), the data has a linear trend. This not only suggests that a positive correlation exists between aggradation and the distance down the valley, but also that a marked change occurs between elapsed times of 15 and 30 minutes. The data points in the T15 curve display relatively higher aggradation in the upstream reach of the experimental channel, and lower aggradation in the downstream reach

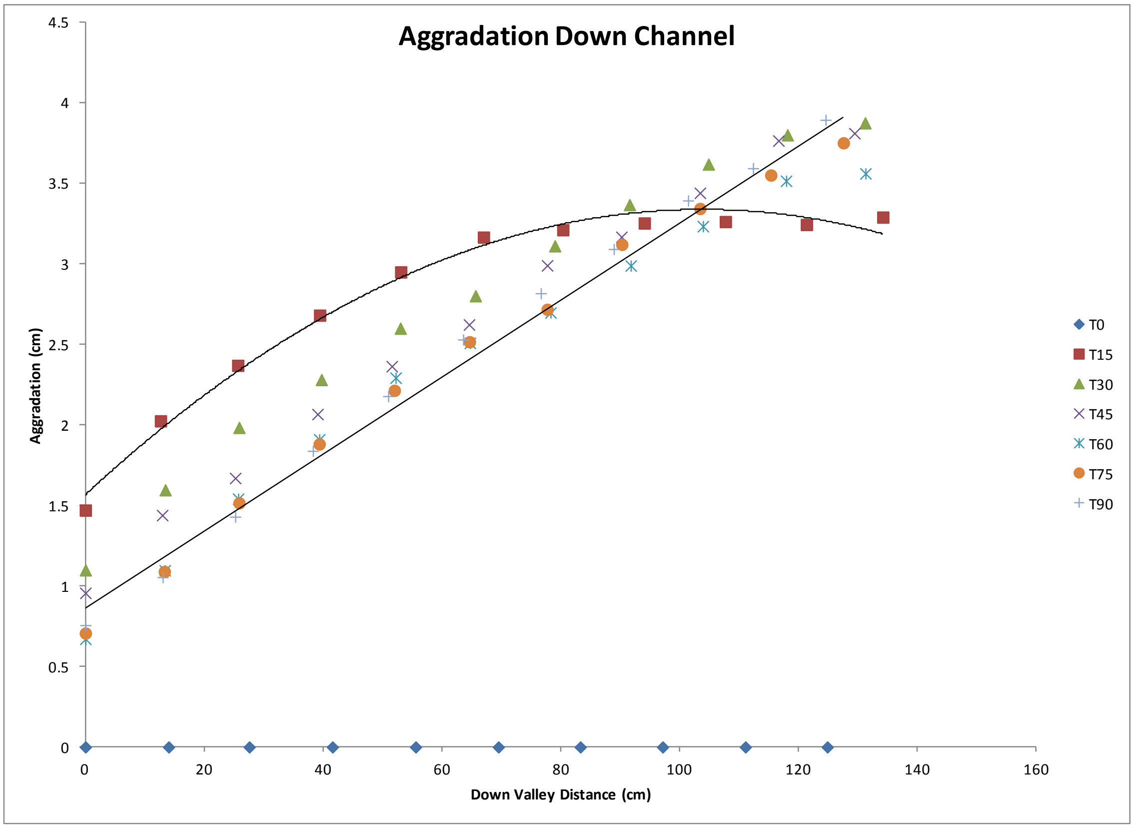

Figure 9: Aggradation vs. Down Valley Distance

This data (more specifically the anomaly at T15) may indicate that the stream has not yet been able to transport most of its sediment load down the channel after 15 minutes have elapsed since the initiation of the experiment. Sediment is being constantly eroded from the banks and being deposited in the upstream reaches of the channel. This erosion on the banks causes periodic pulses of sediment to be introduced into the channel through bank failure. The increased sediment load upstream, overcomes the competence of the stream and its ability to fully transport the sediment to the end of the channel. Slowly, the stream begins to rework the sediment until it is able to transport the sediment load downstream. Observations conducted during the course of the experiments confirm this interpretation. As in the plots in Appendix B (B1-B6), the data suggest that the stream reaches some equilibrium state with regard to aggradation down the valley by 30 minutes after beginning the experiment.

Figures in Appendix C plot aggradation down the valley at different elapsed times. Each figure is for one specific time and the series in each figure represent different experiments. Seven separate experiments are compared at elapsed times of 15 (C1), 30 (C2), 45 (C3), 60 (C4), 75 (C5), and 90 (C6) minutes. Best fit lines were added to the data series and again (with the exception of T15), we notice a positive linear relationship between valley length and aggradation. The same interpretation of the polynomial trend in T15 and the linear trends in the remainder of time intervals explained in Figure 9 applies here as well.

Examining the differences between each series in the figures, we notice that both the slopes and Y-intercepts of the best fit lines vary from experiment to experiment. Higher Y-intercepts tell us that more sediment is present in the channel upstream. Experiments with higher Y-intercepts also exhibit higher aggradation throughout the entire channel. This variation is likely due to unintentional variation in sediment preparation techniques; namely differences in sediment wetting and packing. Experiences running experiments on the table has shown that wetting and packing techniques have a high control over the apparent cohesion of our sediment. This, in turn, also effects how much sediment is introduced into the channel (influencing aggradation) through bank failure. The differences in the slopes of the best fit lines may indicate that packing was unintentionally non-uniform throughout the table, although further experimentation may be needed to confirm this claim. The role of wetting and packing techniques in sediment preparation will be discussed in further detail in Chapter 5.

The following figure shows the relationship between average width of the floodplain and channel growth against elapsed time in the experiment (Figure 10). This plot was made in an effort to illustrate the nature of floodplain widening through time as demonstrated by the images shown in Figure 11.

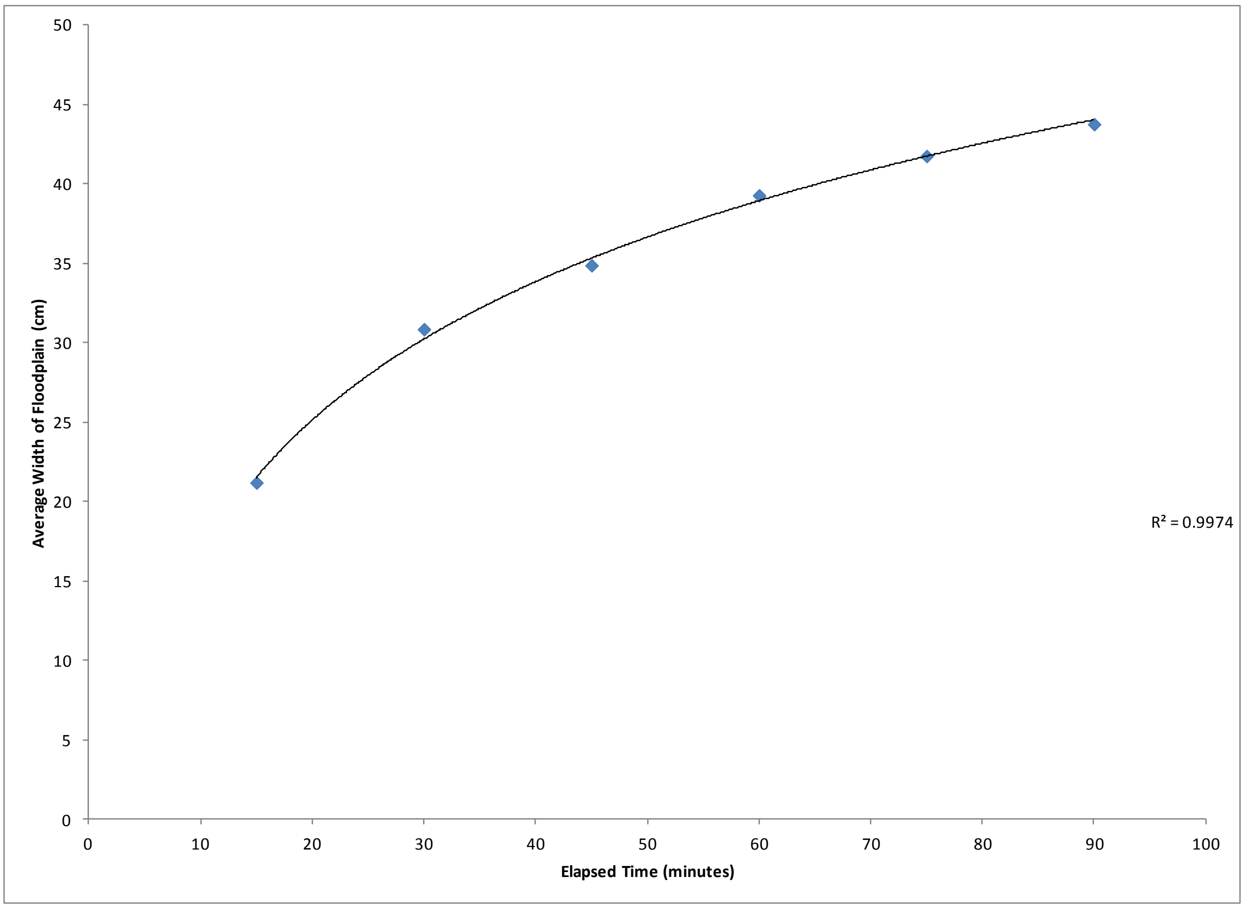

Figure 10: Average width of the floodplain through time

Figure 11: Evolution of the floodplain – These two images show the evolution of a floodplain developed on the EM4. The photo on the left was taken just before the start of the experiment and the photo on the photo on the right, after 90 minutes of elapsed time in the experiment.

The data points in Figure 10 represent the average width of the floodplain for all experiments (average taken from data throughout the channel). A polynomial best fit line was fit to the data and has an R^2 value of 0.9974. The exceptional fit of this line to the data, demonstrates that floodplain growth rate varies through time. In the early stages of the experimental channel, the floodplain widens rapidly. The rate of widening appears to decrease as time elapses, although a linear regression also yields a high R^2 value of 0.9743 (when excluding the T15 data point). Because both linear and polynomial lines fit the data well, it is unclear how to exactly characterize the evolution of the experimental channel's floodplain through time. If data were collected past the 90 minute mark of the experiment, the floodplain width would eventually reach a limit. At the most, this limit would represent the width of the EM4 model. Even so, one would expect the rate of widening to reach an apparent plateau, where the only very minor widening could be detected with increased elapsed time.

Figures shown in Appendix D plot floodplain width down the channel at the specified time intervals. Data points in each plot represent all data collected from all of the experiments at that specific elapsed time interval. Best fit polynomial lines were fit onto the datasets and seem to represent the general trends of the data well; the floodplain widens rapidly in the upper reaches of the experimental stream and seems the width seems to stabilize in the very lower reaches of the stream.

The following plot was made to investigate the trend in average aggraded sediment within the channel through time (Figure 12).

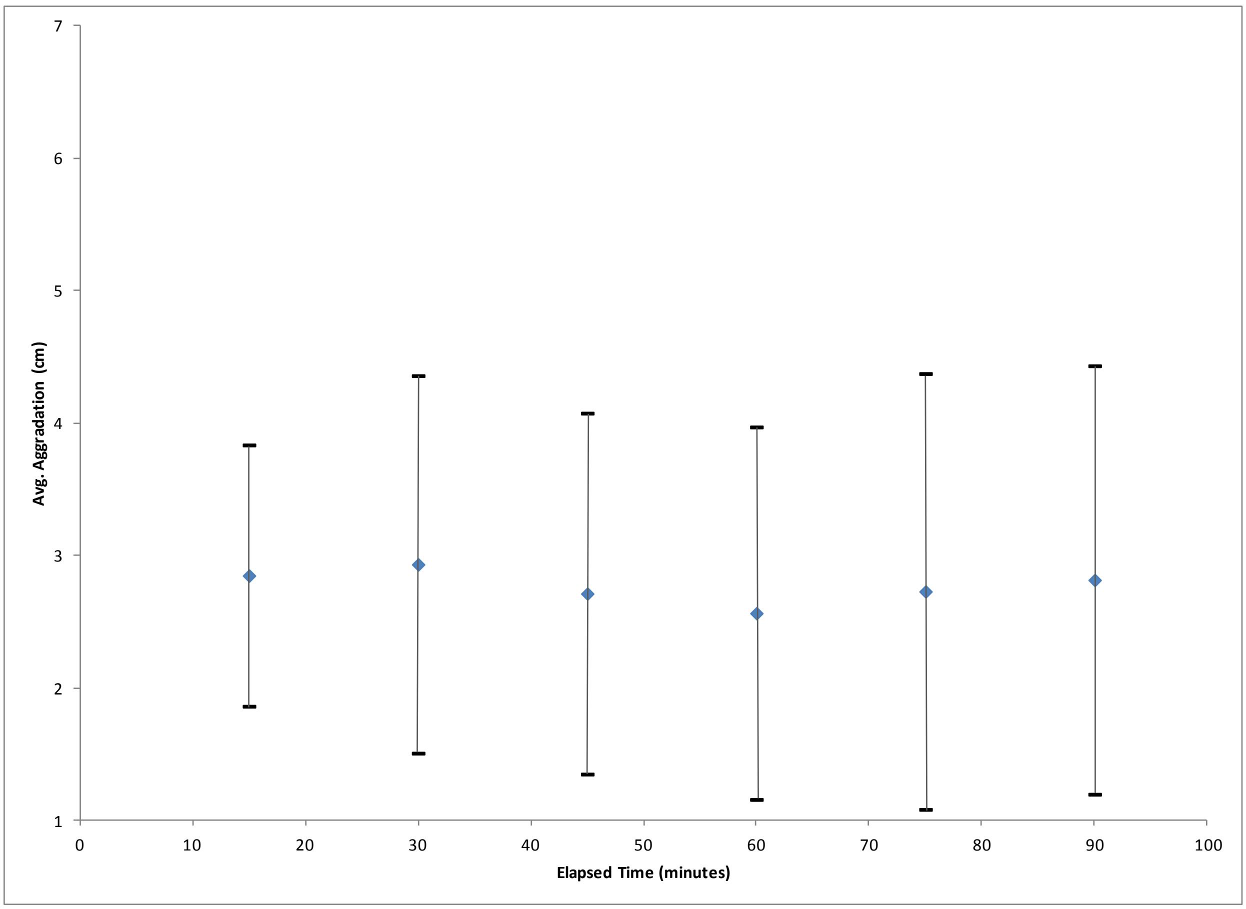

Figure 12: Average aggraded sediment within the active channel

The figure above demonstrates that the average amount of sediment present within the channel (volume) is approximately constant through time.

In order to better compare the plots (representing different time intervals), the solid, red line was inserted into the figures and represents a floodplain width of 45 cm. This 45 cm line was chosen because the width of the floodplain in Figure D6, which represents T90, seems to reach a plateau or a maximum floodplain width at 45 cm. The figures, which represent evolution of the experimental stream's floodplain through time, suggest that not only does the floodplain width appear to stabilize first downstream, but also that widening of the channel migrates upstream as time passes. Using the data given here, it is difficult to determine if this floodplain widening would continue to migrate upstream; resulting in an essentially evenly wide floodplain throughout the channel. One would expect the width of the floodplain to always be less near the water input, where the water always enters the table at a fixed point.

Summarizing the data collected in these experiments, we notice that there are certain trends that hold true throughout each experiment. The figures in Appendix B show that there is a relationship between aggradation in the channel and width of the floodplain for any given location. Since no sediment is being added to the channel manually, the main mechanism for the addition of sediment into the channel is bank erosion. The direct result of bank erosion is floodplain widening, so we should expect aggradation and floodplain width to be related.

Figures in Appendix C and D in addition to Figure 9 also indicate that both aggradation in the channel and width of the floodplain increase with distance down valley. Figure 10 illustrates that width of the floodplain increases with time, while Figure 12 suggests that the volume of aggraded sediment in the channel remains fairly constant throughout the experimental time frame. Using this knowledge, Figure 13 below uses the data from these "static" channel experiments to summarize, in a simplified diagram, the general geometry of channel deposits in the EM4 stream model.

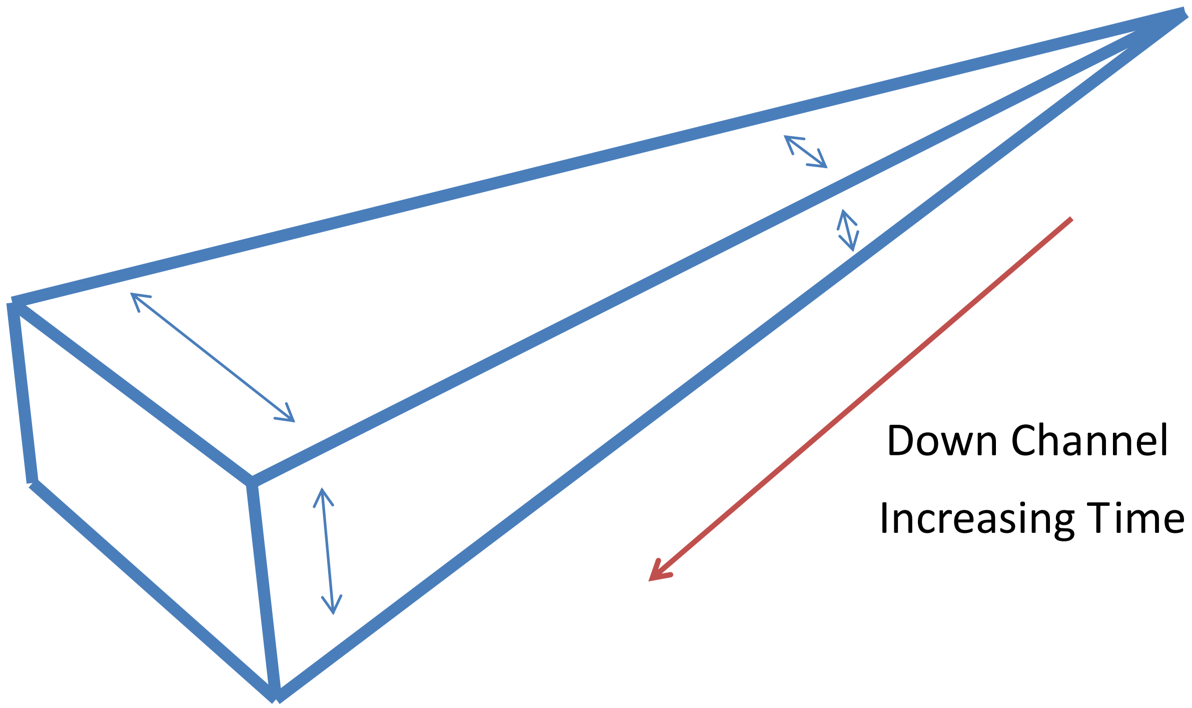

Figure 13: Sediment "Wedge" – This figure is a simplified image illustrating the geometry of the aggraded sediment within the experimental channels, based on the data discussed above.

The data collected from these experiments suggests that as time passes in the experiment, and as we move down the channel, both sediment aggradation and floodplain width increase. We have attempted to simplify this trend in the sediment "wedge" illustration above.

The most promising results from interpretation of the collected data, is that the EM4 model (given the specific preparation methods outlined above) indicates that although some variance in channel evolution is encountered, we are still able to reproduce similar trends throughout multiple experimental runs (e.g. correlations between width and aggradation through elapsed time and distance down valley).

Base Level Change Experiments

The base level change experiments were conducted in an effort to investigate the response of the experimental channel to a rapid change in base level. Since base level change is a common occurrence over geologic time, investigating the effects of a base level change on fluvial systems is of significant scientific importance. Using physical models it is possible to simulate base level change in a laboratory setting and both observe and measure the effects of such a change on the fluvial system. The compressed time scale of these physical models allows us to observe a change in the physical model that may take hundreds to thousands of years in natural systems.

Sediment aggradation (normalized for the longitudinal tilt of the stream table) is plotted against the length down valley in the figure below (Figure 14). Data colored in red and green represent data collected before and after the base level drop respectively. All plotted data points represent averaged values from 4 successfully implemented base level change experiments.

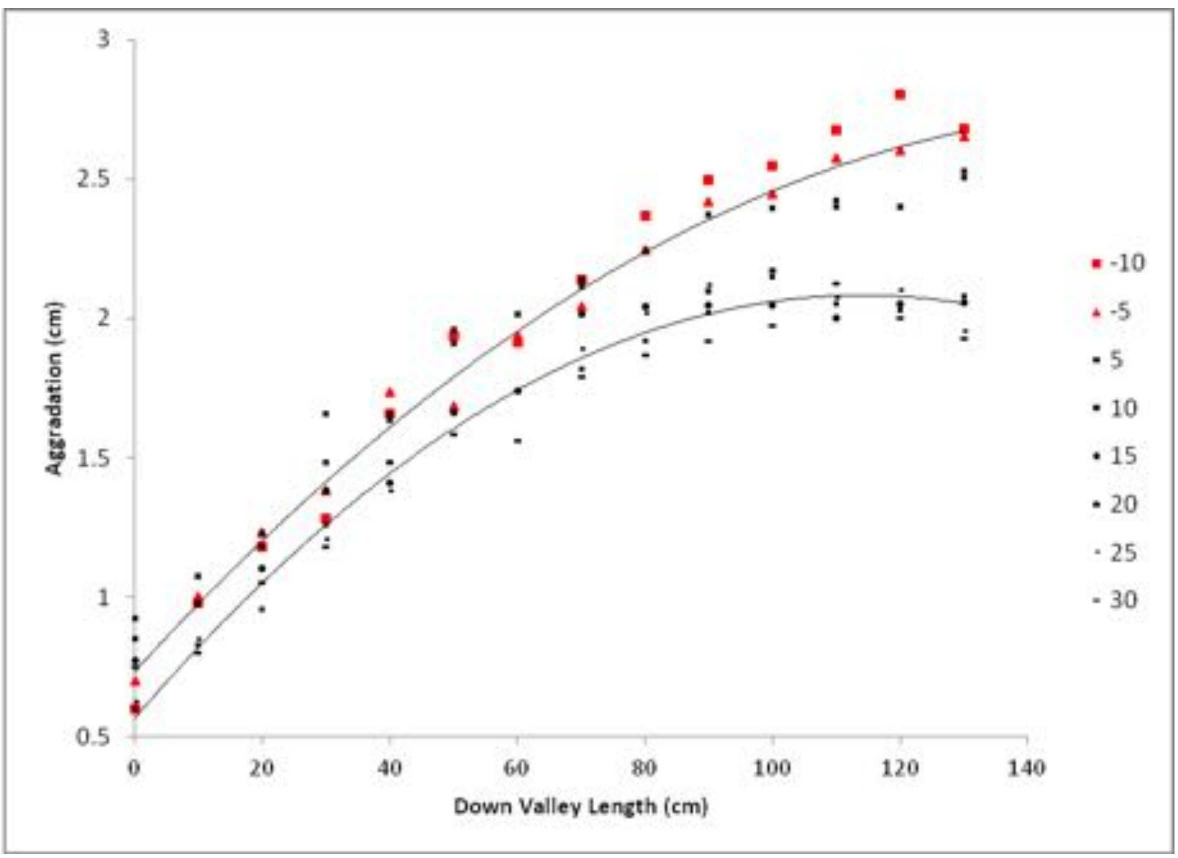

Figure 14: Channel response to base level change – the two trendlines that were fit to the data in the above figure, best fit the two data populations represented here.

Figure 14 confirms the positive correlation between distance down the valley and aggradation in the channel seen in the previous experiments. The data also illustrate that incision occurs in our channel following the base level drop. The maximum change in aggradation occurs between 10 and 15 minutes after the base level drop. Observations made during the experiment confirm that this time delay merely reflects the time for incision to migrate up channel from the distal end of the delta deposit to the 154cm mark of the channel (the furthest extent down channel in which measurements were made). Since measurements were not being taken further down channel (in the deltaic deposits), this "time lag" is expected. The figure also illustrates that the effect the base level drop on the experimental channel tapers out, and is no longer significant upstream of the 60cm interval.

This data seems to support the conclusions reached by Leopold and Bull (1979; 195) that state, "base level has an effect only locally and has an influence that extends only a short distance up the tributary." Given the data here, it is not fully possible to refute Lane's assertion that the profile of the stream will eventually return to its' original state (Lane, 1955). If the experiment were allowed to run longer, perhaps Lane's hypothesis would eventually be validated; although the data collected here seem to suggest a full stream profile adjustment to the base level change within the experimental time frame.

In addition to the data discussed above, the videos (Base Level 1-4) provide additional qualitative information. The "Base Level 3" video shows the immediate response of the experimental channel to a sudden base level drop at the 12:00 minute mark. We can immediately observe incision beginning at the distal end of the delta and migrating up the channel. Simultaneously occurring is slope failure along the distal edges of the delta, making the delta appear to prograde by "sliding". The delta subsequently begins to deposit new lobes further down the stream table. The video shows that incision into the left side of the delta has caused the abandonment of the right side of the delta, leaving it as an abandoned terrace. Not until ten minutes after the base level drop (Basel Level 3; 22:10) do we see the channel beginning to rework the deposits left on the right and central portions of the delta. Twelve minutes after the base level drop (Base Level 3; 24:00), incision has migrated roughly halfway up the channel, leaving abandoned terraces adjacent to the active channel.

Progradation of the delta continues to occur as the experiment progresses. At the 1:30 mark of the "Base Level 4" video, we can see seepage occurring. Headward erosion by groundwater seepage continues upstream until it finally captures the flow of the main channel (stream piracy), by 11:00 in the "Base Level 4"video.

Lateral Tilt Experiments

The lateral tilt experiments were conducted to investigate the response of the experimental channel to a differential lateral uplift. After allowing the channel to develop for 60 minutes, the stream table was tilted laterally 2.2°. The initial hypothesis was that the stream would incise into the lowered side of the channel.

Data collected from these experiments allow us to determine the average lateral slope (across the channel) of the channel (Figure 15). The various depth measurements taken across the channel, at the specified locations and time intervals, were each fit with a linear regression. These linear regressions were averaged throughout the channel for specific time intervals to obtain the plot below. The lines represent the average slope across the channel at specific time intervals. Data from all four "lateral tilt" experiments were used in generating this plot. This plot was made in an attempt to characterize the asymmetry of the active channel through time. Blue lines represent the average slope across the channel before the lateral tilt, and red lines represent the slopes after the tilt. Positive slopes indicate overall aggradation on the down-tilted side of the table throughout the experimental channel, and negative slopes indicate aggradation on the up-tilted side of the table.

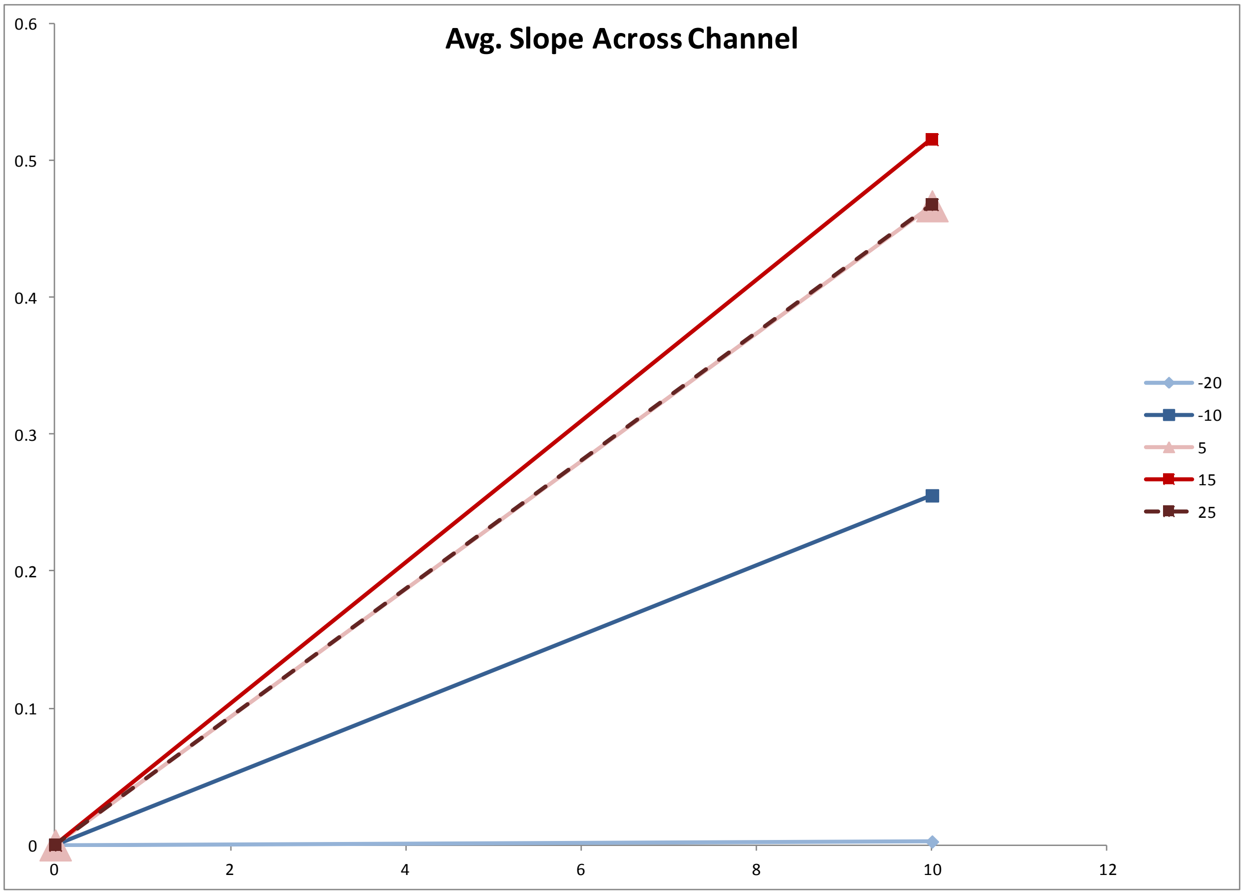

Figure 15: Asymmetry of channel bottom

The data shown in Figure 15 is contradictory to our initial hypothesis. Instead of incision occurring on the down-tilted side, we see evidence of aggradation. Observations conducted during the experiment confirm that significant sediment deposition occurred on the down-tilted side of the table. Sediment deposition occurred on this lowered side until the channel bottom was essentially flat. This deposition occurred quickly (within 5 minutes) after the lateral tilt, which is confirmed by the apparent stabilization of average channel shape 5 minutes after the lateral tilt (series 5, 15, and 25) shown in the figure.

It is not clear why channel asymmetry changes between T(-20) and T(-10), which is before lateral tilting of the table surface. During this time interval the channel already is preferably aggrading on one side of the channel. This trend reflects the dynamic nature of the experimental channel; meanders, bars, and bedforms are constantly changing position and geometry within the channel. Although we can observe this natural variability in channel asymmetry, Figure 15 also asserts that, qualitatively, after a lateral tilt, sediment deposition occurs on the side that was lowered.

Standard deviation of the channel position against down valley length is shown in Figure 16. The standard deviation of channel position reflects how much the active channel wanders about its floodplain. Data points in red reflect measurements taken in, or close to, the deltaic deposits. This figure illustrates that channel avulsion is more prevalent further downstream. This data is consistent with Figure 10. As the floodplain widens, the channel has more freedom for lateral mobility.

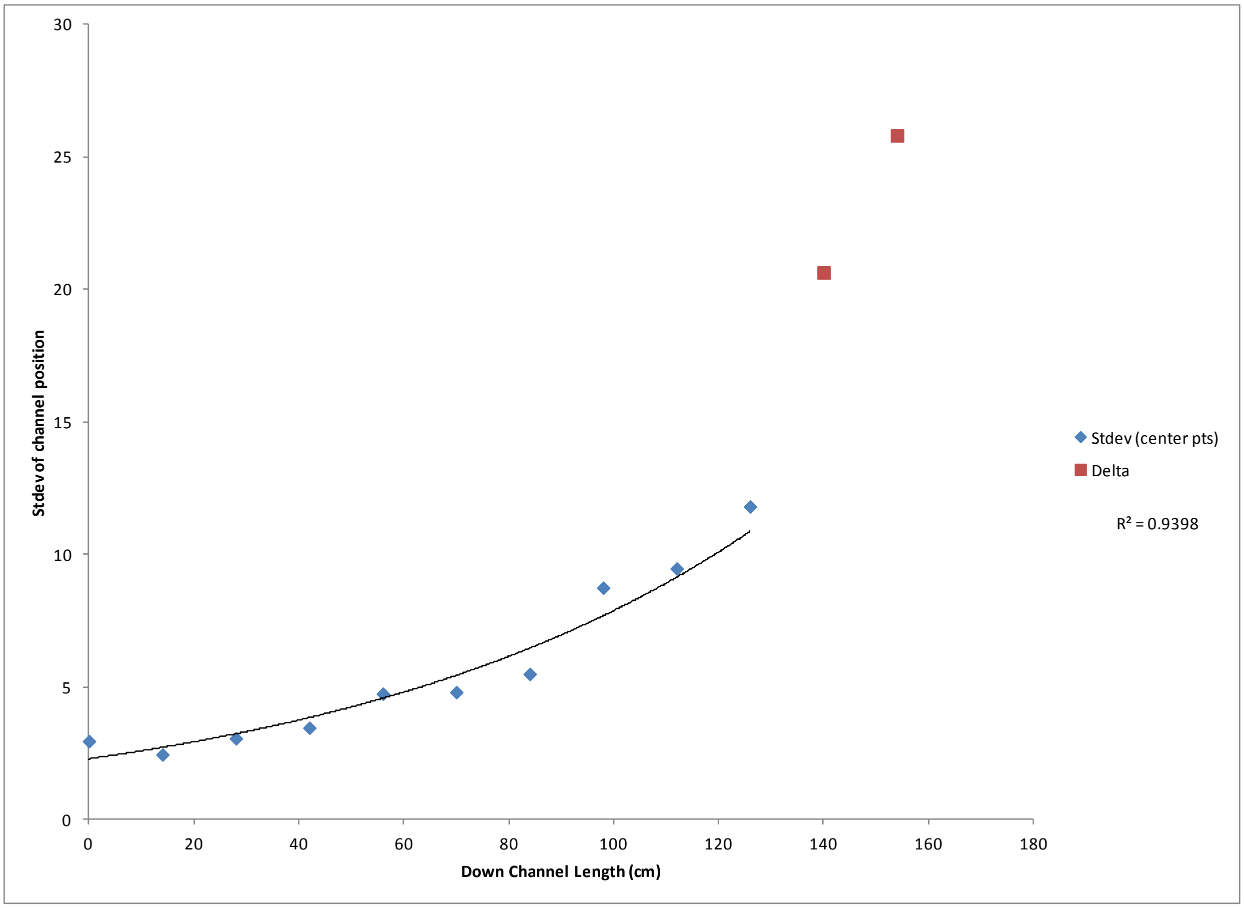

Figure 16: Channel avulsion frequency with length

The standard deviation of channel position against elapsed time is plotted below (Figure 17). This plot seeks to understand how much the experimental channel "wanders about" as time passes? The solid red line in the figure illustrates when the lateral tilt was implemented.

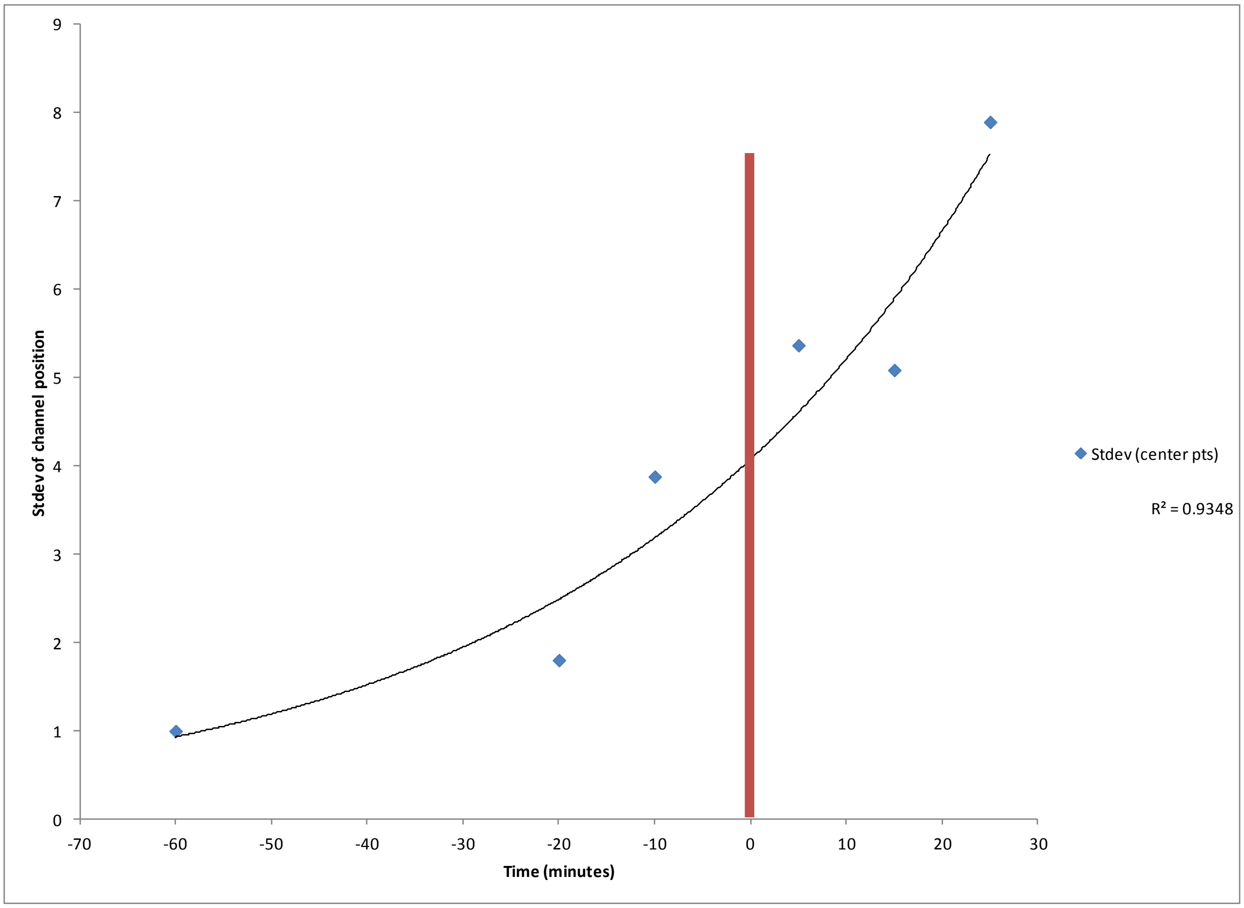

Figure 17: Channel avulsion frequency with time.

Notice the slight decrease in the value of the standard deviation of channel position between 5 and 15 minutes after the lateral tilt and the increases seen between all other time intervals. Observations conducted during the experiment confirm that after the lateral tilt, the channel preferably migrated to the down tilted side of the table. The channel was mainly confined to this down-tilted side until enough sediment aggradation on the same side occurred on the channel bottom so that it approached the elevation of the adjacent floodplain. After this occurred, the channel continued its' more frequent lateral migration along the floodplain.

Aggradation in the channel was plotted against down valley distance in the following figure (Figure 18). Data points in this plot represent averages of data, at specified length intervals down valley (at all times), from the four “Lateral Tilt” experiments. Error bars represent one standard deviation of the data.

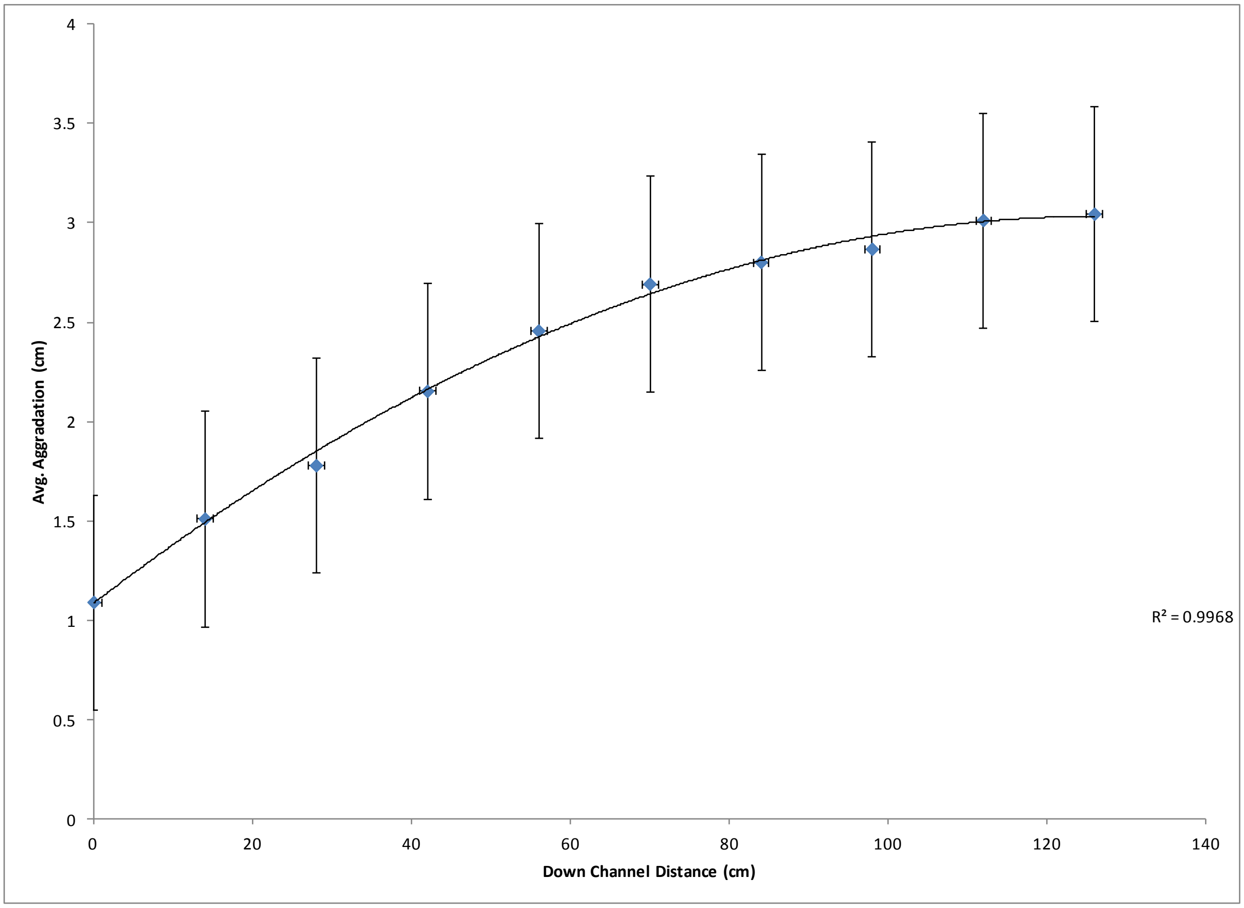

Figure 18: Average thickness of sediment down channel. Thickness of the deposited sediment bed increases with distance down the valley.

Average aggradation in the channel was plotted against elapsed time to evaluate the sediment flux in the channel over time, (Figure 19). Data points in this plot represent averages of data, at specified times (at all valley lengths), from the four “Lateral Tilt” experiments. Each data point is indicative of how much sediment was presently deposited in the channel at the given time. Error bars represent one standard deviation of each data point. The solid red line in the figure illustrates the time when the table was tilted laterally.

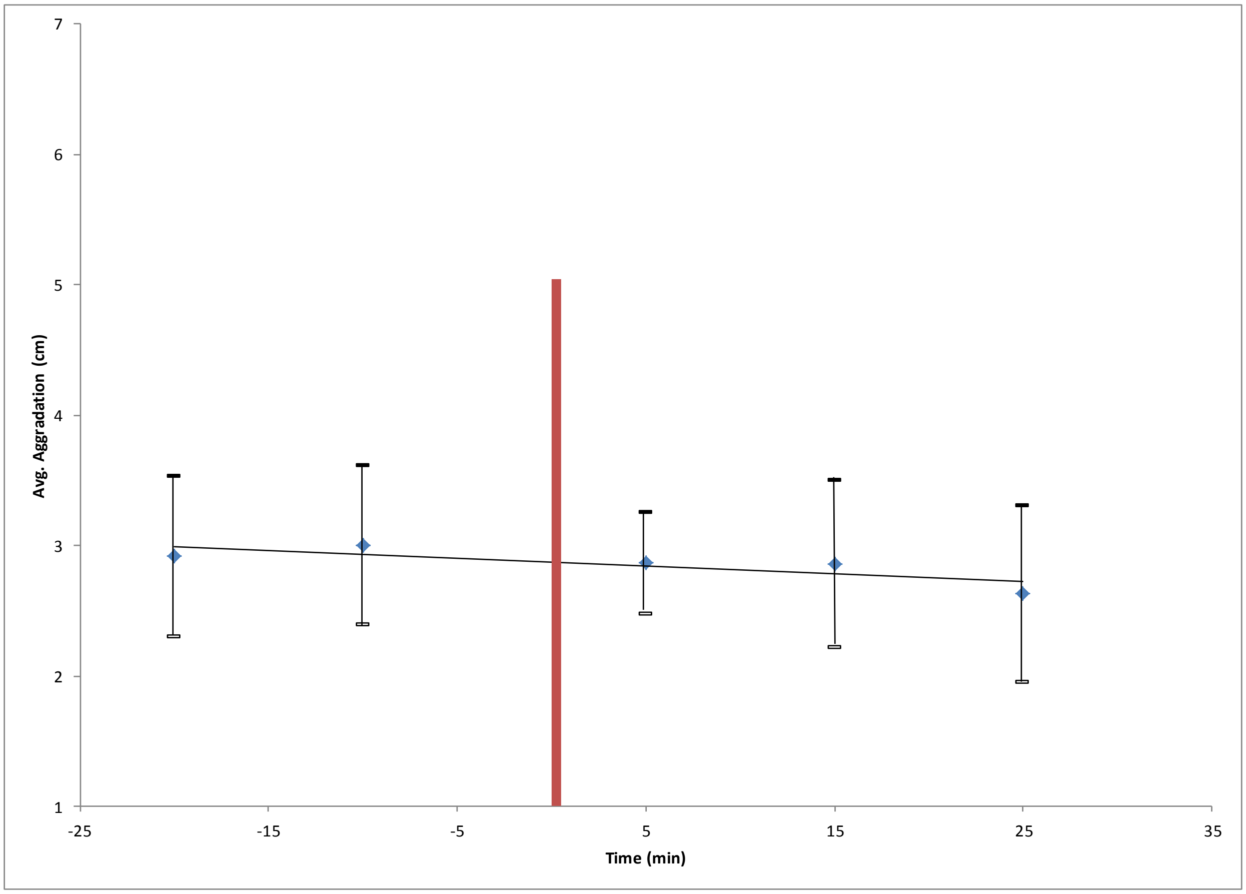

Figure 19: Average aggraded sediment within the channel through time.

Data from the experiments indicate that time does not have a significant effect on the data (Figure 19). It also appears that the induced lateral tilt does not affect the data either. This suggests that the channel has reached an equilibrium state regarding sediment flux; new sediment introduced into the channel approximately equals the sediment being transported out of the channel and deposited on the growing delta. It is important to note that since data collection for this experiment only began 40 minutes after the start of the experiment, we cannot determine how long it took for the experimental channel to reach this state.

In addition to the data discussed above, the videos (Lateral Tilt 1-4) provide additional qualitative information. The "Lateral Tilt 3" video shows the immediate response of the experimental channel to a sudden differential uplift at the 10:55 mark; here, the active part of the channel migrates to the down-tilted side of the table (right side). With the tilting, the right side of the delta is now submerged under water and the left side has been uplifted. A new set of abandoned terraces can be seen throughout the channel on the left (uplifted) side.

For a few minutes after the lateral tilt, avulsion appears to be less frequent as the active channel remains on the right side of the channel's floodplain and its' delta. Surface water can be seen occupying some of the abandoned channels, but no significant sediment transport appears to be occurring.

Throughout the remainder of the experiment, delta deposition remains largely on the right side, although slight avulsions can be observed. Abandoned terraces remain evident and are gradually eroded as the channel reworks the bars and channel deposits.

CHAPTER 5: DISCUSSION

Static Channel Experiments

It was hoped that data collected from these "Static Channel" experiments would answer some important questions regarding the performance of the table. Perhaps the most important question is whether or not the EM4 is able to consistently reproduce similar results. The data from this set of experiments tells us that the answer to this question is two part.

Figures shown in Appendix C demonstrate that there is difficulty in reproducing quantifiable results on the EM4 regarding sediment aggradation. The wetting and packing techniques discussed in Chapter 2 are considered to be the main factor in determining the cohesion of the banks, which ultimately determines the rate and volume of sediment that is introduced into the channel. This has a profound effect on the measured aggradation in the experimental channel. Observations conducted during the experiments, confirm that in experiments where a large volume of sediment was introduced into the channel through bank collapse in the early stages of the experiment, the end result was the development of a disappearing stream. In these cases the evolution of the channel essentially ceased and the experiment was deemed a failure. This failure can be attributed to unintentional variation in the way the sediment was prepared. See Figure 20 below.

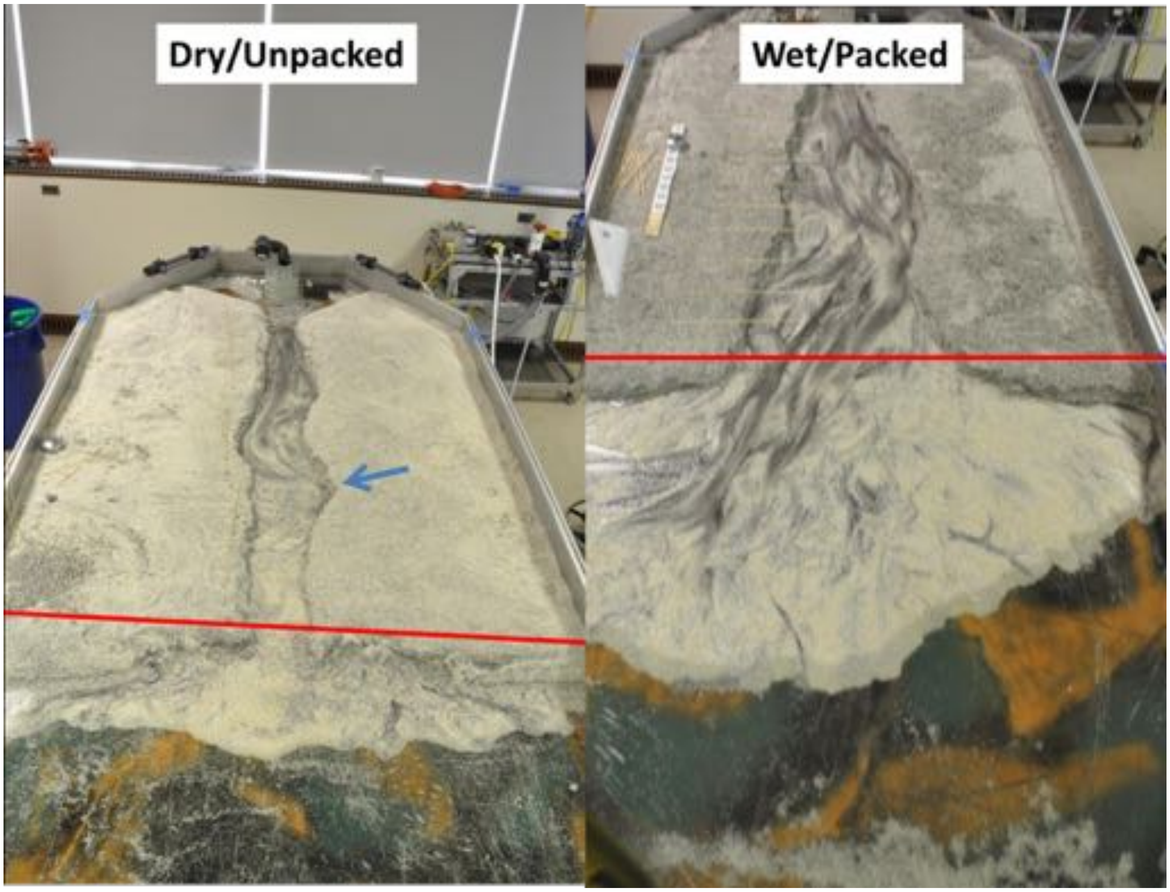

Figure 20: Qualitative comparison of the role of sediment preparation – Both photos were taken after 90 minutes of elapsed time in the experiment. In the experiment shown on the left, the sediment was left dry and unpacked before initiating the experiment. The blue arrow indicates where water disappeared into the sediment bed (disappearing stream). The photo on the right shows an experiment where the sediment was wetted and packed.

Since no sediment was manually added to the headwaters of the channel, the main mechanism for sediment input into the channel was the erosion of the banks. More cohesive banks result in a lower rate of bank erosion and less cohesive banks result in higher rates of bank erosion. When massive bank failure occurs early in the experiment before the channel has widened sufficiently, the sediment effectively dams up the channel and the water is more likely to convert to groundwater flow.

Examining the variability of sediment behavior on the EM4

To investigate the role of wetting and packing has on the cohesion of our sediment, a brief review of soil engineering research was conducted. Research by Likos and Lu (2002) investigates the role of capillary cohesion in unsaturated soils. Capillary cohesion refers to an "interparticle force generated within a matrix of granular particles (*e.g*., silt or sand) due to the combined effects of negative pore water pressure and surface tension." (Likos and Lu, 2002; 1)

Observations in soil engineering recognize the role of pore-water pressures in changing apparent cohesion between saturated and unsaturated soils. Summarizing these findings, Likos and Lu (2002) state that in saturated soils, the positive pore pressure force acted to repel grains away from each other. Highly negative pore water pressures present in "nearly dry" or slightly moist soils created "tensile forces acting to pull the soil grains together" (Likos and Lu, 2002; 2).

Results of this study indicate that, assuming negative pore-water pressures (unsaturated soils), the capillary force is negative. This acts to "compress the granular soil matrix" and creates an "'effective cohesion' in otherwise cohesionless soils" (Likos and Lu, 2002; 4).

Relating the concept of 'effective cohesion' to EM4 experiments

In experiments where the sediment was wetted down and packed before beginning the experiment, we found that the sediment appeared to be more cohesive, allowing cliff forming banks to form adjacent to the stream and often a small degree of undercutting to take place without undermining bank stability (Figure 21). When the sediment, was neither wetted nor packed, the sediment was unable to establish these steep banks (Figure 22).

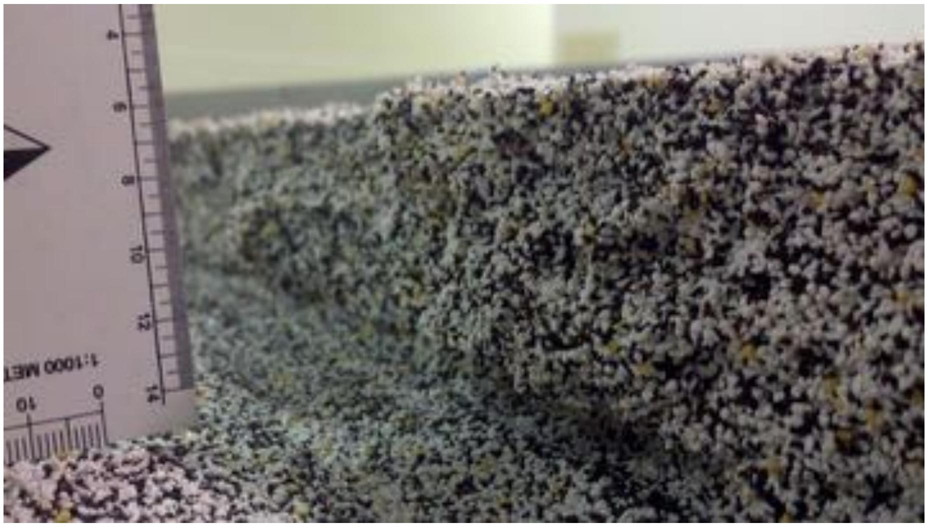

Figure 21: Wetted/Packed EM4 sediment

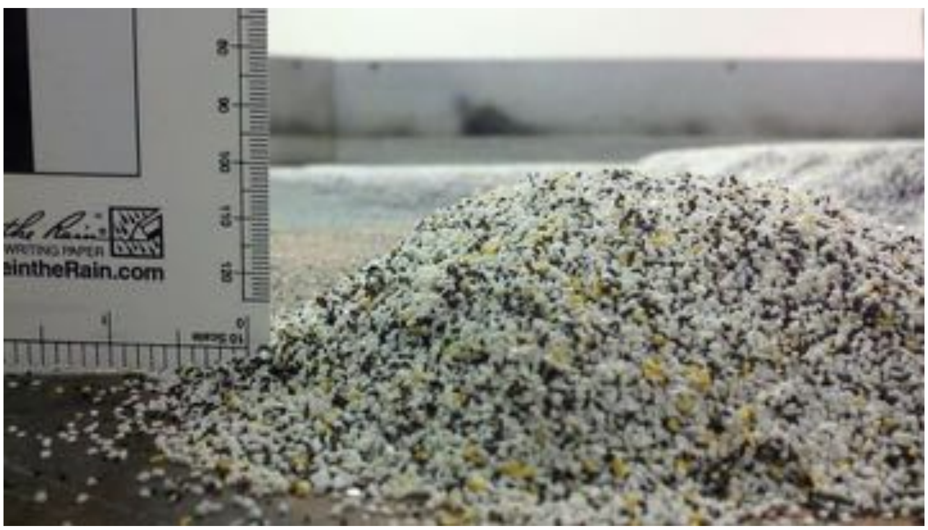

Figure 22: Dry/Unpacked EM4 sediment

Because our sediment has both high porosity and permeability, we were never able to fully saturate the bed (with the set gradient and base level of the experiments); however the sediment was able to retain a small film of water coating the grains. With the exception of a small saturated layer at the interface between the table surface and the sediment, this is analogous to what Likos and Lu (2002) described as a "nearly dry" soil. As Likos and Lu (2002) describe in their paper, this water left behind in our well-drained sediment bed likely caused surface tension and negative pore pressures which resulted in a macroscopically more competent and cohesive bed of sediment.

<u>Possible role of sediment packing in promoting 'effective cohesion'</u>

Likos and Lu (2002) use the following figure (Figure 23) to illustrate both the capillary forces acting on two spherical grains and specific geometrical relationships between the sediment grains and the water lens. θ (the water content index angle) "connects the center of either soil particle to the center of the circle defined by r_1 (Likos and Lu, 2002; 3). Both lengths r_1 and r_2 define the geometry of the lens of water that lies between the two grains (Likos and Lu, 2002). Likos and Lu (2002) state that by changing the relationship between r_1 and r_2 (the geometry and size of the water meniscus), the pore-water pressure will be modified. Small values of r_1 and large values of r_2 result in a more negative pore-water pressure.

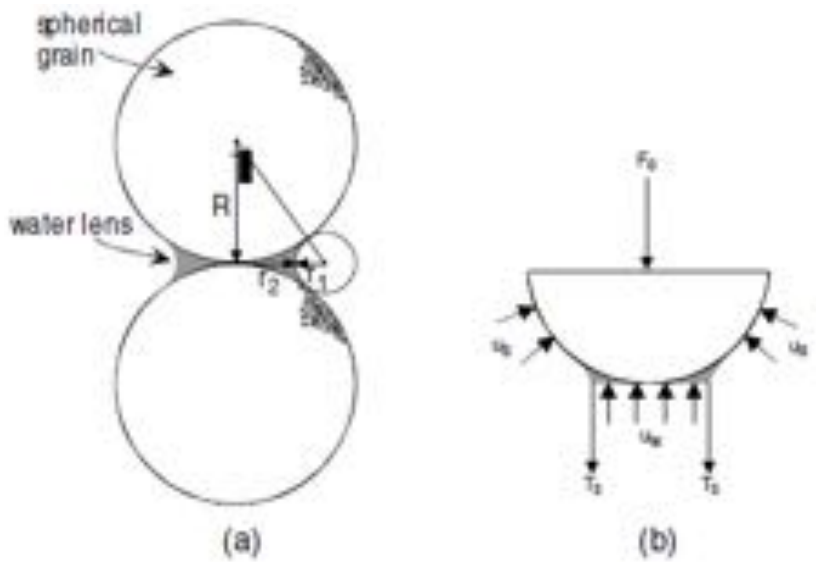

Figure 23: Interparticle geometry of water lens – Figure from Likos and Lu (2002; 3).

Through packing our sediment, we assume two things are occurring; we are rearranging the sediment grains in such a way that they "lock" into each other (in a manner similar to loess deposits). As a consequence of this rearrangement, we are reducing the total amount of available pore space. Although the sediment still remains relatively porous and non-cohesive, the reduction of pore space and rearrangement of sediment grains establishes more inter-granular contact.

In their model, Likos and Lu (2002) assume perfectly spherical soil particles. Assuming the same principal relationship between pore-pressure and r_1:r_2 applies to our sub-angular sediment; we can infer that even more negative pore-pressures are sustained in our wetted sediment bed because of the increased intergranular contact. By ensuring more inter-granular contact, we are effectively decreasing the value of r_1 and increasing the value of r_2. This likely results in a greater cohesion of our sediment.

Applying this concept of effective cohesion to our sediment, we can see that slight variations in how the sediment was prepared may have a profound effect on the behavior of the sediment included with the EM4 Stream Table. These variations can ultimately determine if the experiment fails, due to the development of a disappearing stream, or succeeds in the creation of a fully developed channel. Variations in sediment preparation also explain the differences in aggradation values between successfully completed experiments, as illustrated in Appendices B and C.

In experiments with steeper initial gradients (3.98°), it was found that even when great care was taken in sediment preparation, every experimental channel quickly developed a disappearing stream, at which time, channel evolution stopped. This is thought to be attributed to the increased velocity (and erosive power) of the water for the same discharge at steeper tilts. The increased erosive power of the water promoted more bank erosion and resulted in the stream being choked with sediment; which ultimately led to the formation of a disappearing stream.

Although there is difficulty in reproducing aggradation values measured in the experiments, examining figures in Appendices B, C, and D tell us that the trends and correlations between each successfully run experiment are reproducible. These are promising results and suggest that the EM4 can be used for research purposes if great care is taken in experiment preparation methods. The data from these experiments suggest that both the width of the floodplain and aggradation in the channel reach some state of equilibrium after 30 minutes of experimental run time.

Base Level Change Experiments

The base level change experiments demonstrated a channel's response to a base level drop. In our experiments, we found the same positive correlations between aggradation and distance down valley that were evident in the "Static Channel" experiments. Even with a shallower initial gradient, this channel reproduced the same trend. In plotting aggradation against distance down channel after 30 minutes of elapsed time in the experiment, it appears that a linear regression best fits the data from the "Static Channel" experiments (2.27° initial gradient), whereas a polynomial best fit line best fits the data in the "Base Level Change" experiments (1.3° initial gradient). Further work should be done to investigate this occurrence, but at this moment it is not clear if this comparison has any real significance.

This experiment also illustrates the relatively rapid response of the EM4 to a change in base level. After the base level drop, the channel appears to fully adjust its gradient (implied by aggradation measurements) by the first 15 minutes.

Overall, the results of the "Base Level Change" experiments demonstrate a useful experiment that can be applied to classroom experimentation or research investigating the role of base level change on sedimentation within a channel. It also clearly produces a hypothesis that can be tested on field sites. Future work may investigate if channels in nature respond to a base level lowering in a similar way as the EM4 does. If they do or don't respond in a similar manner, knowledge gained from EM4 experiments may aid in identifying other underlying subtle differences in natural streams that ultimately have control over their behavior.

Lateral Tilt Experiments

Data collected from the "Lateral Tilt" experiments again demonstrates the positive correlation between aggradation and distance down valley. As shown in Figure 19, the lateral tilt does not appear to affect the volume of sediment present in the active channel. For the times in which measurements were taken, the channel appears to have reached an equilibrium state of sediment flux. Since measurements were only taken from elapsed times of 40 to 85 minutes within the experiment, we cannot determine when the channel reached this equilibrium state with regard to aggradation.

The lateral tilt has an effect on the lateral mobility of the channel (Fig. 17). Although the trend of the channel is to laterally migrate frequently with time, there is a slight decrease in the standard deviation of channel position value between 5 and 15 minutes after the lateral tilt. This suggests that the tilting inhibits the ability of the channel to laterally migrate for a short period of time, until the channel has deposited enough sediment to minimize the elevation difference between the up-tilted and down-tilted sides of the table.

Although the lateral profile of the channel is dynamic due to the shifting in meanders and bars (Figure 15); tilting the table induces a shift in the sediment transfer and mass transport phenomenon. After the tilt, sediment deposition largely occurs on the down-tilted side of the table.

The lateral tilt experiments again demonstrate that the EM4 can produce repeatable trends within the experimental fluvial system between experiments. Future work may involve finding appropriate field sites that exhibit differential uplift. Investigating the similarities or differences between a natural landscape response and the EM4's response to such an event may provide more insight into the full characterization of the EM4.

CHAPTER 6: IMPLICATIONS AND CONCLUSION

The main goal of this research was to characterize the behavior and evolution of experimental channels using the provided equipment and sediment. Progress has been made in this respect, although future work with the EM4 is necessary to provide more insight into these processes.

Sediment Used and Variation of Experimental Settings on the EM4

Although considerable effort was taken to run each experiment the same way each time, there remained some variables which were difficult to control. In order for the EM4 to be a more useful tool, users of the stream table must be able to accurately determine experimental parameters and minimize unintentional variations in these settings. If variations are encountered, it is important for the users to be able to recognize the presence of a variation as well as quantify the effects of such a change. Certain additions or changes to the EM4 may help to minimize these variations

Many struggles and failed experiments provided the necessary knowledge with which to conduct successful experiments on the EM4. Perhaps the most important finding was the great care that must be taken when preparing the sediment for an experiment. Trial and error has shown that even slight differences in sediment preparation can have a profound effect on the behavior of experimental channels created on the EM4. It seems that the variability in the cohesion of the sediment ultimately drives these differences. It is because of this reason that our recommendation is to find another, more reliable method for ensuring that the sediment has a uniform and consistent cohesion from experiment to experiment. Experimentation with different materials, in size and/or composition, may be necessary to find the right sediment which can accomplish this goal. The water seepage which ultimately led to the formation of a disappearing stream was a challenge in the experiments. Since this phenomenon is thought to be ultimately driven by the lack of cohesion in the sediment, finding and experimenting with the right mix of material for the EM4 seems to be of paramount importance.

Water discharge was another experimental parameter that was found to vary occasionally. Discharge was approximated by timing the filling of a 2L container. This technique is clearly imperfect however; changes in water discharge could still be detected in this way. Several experiments were discontinued due to large variations in discharge within the experiment and it was determined that the introduction of air bubbles into the water pump was the main culprit behind this issue. Filling the water reservoirs completely tended to minimize this event, although there was no way to be completely sure that the discharge was still not varying slightly. A flow meter would prove to be a cost effective way of measuring discharge more accurately and would enable future users of the EM4 to quantify any variation in this parameter.

Measuring Techniques and Time Constraints on the EM4

Use of alternative measuring techniques would be useful for a full characterization of the behavior of experimental channels on the EM4. Data collection from our experiments with the EM4 was labor intensive, time consuming, and also required the help of other students. Data collection and the completion of this research would have been nearly impossible without their help. The dynamic nature of these experimental channels is not well suited to such time consuming measuring techniques. In the time it takes to conduct in-situ measurements on channels developed on the EM4, changes in channel morphology have occurred. Using in-situ measuring techniques also limits the amount of data that can be collected in a given time. Given the time constraints due to the dynamic nature of these channels, certain parameters to measure must be chosen while other measurements must be ignored.

Measuring sinuosity in our experimental channels proved to be a very difficult undertaking. In Chapter 2, the methods for taking these measurements are discussed. In the first attempts at taking these measurements, a length of cotton string (marked at regular intervals) was used to measure the channel’s sinuosity. After using this method in many experiments, it was found that the cotton string was expanding and contracting after many episodes of wetting and drying. The differential expansion and contraction of the string caused some of the marked intervals to deviate by ±2.5cm. Although this was later resolved by using fishing line, measuring sinuosity was very time consuming and, in the interest of other measurements, attempts at measuring sinuosity were eventually abandoned.

Early experiments using CRP to collect data from a stable scene (no active movement of sediment or water) show promising results (Figure 24).

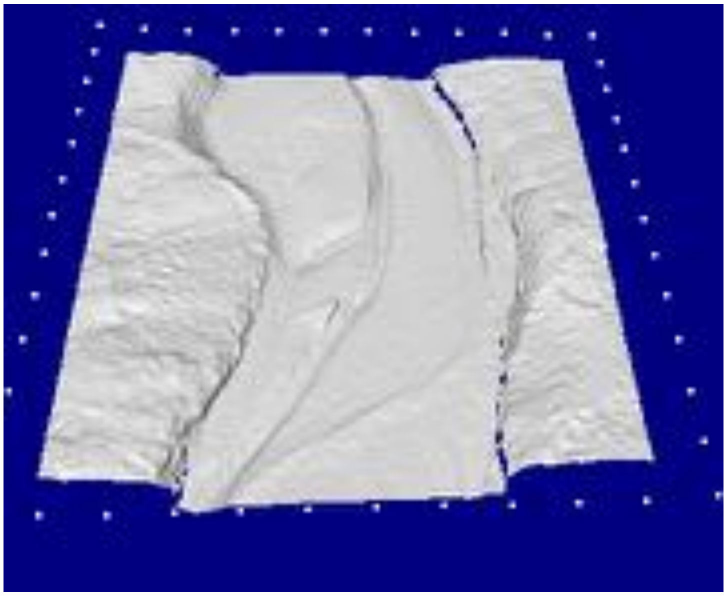

Figure 24: Inactive DSM - generated from photos taken of a portion of the channel developed on the EM4. The photos were taken after the experiment was concluded (no active water or sediment transport). The photogrammetry software was able to produce an accurate model of the photographed scene.

Through our simple experiment discussed in Chapter 2, we showed that the use of CRP may yield very precise data. The issue with using CRP to document experiments on the EM4 was not with the technique, but with the limited equipment that was available to us. Since only one camera was available for use, it was necessary to move the camera between photographs in order to generate a stereo pair for photogrammetric processing. If the object scene changes in any way between photographs, we are unable to use CRP to generate measurable data (Figure 25).

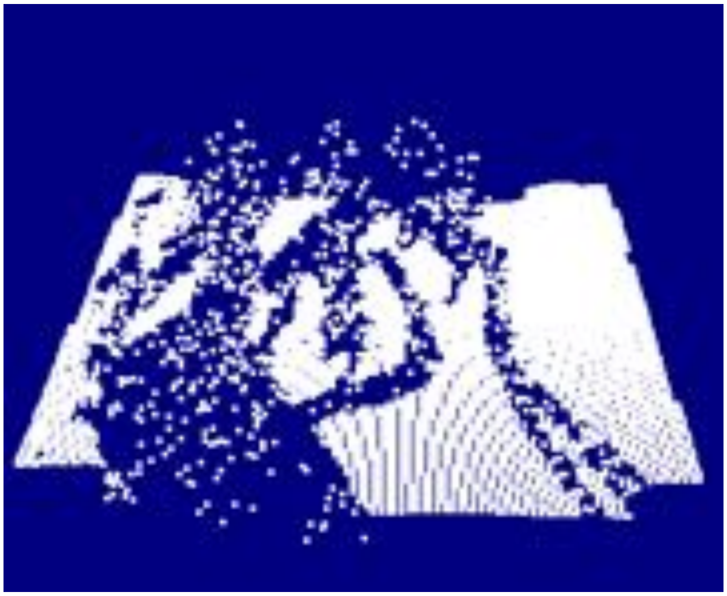

Figure 25: Active DSM - generated from photos taken while the experiments on the EM4 were in progress. Parts of the channel that were active between the time the two photographs were taken are highlighted by the “noisy” and incorrectly placed points.

Because of this reason, in our experiments, in which sediment and water were constantly moving, we were unable to use CRP effectively with only one camera at our disposal. Two synchronized cameras would solve this issue and would make CRP a powerful measuring tool for collecting data on the EM4.

Using techniques such as CRP would solve many issues related to time constraints and variations in the equipment used for measuring (cotton string), as well as minimize human error in the measurements. By using techniques such as CRP, multitudes of data can be collected in an instant. Using CRP, we may also be able to quantify parameters that would be difficult to characterize otherwise, such as the channel’s degree of braiding. Such data collection methods would be invaluable to future research conducted on the EM4.

Conclusions and Comments

Through this research we have investigated the response of experimental braided streams to certain perturbations. As indicated by Figure 14, our experimental stream's response to a base level change is similar to the experimental data generated by Germanowski and presented by Schumm (1993; 287). Incision after a base level drop migrates up channel until no significant change can be detected. This incision following the base level drop tapers out roughly halfway up the channel as indicated by Figures 5 and 14.

We also found that our experimental channel's response to a lateral tilt was somewhat different than anticipated; aggradation occurred on the down-tilted side, contrary to what was initially expected, that incision will occur on the down-tilted side of the channel. Figure 15 indicates that sedimentation in our experimental channels respond to a lateral tilt by a marked increase in sedimentation on the down-tilted side.

Through these experiments we found that the volume of sediment in the channel remains relatively constant throughout time; both Figure 18 and Figure 12 suggests that the amount of sediment present in the active channels quickly establishes a "quasi-equilibrium" and maintains that same relative volume through time. Although Figures 12 and 19 suggest a constant volume of sediment in the active channel, data presented in Figure 9 suggests that the distribution of sediment in the active channel does not reach this "quasi-equilibrium" state until 30 minutes have elapsed in the experiment. After this time, it seems that the aggraded sediment in the channel reaches a linear relationship with length down the channel; thickening at a constant rate with length (Figure 13).

The experiments conducted in this research show that using physical models to demonstrate stream processes and the evolution of experimental channels is a worthy undertaking. In the spirit of Hooke, care must be taken to treat physical geomorphological models such as the EM4, “as small systems in their own right, not as scale models of prototypes.”(Hooke, 1968; 392) Ultimately, it is difficult to use the EM4 to reproduce some real world analog (as with most geomorphological physical models) although the “Base Level Change” experiment suggests that this physical model does successfully demonstrate “similarity of process” as discussed by Hooke (1968). When great care is taken to ensure experimental parameters are as similar as possible, the EM4 produces channels whose trends and processes resonate through all experiments. Next steps in research with this tool should investigate the extent to which the trends and processes, which have become apparent in the use of this stream table may relate to processes operating in nature.

In addition to being a useful research tool in experimental geomorphology, the physical model at Saint Louis University has provided engaging activities for undergraduate classes to observe the dynamics of sediment transport and bedform generation and migration in braided channel systems. Having interactive learning tools available is invaluable and their educational benefit should never be underestimated. Particularly in the field of Geology, it is essential for students to learn by exposure to field sites and physical models. That being said, in order for this physical model to be useful in high level research, it is essential for the user to develop a greater understanding and control of the many variables involved in its’ operation; beyond merely qualitative observations. As noted above, different techniques for measuring change on the stream table’s experiments may aid in this task This research has successfully investigated and characterized many of these variables, and demonstrated the EM4’s promising future in investigating Geomorphologic problems, although much work remains to be done.

APPENDIX A

A EM4 Parts and Accessories

Figures in Appendix A show the various parts, mechanisms, and accessories of the EM4 stream table.

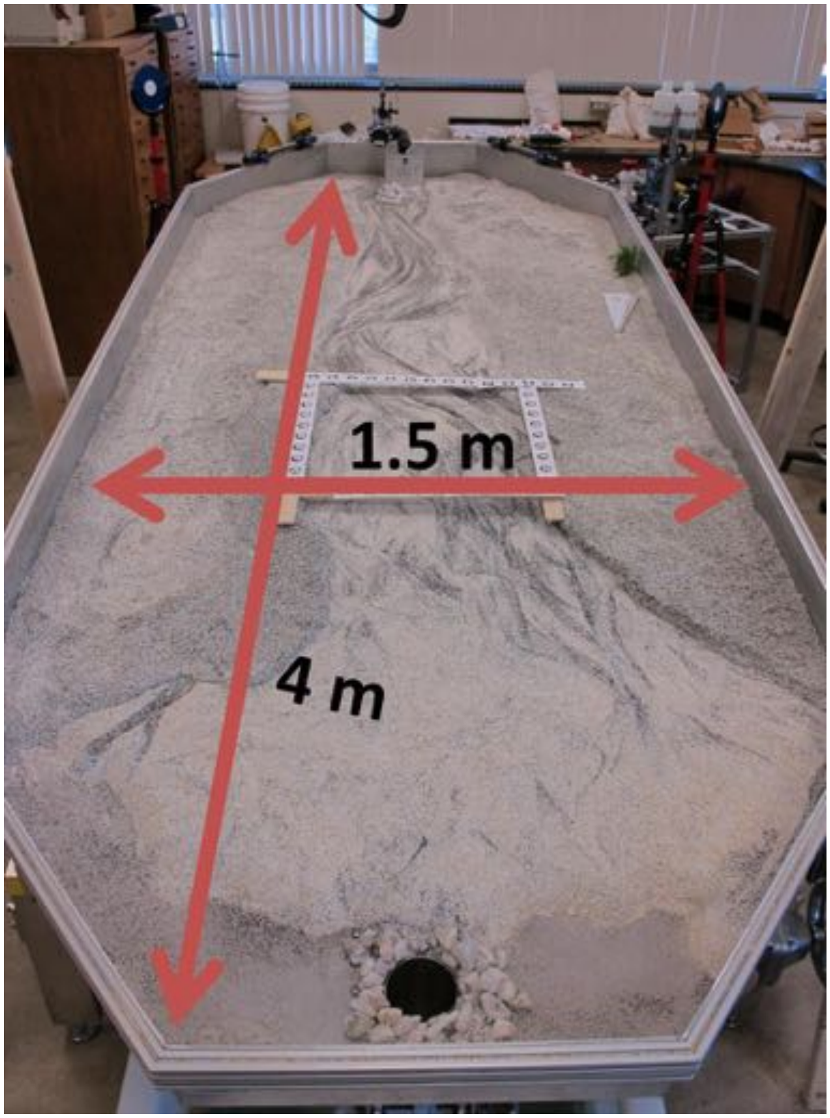

Figure A1: The EM4's surface showing relative dimensions.

Figure A2: Location at the head of the table where water is introduced to the table surface.

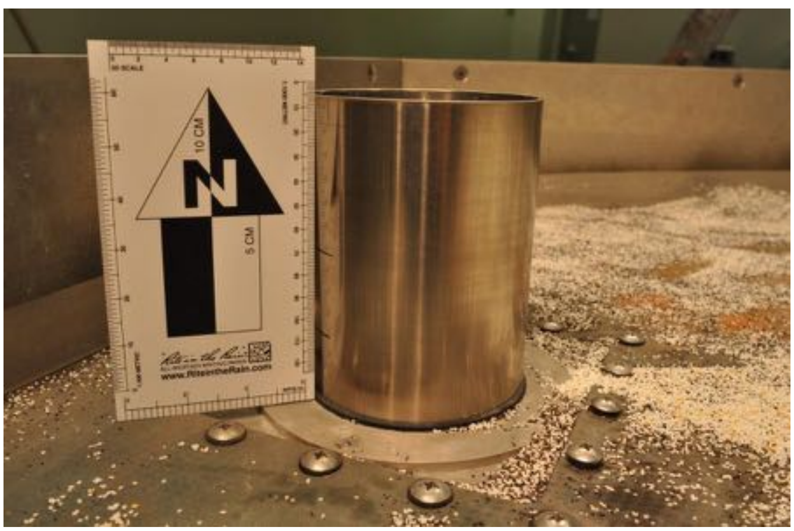

Figure A3: The Em4's "stand pipe" cylinder. This is located the lower end of the EM4 where water is drained from the table. This height of this cylinder can be modified to simulate base level change on the EM4.

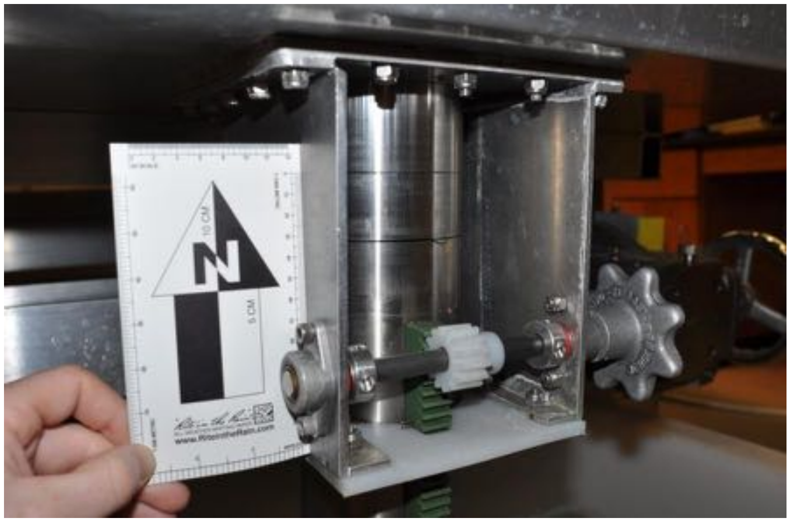

Figure A4: View of the “stand pipe” cylinder from underneath the EM4. The height of the cylinder is modified by turning the knob shown on the right side of the figure.

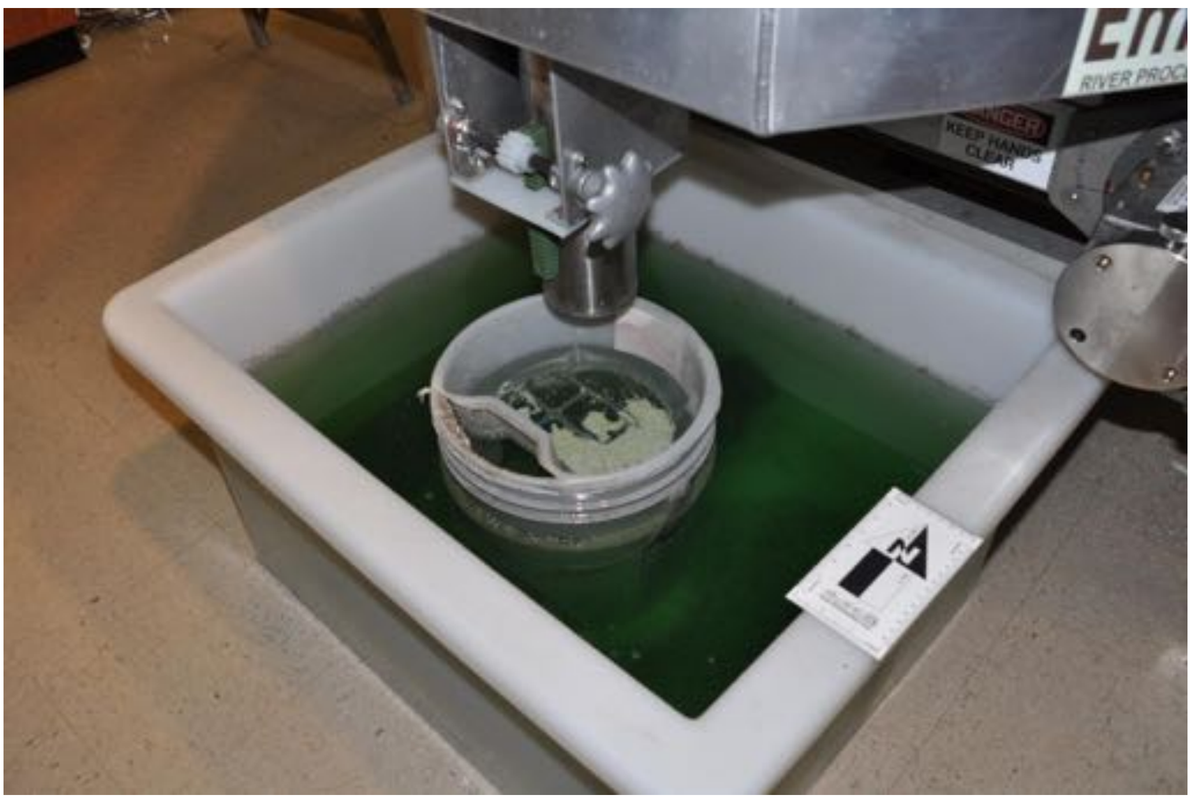

Figure A5: View of the lower water reservoir, located beneath the EM4. Water draining from the table via the stand pipe drains into this reservoir. A 3” hose connects this reservoir to an identical reservoir located beneath the upper end of the EM4. A pump draws water from the upper reservoir and reintroduces it the EM4’s surface (see Figure A2).

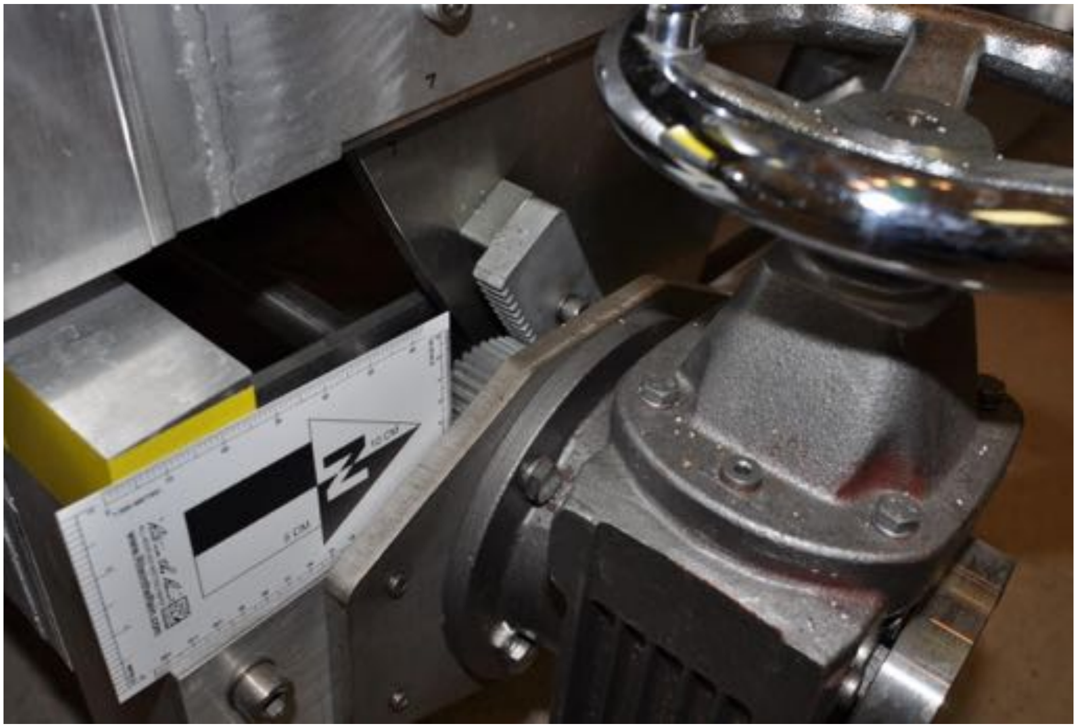

Figure A6: Gear mechanism which allows the user to modify the longitudinal gradient of the EM4's surface.

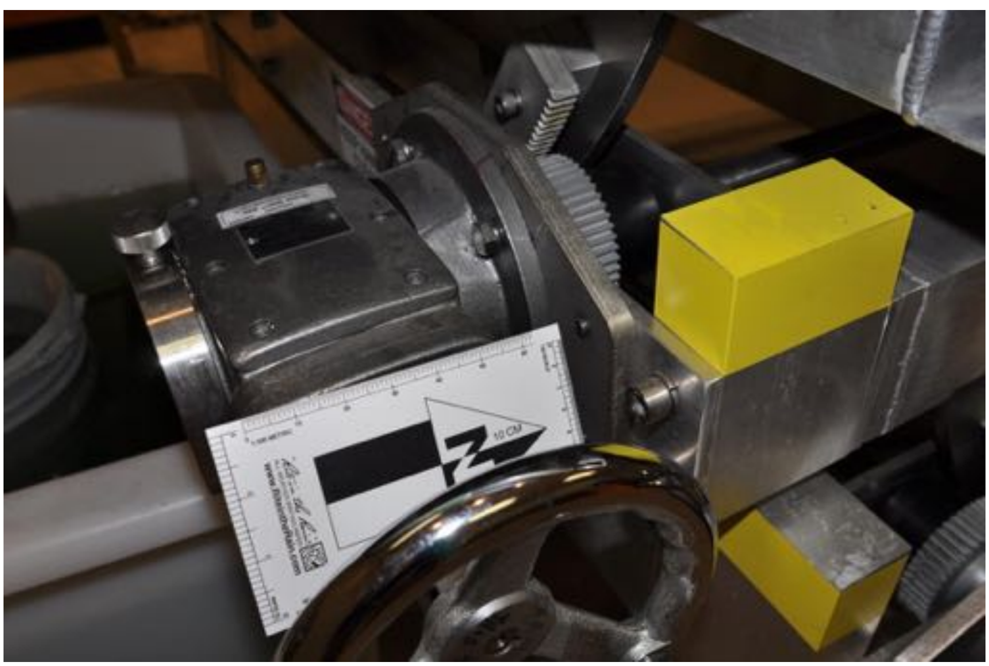

Figure A7: Gear mechanism which allows the user to modify the lateral gradient of the EM4's table surface.

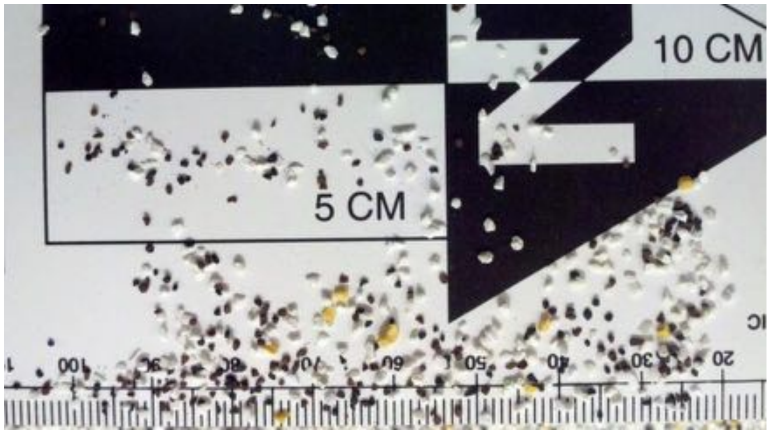

Figure A8: Picture showing the sediment used to simulate the EM4's mobile bed. Sizes range in average diameters from 0.7 to 1.4 mm and are color coded by size.


Figure A9: Image showing the sprinkler system on the EM4. This is located near the head of the table. These sprinklers may be used to simulate groundwater flow.

Figure A10: Image showing the cart containing the controls for the table. Included on this cart are the water pump, discharge control valves, and a dye injection system.

APPENDIX B

B Static Channel Experiments: Floodplain Width vs. Aggradation

Figures in Appendix B contain results from the static channel experiments. The following plots in Appendix B compares aggradatioin in the channel with width of the floodplain. Each graph represents data taken at specific time intervals. The series in each of the graphs represent different experiments (eg. Series 5 = Experiment 5).

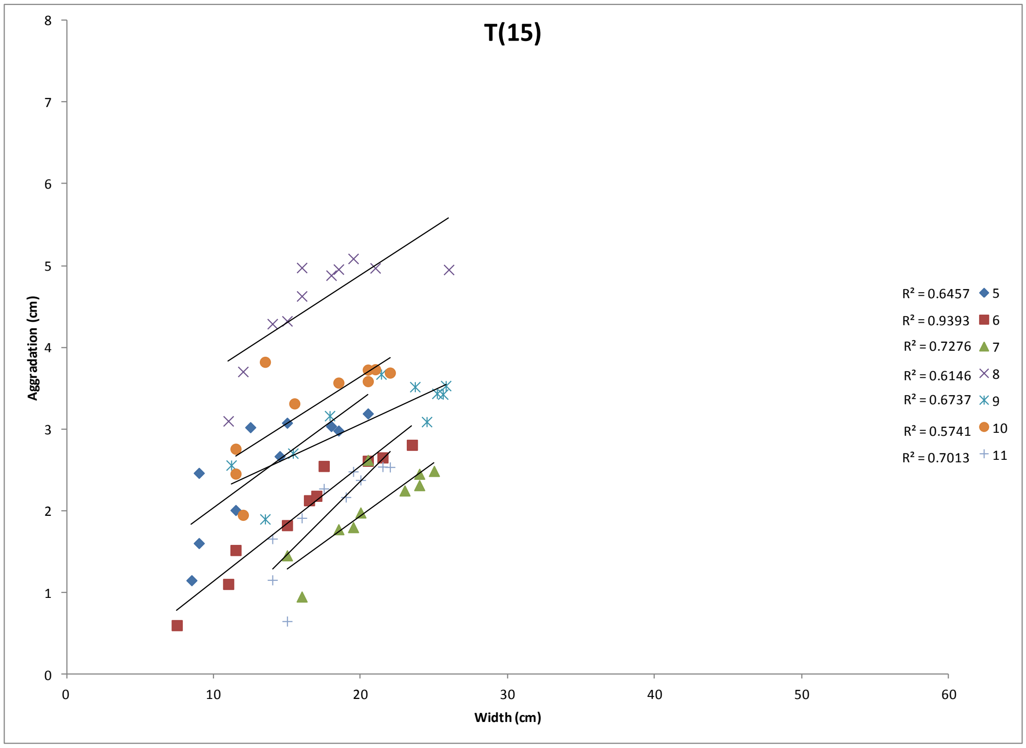

Figure B1: Aggradation against width 15 minutes after experiment initiation.

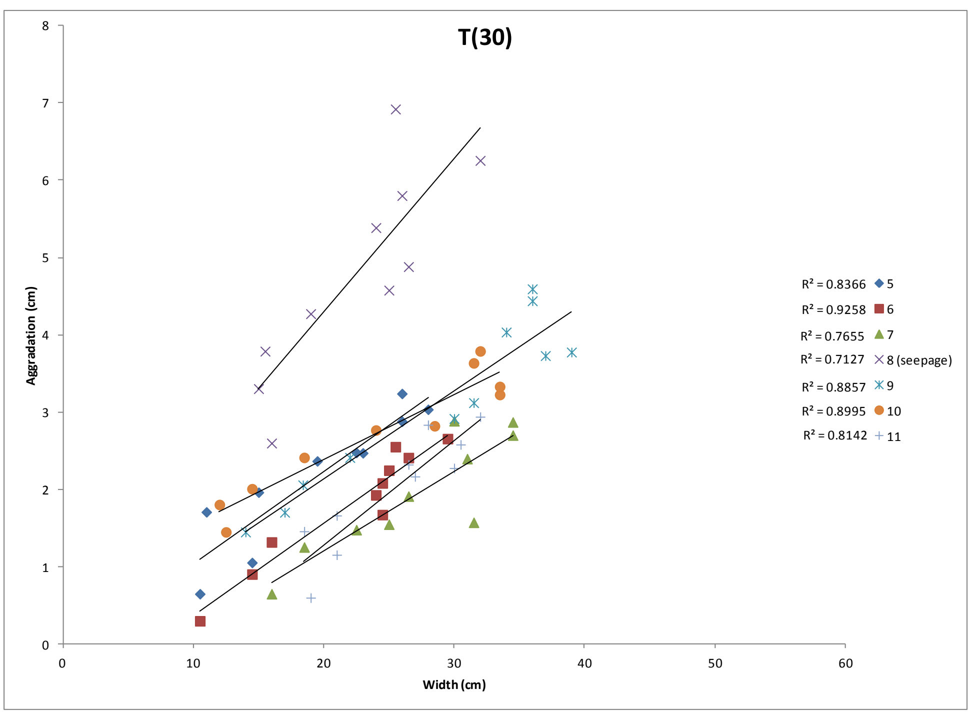

Figure B2: Aggradation against width 30 minutes after experiment initiation.

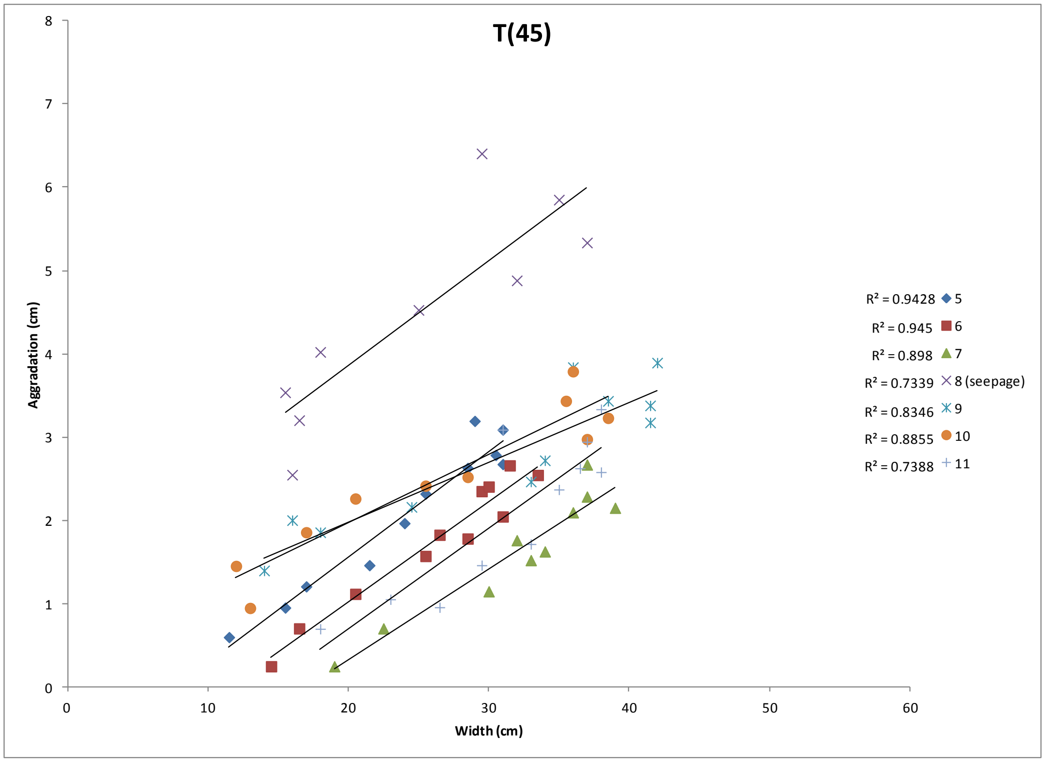

Figure B3: Aggradation against width 45 minutes after experiment initiation.

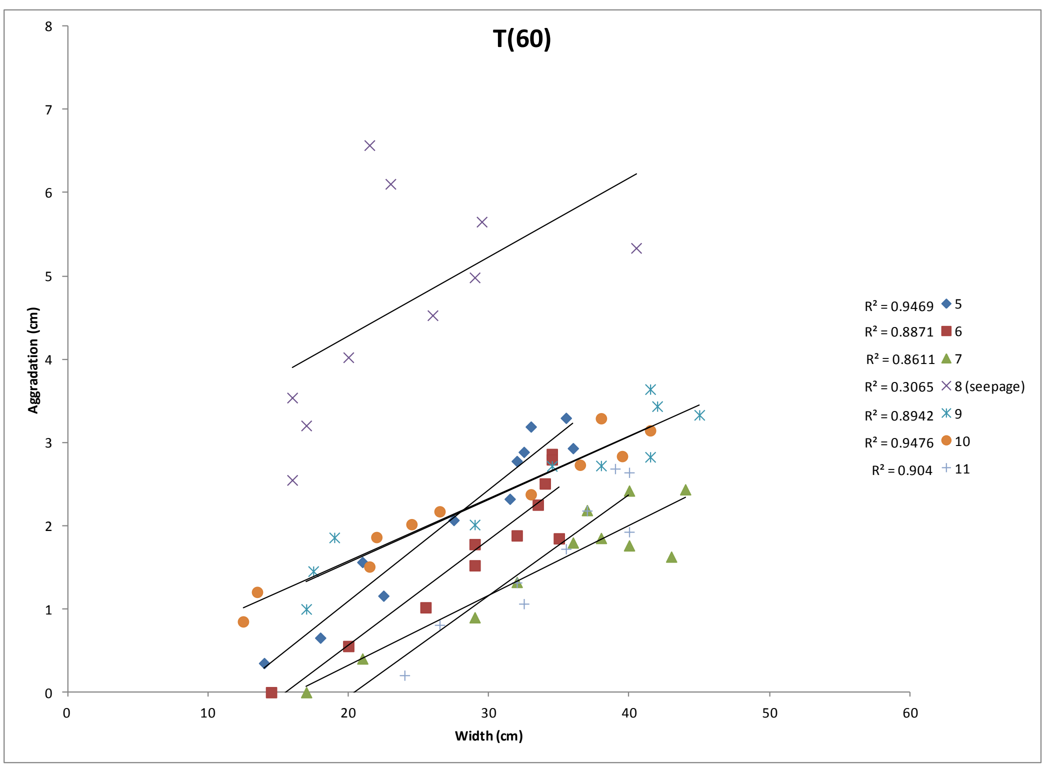

Figure B4: Aggradation against width 60 minutes after experiment initiation.

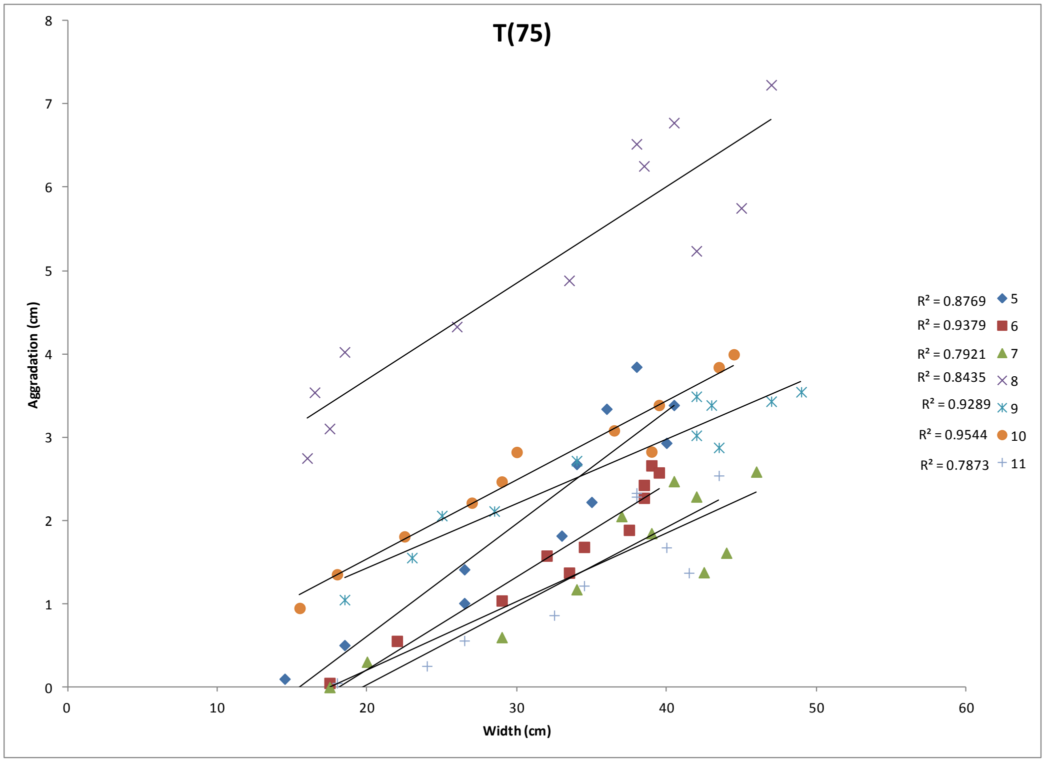

Figure B5: Aggradation against width 75 minutes after experiment initiation.

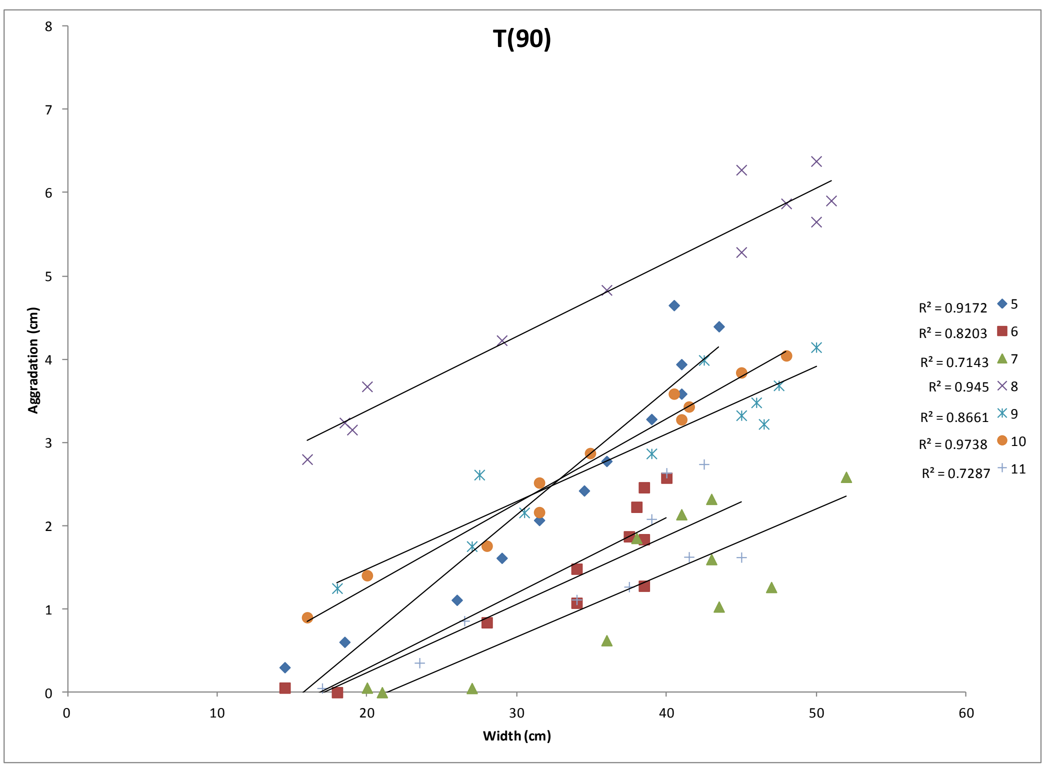

Figure B6: Aggradation against width 90 minutes after experiment initiation.

APPENDIX C

C Static Channel Experiments: Valley Length vs. Aggradation

Figures in Appendix C contain results from the static channel experiments. The following plots in Appendix C compares aggradatioin in the channel with down valley distance. Each graph represents data taken at specific time intervals. The series in each of the graphs represent different experiments (eg. Series 5 = Experiment 5).

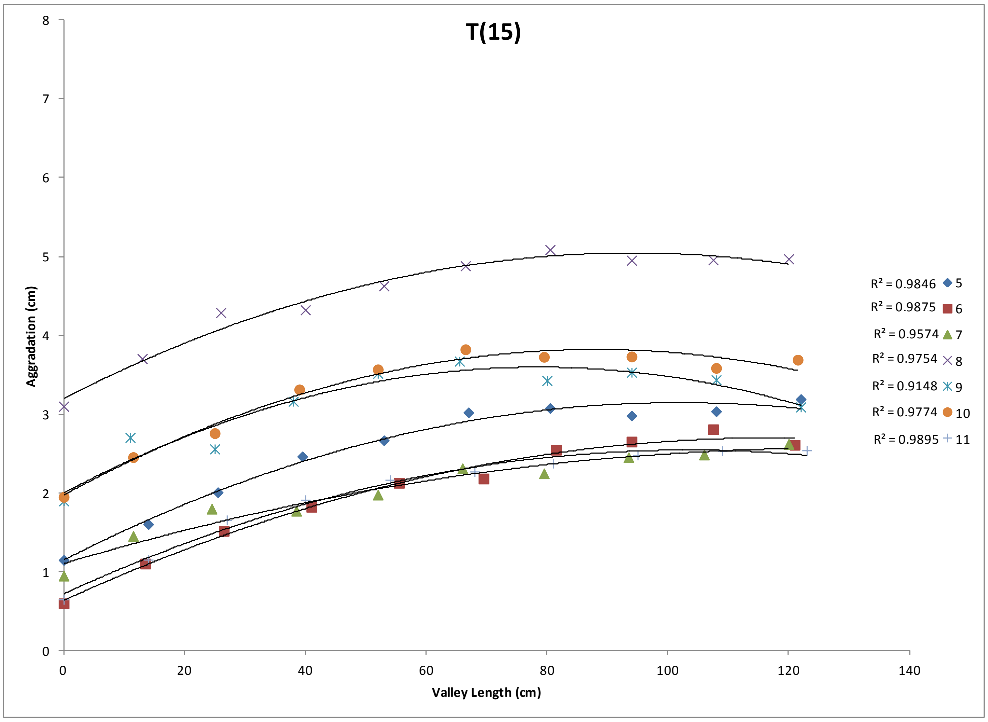

Figure C1: Valley length against aggradation 15 minutes after experiment initiation.

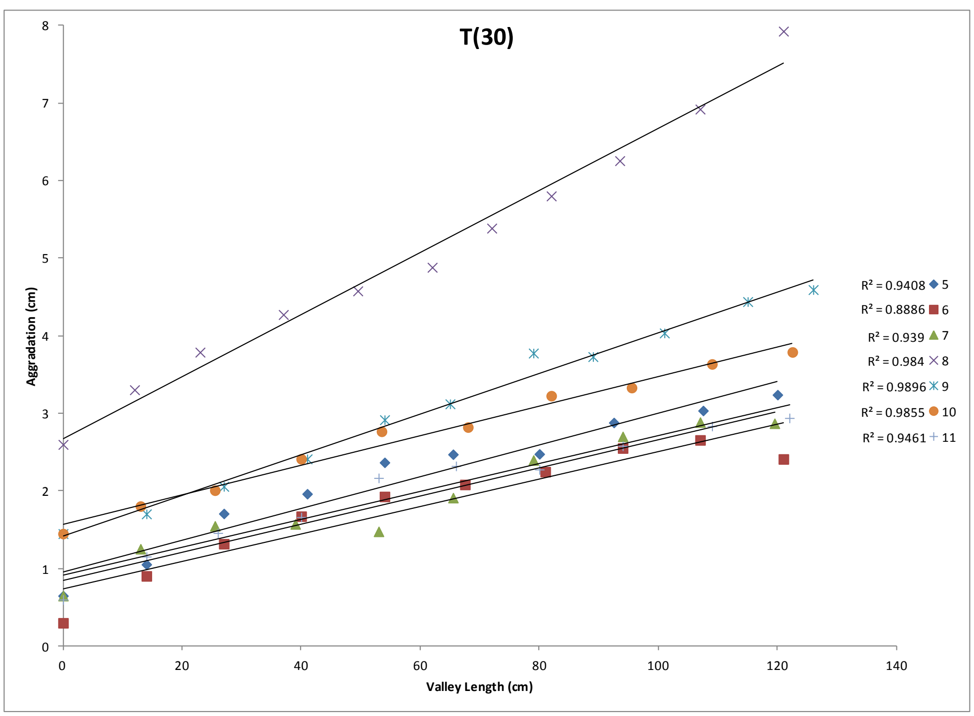

Figure C2: Valley length against aggradation 30 minutes after experiment initiation.

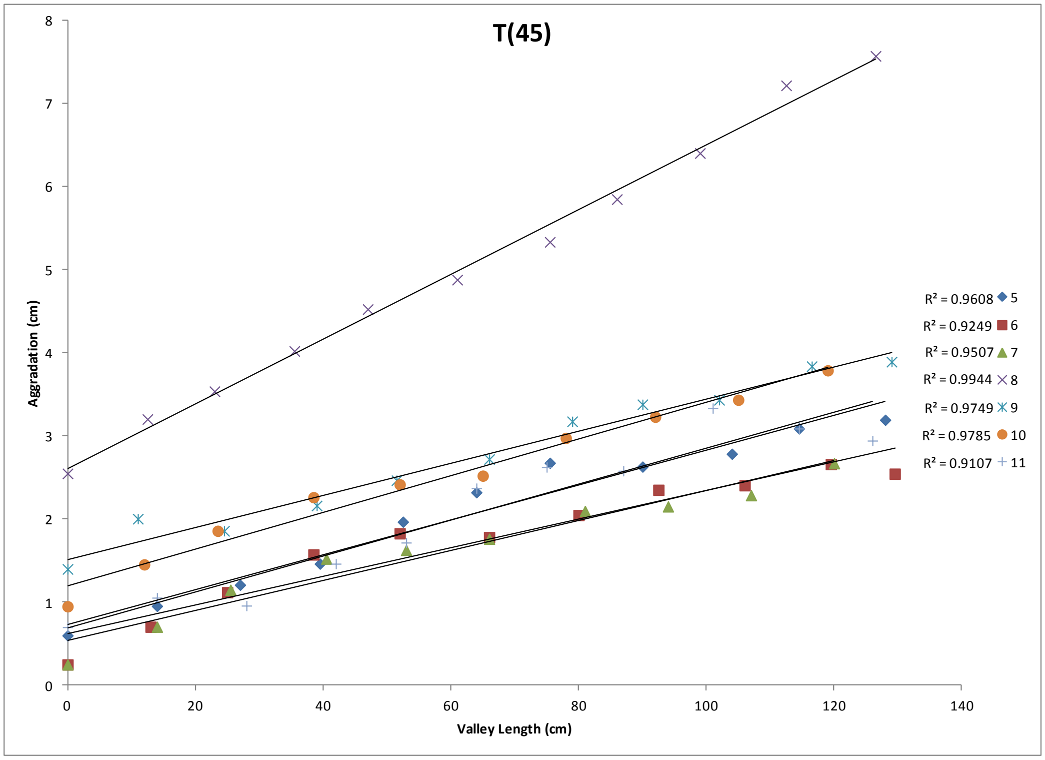

Figure C3: Valley length against aggradation 45 minutes after experiment initiation.

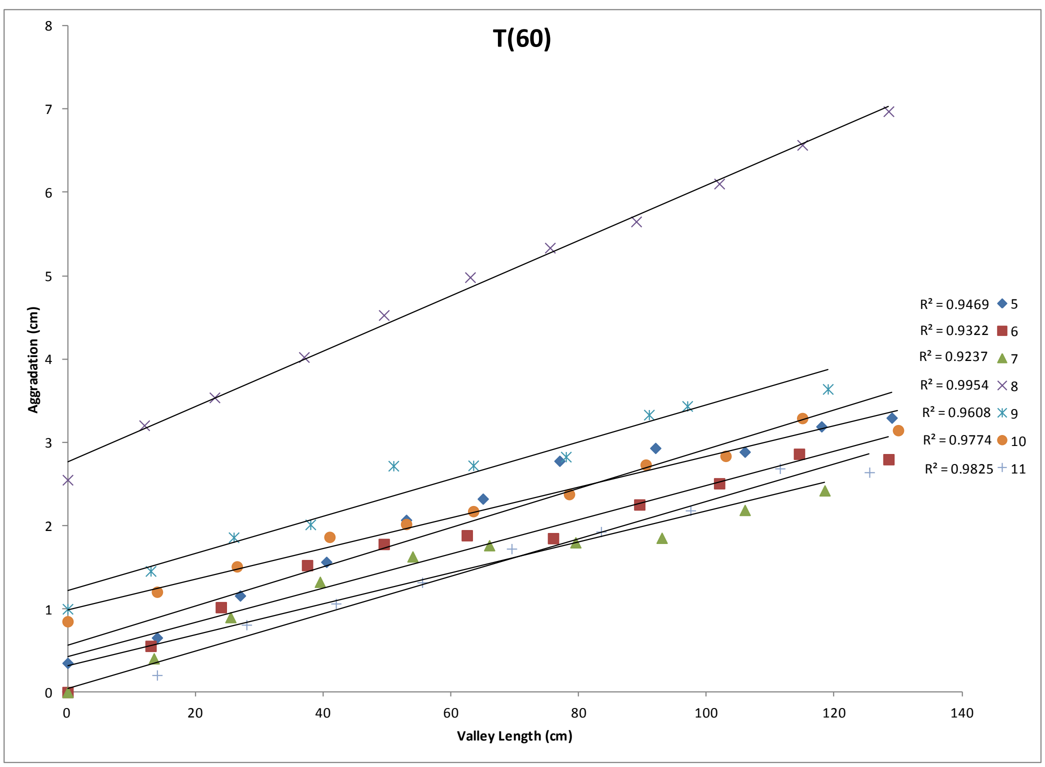

Figure C4: Valley length against aggradation 60 minutes after experiment initiation.

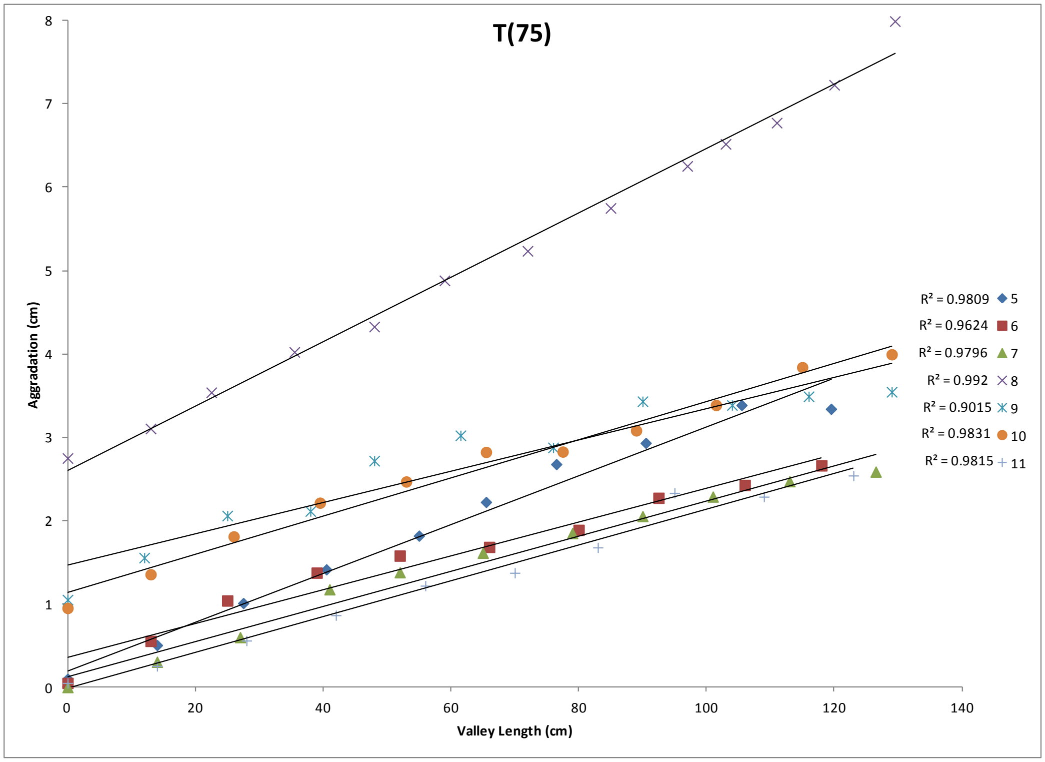

Figure C5: Valley length against aggradation 75 minutes after experiment initiation.

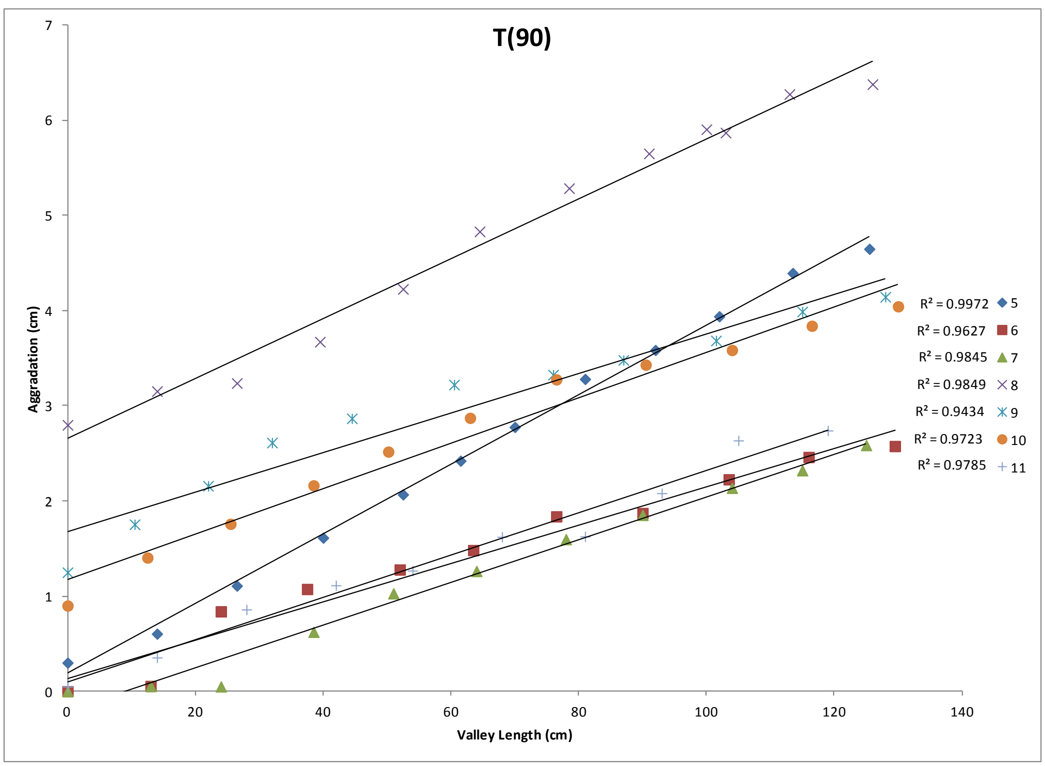

Figure C6: Valley length against aggradation 90 minutes after experiment initiation.

APPENDIX D

D Static Channel Experiments: Valley Length vs. Floodplain Width

Figures in Appendix D contain results from the static channel experiments. The following plots in Appendix D compares width of the floodplain against down valley distance. Each graph represents data taken at specific time intervals. The series in each of the graphs represent different experiments (eg. Series 5 = Experiment 5). The solid red line in the figures represents the “plateau” discussed in the text.

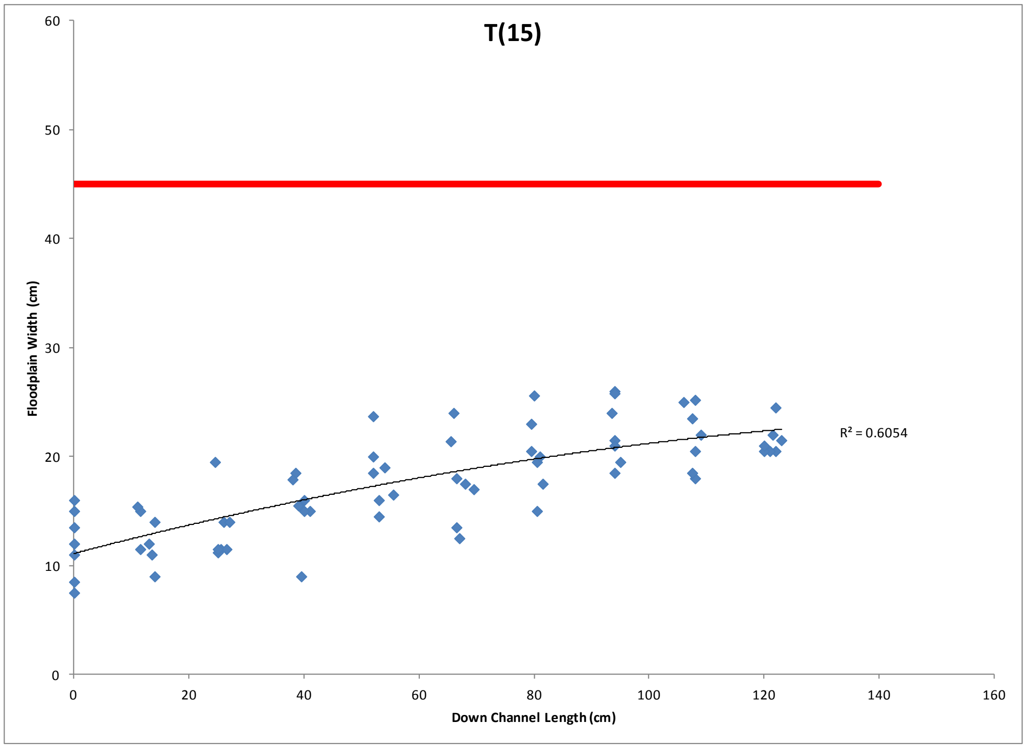

Figure D1: Valley length against floodplain width 15 minutes after experiment initiation.

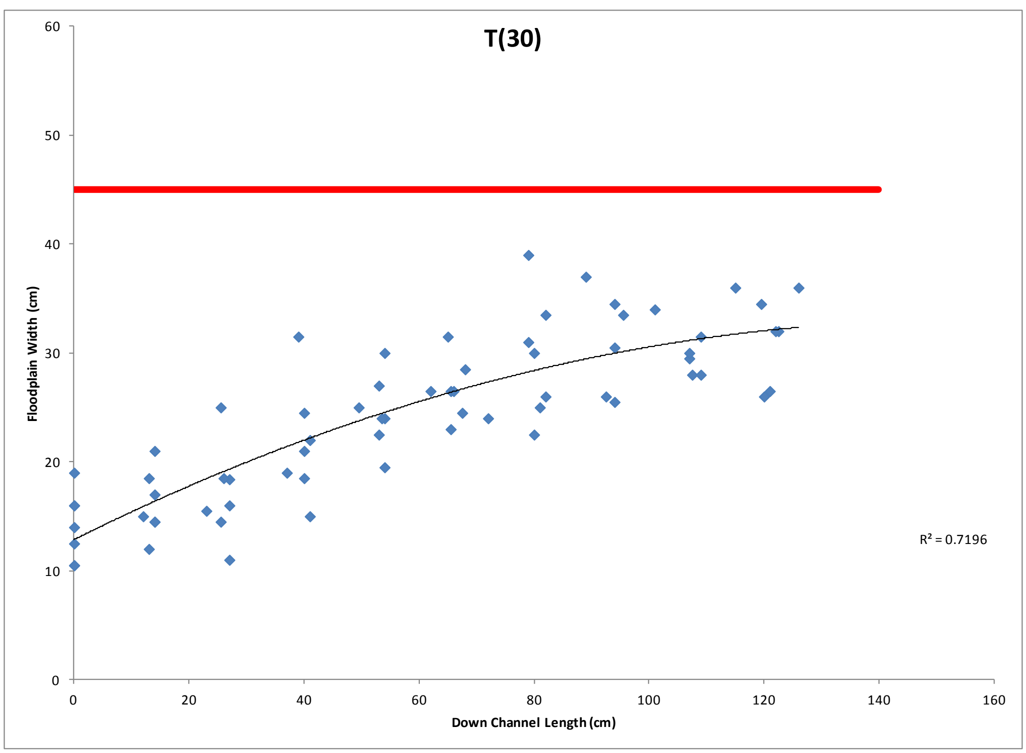

Figure D2: Valley length against floodplain width 30 minutes after experiment initiation.

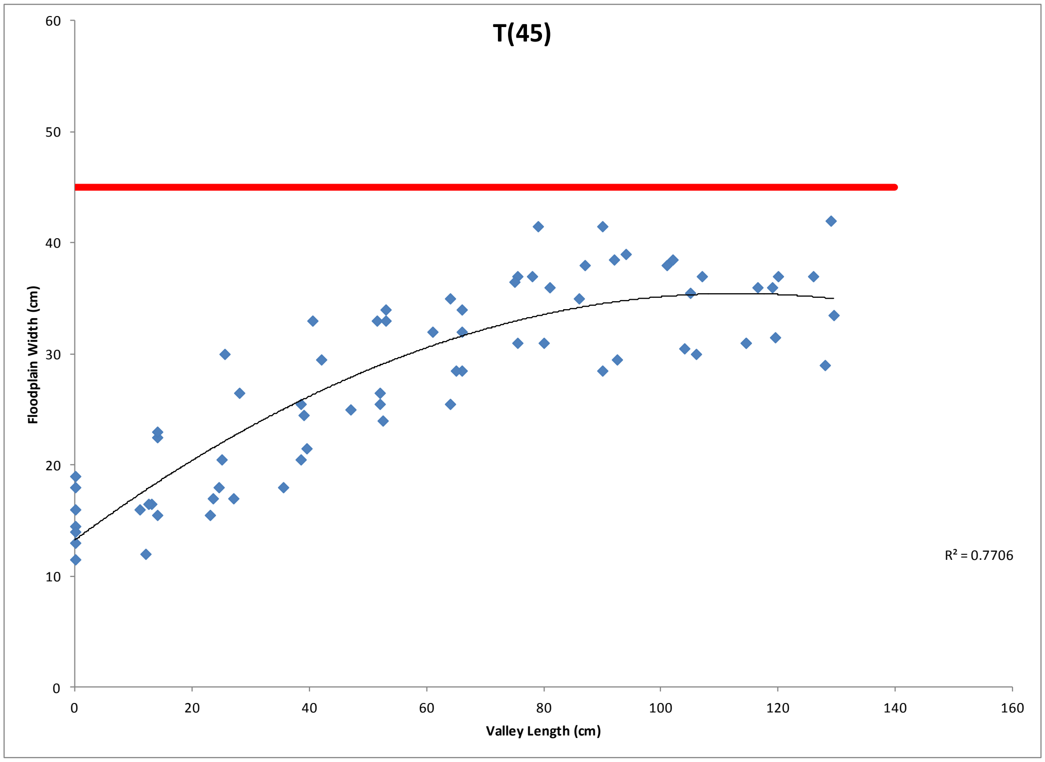

Figure D3: Valley length against floodplain width 45 minutes after experiment initiation.

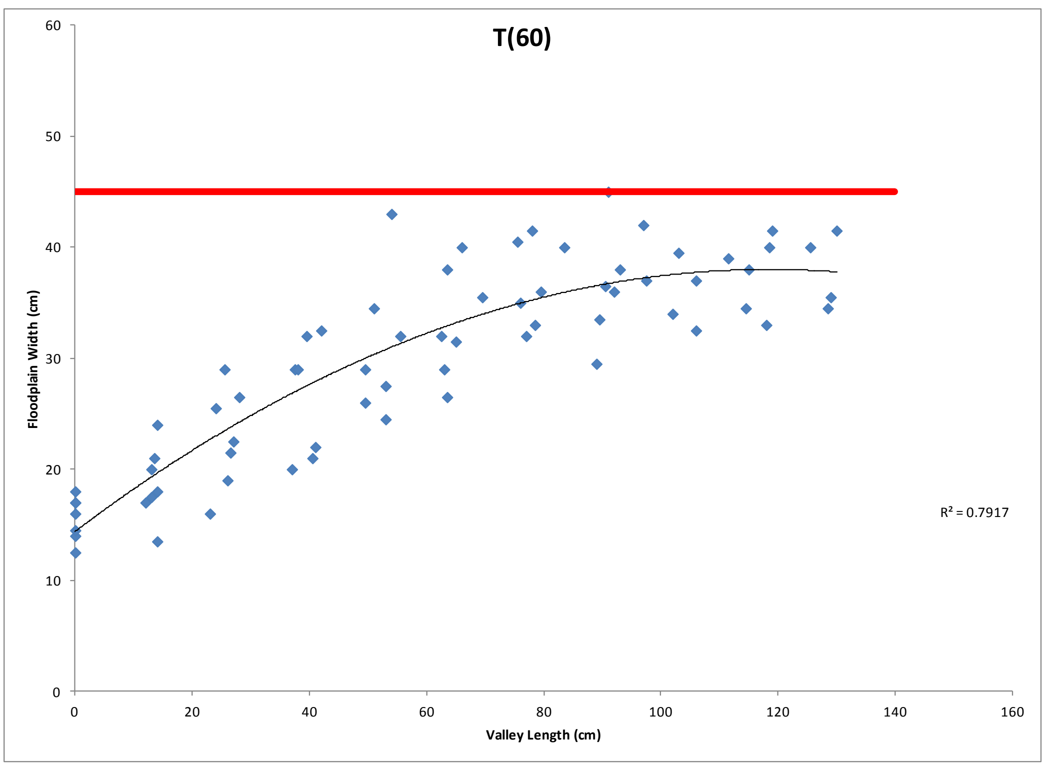

Figure D4: Valley length against floodplain width 60 minutes after experiment initiation.

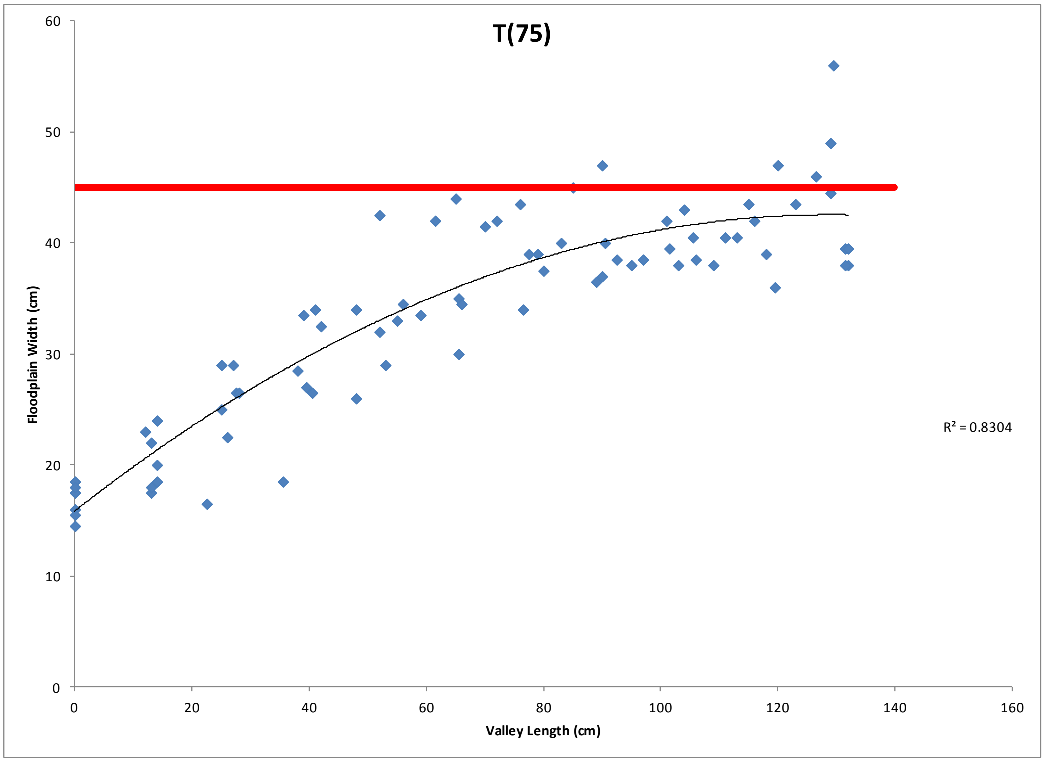

Figure D5: Valley length against floodplain width 75 minutes after experiment initiation.

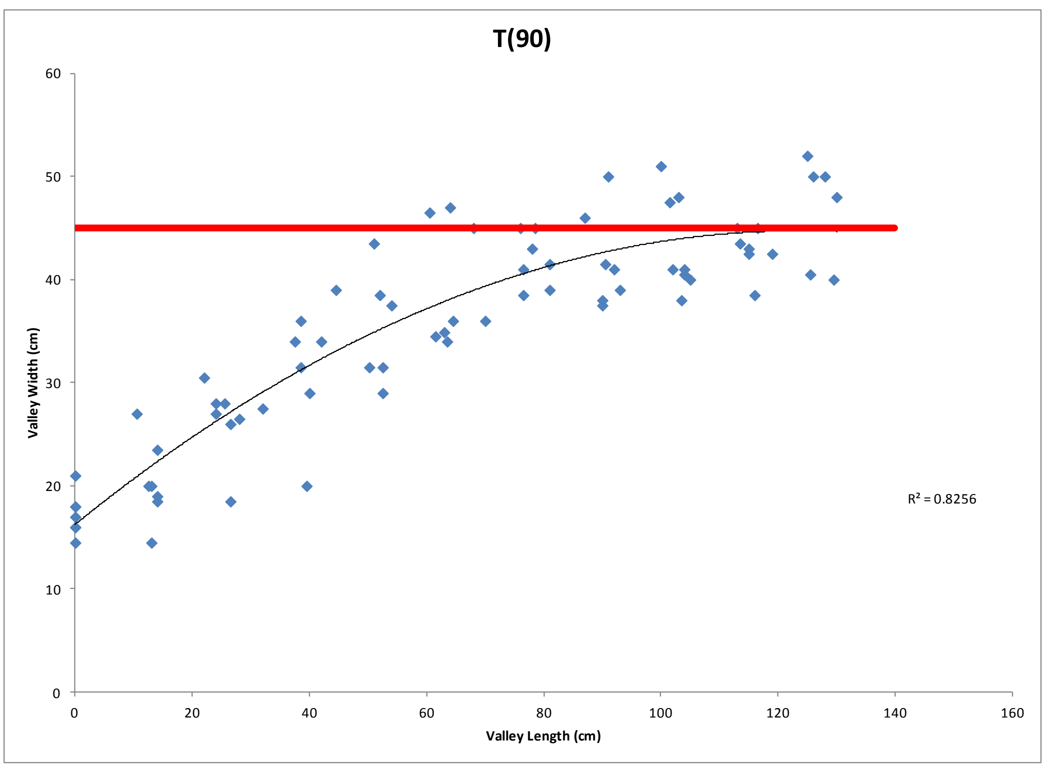

Figure D6: Valley length against floodplain width 90 minutes after experiment initiation.

APPENDIX E

E Experimental Videos

These are digital videos taken during both the “base level change” and the “lateral tilt” experiments. One video (comprised of four individual files) for each experimental type is available. Please contact author for requests of these files.

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VITA AUCTORIS

Tim Keenan was born in 1983 in St. Louis, Missouri. He graduated from Webster Groves High School in 2002 and received his Bachelor of Science in Geology from Saint Louis University in 2008. Following graduation in 2008, Mr. Keenan worked as a Geologist for Brotcke Well and Pump, a geotechnical drilling company. In the Fall of 2010, Tim enrolled once again at Saint Louis University in pursuit of an M.S. in Geology. Tim is currently resides in Webster Groves, Missouri with his wife Katherine and son Dexter, and will be pursuing a PhD in Geology at Saint Louis University with a focus on Tectonics.