TR-541

THE EFFECTS OF HEADCUT AND KNICKPOINT PROPAGATION ON BRIDGES IN IOWA

Final Report

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Iowa Department of Transportation, Highway Division
Iowa Highway Research Board
800 Lincoln Way
Ames, Iowa, 50010

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16. ABSTRACT

The overarching goal of the proposed research was to provide a predictive tool for knickpoint propagation within the HCA (Hungry Canyon Alliance) territory. Knickpoints threaten the stability of bridge structures in Western Iowa. The study involved detailed field investigations over two years in order to monitor the upstream migration of a knickpoint on Mud Creek in Mills County, IA and identify the key mechanisms triggering knickpoint propagation. A state-of-the-art laser level system mounted on a movable truss provided continuous measurements of the knickpoint front for different flow conditions. A pressure transducer found in proximity of the truss provided simultaneous measurements of the flow depth. The laser and pressure transducer measurements led to the identification of the conditions at which the knickpoint migration commences. It was suggested that negative pressures developed by the reverse roller flow near the toe of the knickpoint face triggered undercutting of the knickpoint at this location. The pressure differential between the negative pressure and the atmospheric pressure also draws the impinging jet closer to the knickpoint face producing scour. In addition, the pressure differential may induce suction of sediment from the face. Other contributing factors include slump failure, seepage effects, and local fluvial erosion due to the exerted fluid shear. The prevailing flow conditions and soil information along with the channel cross-sectional geometry and gradient were used as inputs to a transcritical, one dimensional, hydraulic/geomorphic numerical model, which was used to map the flow characteristics and shear stress conditions near the knickpoint. Such detailed flow calculations do not exist in the published literature. The coupling of field and modeling work resulted in the development of a blueprint methodology, which can be adopted in different parts of the country for evaluating knickpoint evolution. This information will assist local government agencies in better understanding the principal factors that cause knickpoint propagation and help estimate the needed response time to control the propagation of a knickpoint after one has been identified.

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1. INTRODUCTION

1.1 Problem Statement

Over the last century, the severity of channel erosion in the Deep Loess Region of western Iowa has increased due to channelization of the stream corridor and intensive agriculture, coupled with the highly erodible loess soils. The persistent down-cutting and widening of the channels have formed canyon-like systems. In these "hungry canyons", as termed by local residents, an estimated 450 million metric tons of sediment are eroded annually from nearly 480,000 km of channel reaches in the Midwestern United States (Baumel, 1994). A local example of the problem is the silt-bedded West Tarkio Creek in western Iowa (Figure 1), where channel degradation has yielded an estimated loss of 147,000 metric tons/year resulting in a 6-m increase in channel depth (Simon, 1992).

Figure 1. West Tarkio Creek in western Iowa. The steep banks are a reflection of the severe down-cutting of the channel in this system.

Channel erosion in Midwestern streams has produced severe damage (on the scale of $1.1 billion) to highway and county road infrastructure from scour around bridge piers, pipelines, and fiber-optic lines, as well as loss of farmland adjacent to the channels due to stream bank collapses (Baumel, 1994). Government agencies, including the Hungry Canyons Alliance (HCA) and Iowa Department of Transportation (IDOT), have constructed more than 700 weirs, flumes, and other types of grade control structures in western Iowan streams to stabilize the channel reaches and prevent further damage to downstream infrastructure. However, channel degradation is expected to continue in western Iowa due to several factors including the lack of alluvial sand delivery and freeze/thaw mechanisms (Simon and Rinaldi, 2000).

This ongoing channel degradation occurring in western Iowa and the high likelihood of further damage to downstream infrastructure prompts the following questions:

1. Is further channel degradation preventable?
2. Is channel degradation a predictable process?
3. What monitoring methods can most accurately predict channel degradation?
4. Can researchers and engineers develop a reliable model based on field observations to forecast future channel degradation?

Current efforts by the IDOT, as well as county and city agencies, include routine monitoring of bridges using established procedures and checklists, which have been reasonably effective (http://de.usgs.gov/publications/ofr-96-554). However, a protocol to evaluate the eminent problem of channel degradation is lacking. The primary reason for this deficiency stems from the lack of field-oriented research related to the processes producing channel degradation (May, 1989). To date, laboratory studies, which cannot obtain the morphologic similarity of degrading channels, have been used almost exclusively. Although the available laboratory studies provide an improved insight regarding the mechanisms triggering channel degradation, they do not provide upstream migration rates.

The purpose of this study was to conduct a field-oriented evaluation of the upstream migration rate of a knickpoint, a common form of channel degradation in western Iowa, in a representative channel reach using various methods.

The purpose of this study was to conduct a field-oriented evaluation of the upstream migration rate of a knickpoint, a common form of channel degradation in western Iowa, in a representative channel reach using various methods. The observations recorded in the field study were then implemented into a one-dimensional, hydrodynamic/ sediment transport model developed by the PI, known as the Steep Stream Sediment Transport 1-D model, or 3ST1D, to predict further migration rates. This study will lead to the development of a practical guidebook or manual for the IDOT and County Civil Engineers during bridge monitoring efforts. The guidebook would describe the means, by which bridge waterways deteriorate and bridge foundations fail. This information will assist local government agencies in better understanding the principal factors that cause knickpoint propagation and help estimate the needed response time to control the propagation of a knickpoint after one has been identified.

1.2 Definitions

Streambed degradation occurs in the loess soils of western Iowa by the formation and headward migration of a geomorphologic feature, known as a knickpoint. Ongoing research suggests that knickpoints may account for more than 60% of the erosion in the streams, where they form (Alonso et al., 2002). In addition, preliminary observations suggest that knickpoints greatly influence the flow thalweg (i.e., line of deepest flow) in small rivers, a prime factor contributing to bank erosion and scour.

A knickpoint is a point of discontinuity in bed slope or elevation along the longitudinal stream profile (May, 1989). Two prominent types are primary knickpoints, called headcuts, and secondary knickpoints, simply identified as knickpoints (Figure 2a). Headcuts and knickpoints form in over-steepening stream reaches and, in western Iowa, manifest themselves as short waterfalls, often occurring in series. Flow plunges over the knickpoint, scouring the bed, which leads to cantilever toppling and plunge pool development. Fluid boundary shear, secondary flow currents, seepage, and pore pressure may also contribute to the formation and evolution of headcuts and knickpoints (Clemence, 1987). As the downstream extent of the bed of the tributary channel erodes, the knickpoint is moved upstream. This process of knickpoint upstream migration is illustrated in Figure 2b. For a bed comprised of sandy alluvium, bed erosion and knickpoint movement occur relatively quickly. For a bed formed of cohesive sediment (clay) or soft sedimentary rock, knickpoint movement can be relatively slow but not always. For channel beds formed from sediment that is extensively cohesive, or from rock, the upstream movement of the knickpoint occurs by means of a process called headcutting.

Headcuts are step-changes that occur at the heads of channel networks and may eventually lead to gulley formation within fields (Figure 3; Bennett et al., 2000). Headcuts are fed by ephemeral or intermittent channels and tend to have smaller drainage areas than

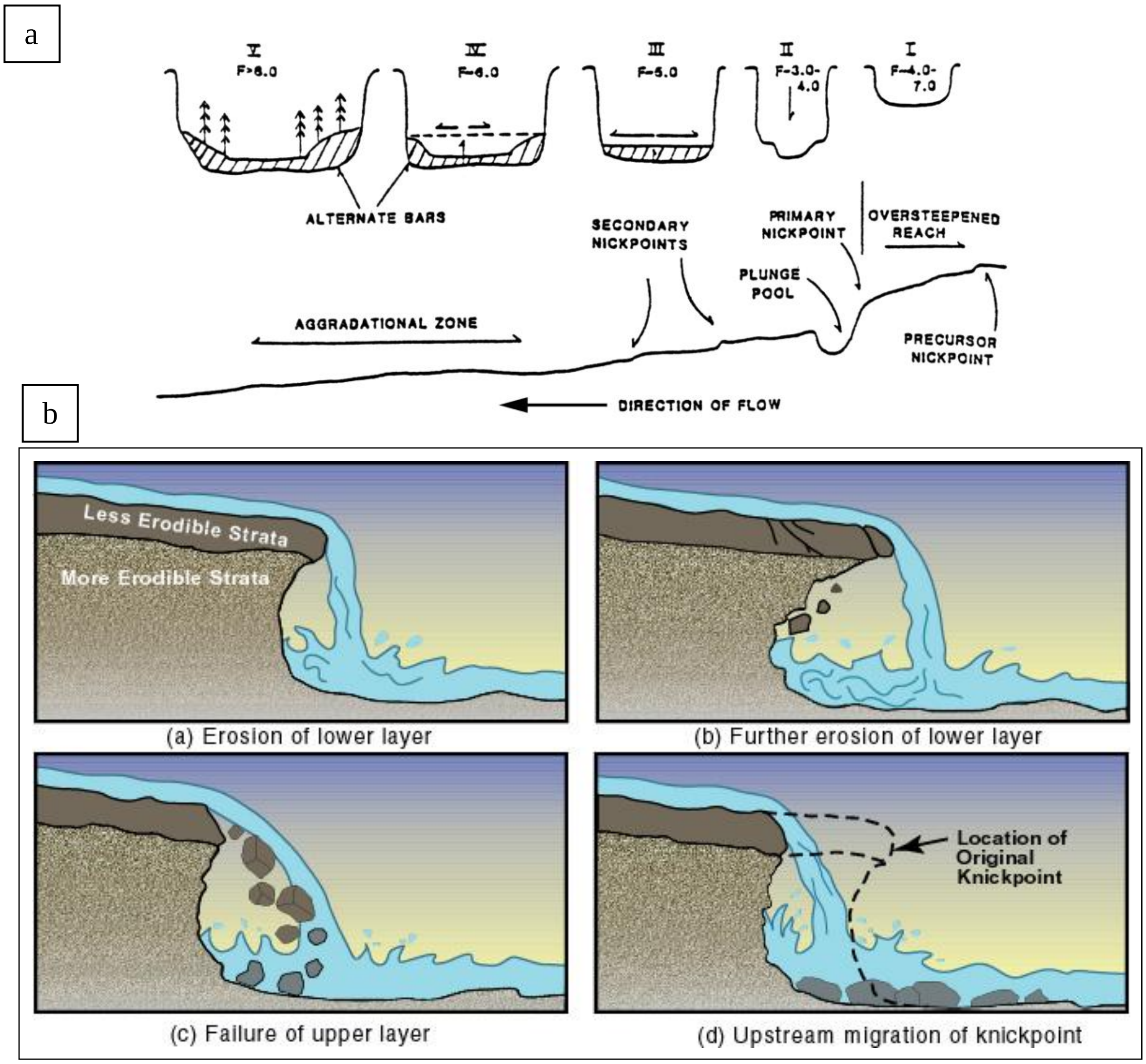


Figure 2. Types of knickpoints. (a) A definition sketch of headcut (primary knickpoint) and knickpoint (secondary knickpoint) formation. (b) A sketch of the steps involved in knickpoint migration.

knickpoints. In addition, headcuts will likely have smaller width to height ratios but will also have longer lifespans than knickpoints (Daniels and Jordan, 1966). Severe headcut occurring in the Fox River in Missouri is shown in Figure 3b. The “grandfather” of headcuts in North America is the Niagara Falls.

A step-change that is confined within the channel banks (Figure 4) is referred to as a knickpoint (Bennett et al., 2000). Knickpoint erosion often follows a particular sequence: gradual scour of a lower, more erosive layer leads to undercutting and, ultimately, collapse of a more resistant capping layer (Figure 2b). There are generally four mechanisms of mass failure observed at knickpoints (May, 1989):

1. Undercutting leading to cantilever toppling,
2. Undercutting leading to tensile failure and toppling,
3. Rafting of material from water entering fractures,
4. Undercutting leading to shear failure.

a

b

Figure 3. Headcut formation. (a) A headcut is shown developing into a gully at Treynor, Iowa. (b) Headcut progression up the Fox River, Missouri.

Once a knickpoint has formed it will continue to advance upstream, eroding the channel bed, lowering the base level for tributary streams, and, if unchecked, eventually affecting the entire watershed. The knickpoint may cease advancing upstream once it reaches a more resistant bed layer, when it has advanced so far upstream that the drainage area does not provide enough runoff to continue the erosional cycle, or if tailwater conditions change downstream.

Several factors that may affect the upstream migration of knickpoints (e.g., Schumm, 1973; Grissinger, 1984; Clemence, 1987; Cameron, 1988; May, 1989) include both geological characteristics (e.g., channel and knickpoint gradient, channel and knickpoint geometries, scour depth, the presence of joints or cracks, as well as bed material characteristics like cohesion, erodibility, density, and homogeneity) and hydraulic variables (e.g., water discharge, shear stress, angle of impinging flow into the scour hole, conditions under the nappe, negative pore-water pressures, tailwater depth, the presence of upward directed seepage forces on the falling limb of hydrographs).

Figure 4. Knickpoint formation. The circled area is a knickpoint in Mud Creek, Iowa.

The geological controls of knickpoint migration stem from either structural discontinuities, which are products of natural compressive or tensile forces, or stratigraphic discontinuities, which are represented by unconformities, different bedding planes, or changes in sediment structures/textures (May, 1989). Examples of knickpoints in the loess regions of Mississippi are products of stratigraphic discontinuities between the highly erodible loess and more resistant, underlying paleosol (Whitten and Patrick, 1981). Knickpoint migration and associated headcutting are also very common in western Iowan streams like the Boyer River, in Harrison, Crawford, and surrounding counties.

The hydraulic controls of knickpoint migration predominantly influence the angle of the impinging flow, which leads to scour and undercutting of sediments below the knickpoint. Two scenarios, namely the vented and unvented condition (Figure 5), occur under the nappe that affect the impact angle. In the vented condition, pressures under the nappe are equivalent to atmospheric pressure. The impact angle is controlled by the ratio of the knickpoint face height to the critical flow depth atop the knickpoint (May, 1989). When this ratio exceeds 8, the angle between the jet impact and the knickpoint face approaches 90 degrees. As the impinging jet is drawn closer to the knickpoint face, more of the flow is entrained into the reverse roller effect thereby enhancing scour. Under the unvented condition, pressures below the nappe are below atmospheric pressure (May, 1989). This pressure differential also draws the impinging jet closer to the knickpoint face producing scour. In addition, the pressure differential may induce suction of sediment from the face.

In both scenarios, low flows may be more influential on knickpoint erosion than higher flows because it is at these lower flows that the impinging jet is closest to the knickpoint causing more scour (May, 1989). Moreover, the unvented condition tends to produce more scour than the vented condition (May, 1989). During a runoff event, the relative amount of scour changes as the discharge changes (Figure 6), i.e., as flow increases the impinging jet moves further from the knickpoint face thereby decreasing scour. Thus scour most likely occurs at the beginning and end of the runoff events.

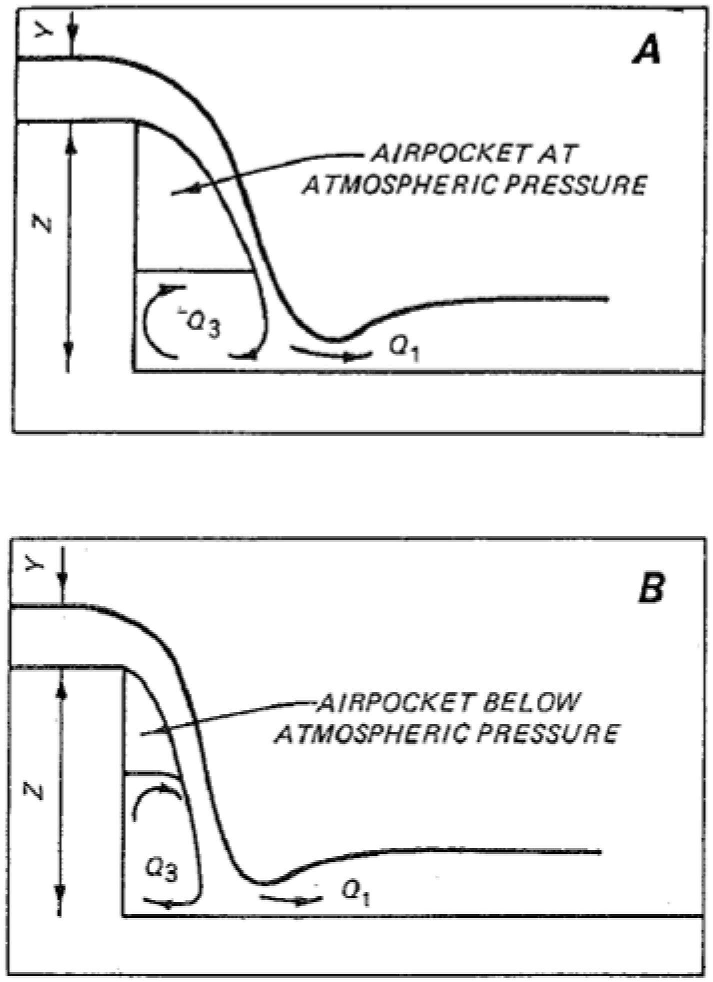


Figure 5. Hydrodynamic forces at a knickpoint. From May (1989). The (A) vented and (B) unvented conditions below the nappe of a knickpoint.

1.3 Previous research

In western Iowa, most knickpoints form in unlithified, cohesive sediments. Previous studies of knickpoints in these environments have been either theoretical or conducted under simplified, scaled-down laboratory conditions.

Theoretical studies of knickpoints in cohesive sediments have focused on the hydraulic forces affecting them. The flow structure upstream of the nappe entry point in the plunge pool has been described as a reverse roller (Robinson et al., 2000b), vortex flow (Frenette and Pestov, 2005), or analogous to a reattached plane turbulent wall jet (Rajaratnam and Subramanya, 1968; Bennett and Alonso, 2006). The origin of the secondary scour occurring upstream of migrating knickpoints has been described based observations of the sensitivity of headcut migration rates to uncertainties in soil erodibility and jet entry angle data (Alonso, 2002). Finally, Parker and

Izumi (2000) demonstrated that supercritical flow often produces a series of knickpoints on an erodible, cohesive bed, rather than a singularity.

The laboratory studies of knickpoints also have provided well documented descriptions of the hydraulic stresses and pressures acting on a headcut under different discharges, drop heights, backwater effects, soil properties, and flow structures (Robinson, 1989, 1992; Robinson and Hanson, 1995, 1996a, b, 2001). The shear stress acting on the headcut was positively correlated to discharge and drop height. The largest stresses to the vertical wall resulted from intermediate backwater levels, with a backwater to overfall height ratio of approximately 0.8 producing maximum headcut migration rates. As soil strength, water content, and density increased, headcut migration rates decreased. Weathering of the headcut between flow events and the exposure of a sand layer underlying a more resistant layer increased migration rates.

Several laboratory studies have analyzed the long-term morphology and stability of migrating knickpoints and headcuts. However, these studies have produced contradictory results. Knickpoints have been shown to reach steady state dimensions (Bennett and Casali, 2001), as well as to grade out over time, thereby being short-lived (Brush and Wolman, 1960; Holland and Pickup, 1976; Stein and LaTray, 2002). In addition, a headcut either may rotate (incline) becoming a riffle reach when potential energy is dissipated over a longer reach over time or maintain a stepped or parallel retreat when potential energy remains concentrated over a limited channel length over time (Stein et al., 1997).

In laboratory flumes, knickpoint retreat was shown to follow three different morphologic models: parallel retreat, replacement, and inclination or toppling (Gardner, 1983). Migration rates have been correlated to soil strength and erodibility parameters of the material (Hanson et al., 1997b, 2001), as well as stream power (Hanson et al., 1997a). Knickpoint migration was shown to continue as long as the channel has the capability to transport eroded sediments (Begin et al., 1980a; Lee and Hwang, 1994).

An extensive literature search provided limited examples of field studies regarding knickpoint migration in unlithified, cohesive sediments. One study conducted in the loess alluvium deposits of Willow Creek, IA (Daniels, 1960) described a knickpoint that migrated upstream 2,819 m over a five-year period. The highest recorded migration (183 m over 4 days) resulted from a single high water event. Knickpoint advancement at this site followed a general process:

1. Undercutting of the vertical face,
2. Development of shear planes in the unsupported sediment,
3. Slumping of the undercut sediment,
4. Re-establishment of the vertical face.

The initial undercutting was caused by a combination of water flowing down the face of the knickpoint, wave action in the plunge pool, and seepage emitting from the saturated sediments at the base of the knickpoint rather than the dryer, less erodible, overlying material. Further studies (Daniels and Jordan, 1966), which measured the advance of 18 headcuts in Thompson Creek, IA, observed that freezing and thawing, in conjunction with runoff, exacerbated annual migration rates.

Extensive observations over 5 years of 11 major knickpoints in the Yalobusha River, MS watershed documented knickpoint migration rates between 0.4 and 16 m/yr, dependent on the parent material (Simon et al., 2000; Thomas et al., 2001; Simon and Thomas, 2002; Simon et al., 2002). Measurements of the critical shear stress and erodibility for the different bed materials demonstrated a discrepancy between observed knickpoint retreat rates and available hydraulic shear stress, which suggested other mechanisms influencing the knickpoint retreat (Simon and Thomas, 2002; Simon et al., 2002), namely:

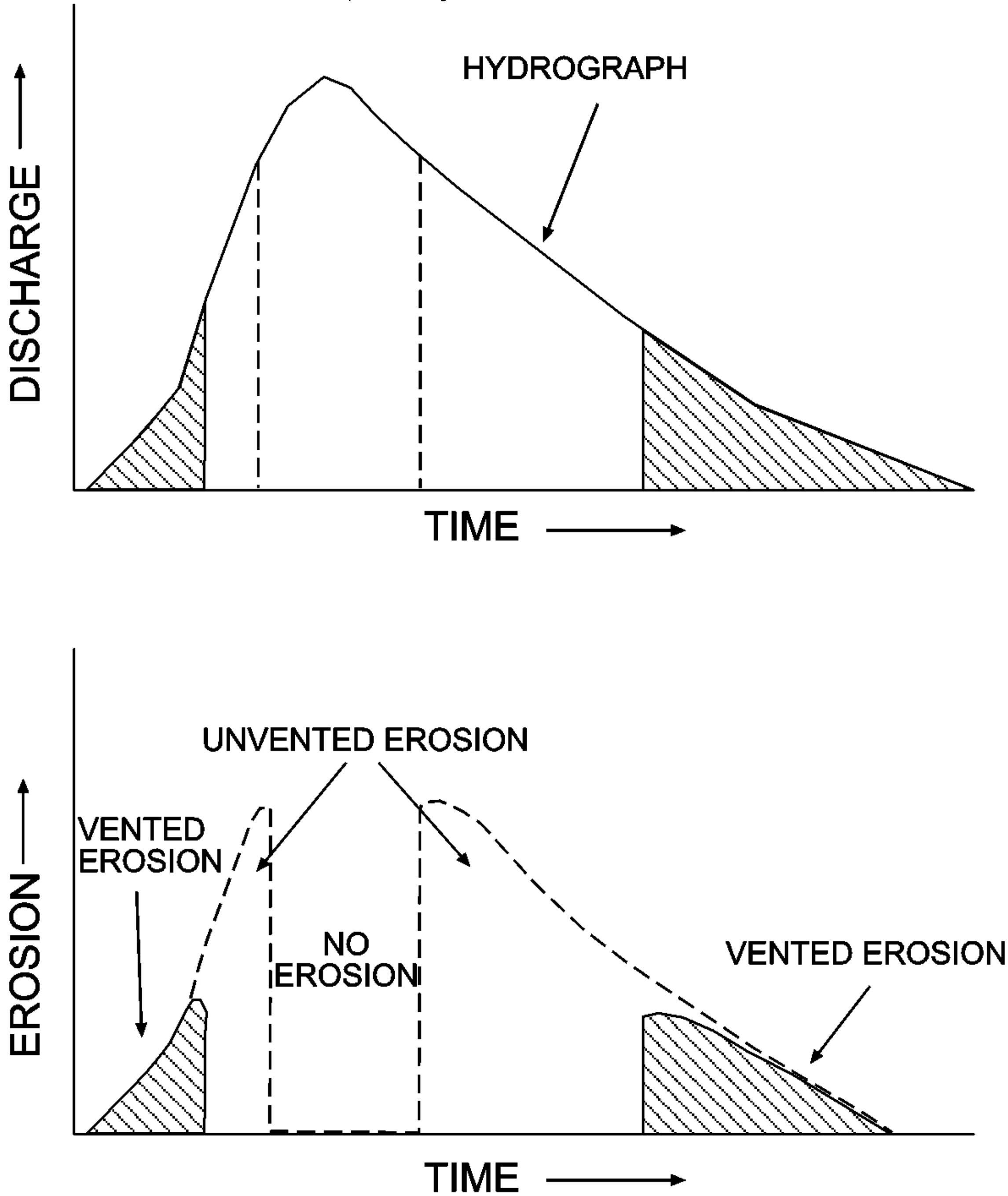


Figure 6. Scour during runoff events. From May (1989). The cross-hatched areas are the times during a runoff event when scour under vented conditions will occur. The dashed areas are conditions when unvented scour most likely will occur.

1. Partial exposure during low-flow periods resulted in weathering and crack formation, including tension cracks on the headwall related to pressure release and stress-induced deformation. Particle-by-particle (or fluvial) erosion widened the cracks during high flow

events. The expanded cracks concentrated low and moderate flows, leaving other areas of the bed exposed to dry and desiccate. Erosion pathways then shifted to the dried, exposed areas of the bed during subsequent flood events.

2. Detachment of aggregates during the falling limb of hydrographs resulted from upward-directed seepage due to a pressure imbalance at the bed surface and the inability of the streambed to dissipate excess pore-water pressure (Simon and Collison, 2001).

3. Upward-directed seepage forces produced static liquefaction in areas with little jointing. Strong upward-directed seepage forces increased the distance between cohesive particles resulting in reduced cohesion and an almost fluidized state (Simon and Collison, 2001);

4. More rapid erosion and migration occurred by a cyclical mass failure mechanism that involved increased hydraulic stresses from the presence of a hydraulic jump and turbulence in the plunge-pool undercut the knickpoint face, followed by cantilever or planar mass-failure of the knickpoint face with deposition of the failed material in the plunge pool, which facilitated the removal of this debris exposing the face to more scour and future failure.

> The overarching objective of the study is to develop predictive tools for knickpoint migration and help engineers in monitoring, maintaining, and protecting bridge waterways so as to mitigate or manage scour occurring at the bridge structures.

The relative dominance of the four above mechanisms was a function of the hydraulic and geotechnical resistance of the cohesive material, as well as the nappe structure, tailwater depth, and flow stage. For example, during periods of low tailwater, a steep hydraulic gradient formed within a knickpoint scour hole, which exacerbated seepage and undercutting. During periods of high tailwater, knickpoint erosion by mass failure was less likely because of the confining pressure afforded to the knickpoint face meaning erosion was probably dominated by particle-by-particle shear erosion enhanced by upward-directed seepage forces.

1.4 Objectives

The objectives of this project were twofold:

1. To conduct a semi-automated, field-oriented evaluation of a knickpoint on Mud Creek in Mills County, IA using various methods of monitoring to determine the upstream migration rate of the knickpoint.

2. To implement the collected data into a one-dimensional, hydrodynamic/ sediment transport model, known as 3ST1D, to predict further migration rates.

The goal of these objectives was to provide a reliable method and ultimately a comprehensive and practical manual that will substantially help engineers in monitoring, maintaining, and protecting bridge waterways so as to mitigate or manage scour occurring at the bridge structures.

2. METHODOLOGY

Different methods were employed to evaluate both geotechnical and hydraulic parameters, in order to determine the upstream migration of the Mud Creek knickpoint. The study reach was monitored from Spring 2007 through Summer 2008. Methods included grain size analysis of the bed and bank material, stage and flow discharge measurements, bi-annual surveys of the reach from the bridge through the downstream scour hole of the knickpoint, and daily monitoring of water elevations at the knickpoint using a remotely-mounted state-of-the-art laser.

2.1 Site description

This study focused on a single knickpoint in Mud Creek (HUC12: 102400020505), which is a tributary of the West Nishnabotna River (Figure 7). The Mud Creek watershed covers approximately 97.5 km^2 in Pottawattamie and Mills Counties in the Deep Loess Region of western Iowa. The creek flows southerly 25.75 km through a predominantly agricultural landscape (Figure 7). The knickpoint is approximately 4.44 km above the confluence with the West Nishnabotna River.

The quaternary geology for the watershed is described as Wisconsin loess on Sangamon paleosol in Illinoisan Drift (Ruhe, 1969). Wind-blown loess from the Wisconsin glaciation period (i.e., most recent glaciation) overlain the Sangamon paleosol, which developed in the glacial drift plain of the Illinois glaciation (i.e., second youngest period). Loess is unstratified and unconsolidated silt-sized particles, where as glacial drift consists mainly of larger rock material carried with the glaciers. The base of the loess can be as much as 10 m deep in this area and is approximately 24,000 years old, where the loess summits are 14,000 years old (Ruhe, 1969). The Sangamon paleosol tends to be lighter in color and contain more clay (~ 35%) than the overlying, darker Wisconsin loess (~27%). In addition, the Sangamon paleosol is also less erodible than the loess (Ruhe, 1969).

Three soil series encompass 72% of the drainage area of Mud Creek (Figure 8). These three series (Marshall, Exira, Ackmore-Colo-Judson) transition across the landscape from the uplands to the floodplains. The Marshall series is characterized as loess-derived, well drained, upland soils. Marshall soils are silty clay loams with 2 to 4% organic matter (Nixon, 1982). Soils in the Exira series are similar to those in the Marshall series (Nixon, 1982); however, they are found lower on the landscape. The Ackmore-Colo-Judson Series is in the bottomlands and floodplains. These soils are silt loams to silty clay loams with high organic matter content (3 to 7%) and are primarily derived from alluvium (Nixon, 1982). The Ackmore and Colo series contain somewhat poorly to poorly drained soils, while the Judson series has soils that are moderately well drained (Nixon, 1982). The soils immediately adjacent the knickpoint study area belong to the Nodaway soil series (Figure 8). These soils are similar to those in the Ackmore series but are moderately well drained (Nixon, 1982). The Nodaway series is mainly in the lower part of the watershed, comprising only 2% of the total drainage area, and lies along the channel.

Due to the mid-continental location of Iowa, its climate is characterized by hot summers, cold winters, and wet springs (Ruhe, 1956). Summer months are influenced by warm, humid air masses from the Gulf of Mexico. In southwestern Iowa, the average summer temperature is 30^{o}

C. Dry Canadian air masses dominate the winter months and the average daily temperature near

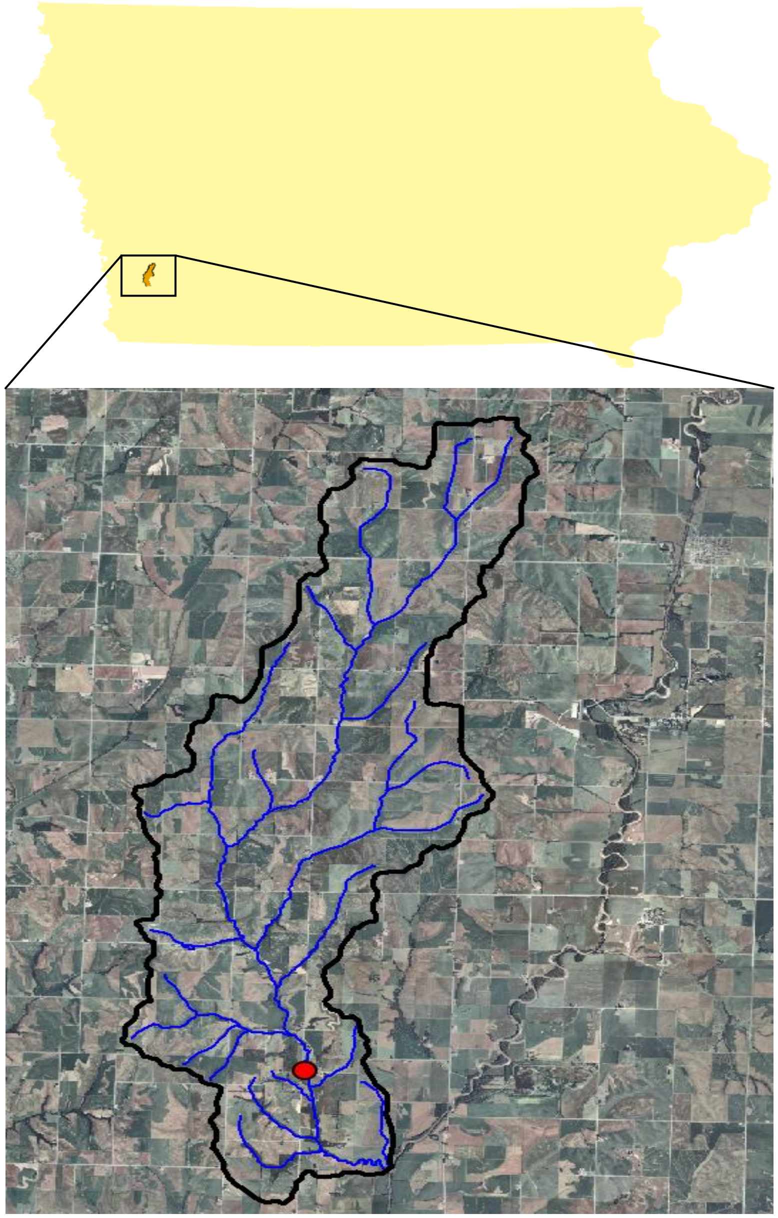


Figure 7. Study Site. Mud Creek, IA is a HUC-12 watershed in southwestern Iowa. The red circle is the focal point of this study.

the study site is about -4^{o} C. The growing season lasts about 162 days in southwestern Iowa. Average annual precipitation is approximately 846 mm/yr with convective thunderstorms prominent in the summer and snowfall in the winter, which averages 813 mm annually. The majority (75%) of the precipitation falls between April and September. There are, on average, 54 days per year with precipitation amounts exceeding 2.5 mm. This data was compiled from National Weather Service (http://www.crh.noaa.gov/oax/) and Iowa Mesonet websites (http://mesonet.agron.iastate.edu/).

The knickpoint (Figure 9) that was the focus of this study was located in northeast Mills County (N41^{O}05’51’’, W95^{O}31’00’’). The knickpoint face is currently 112 m from the Elderberry Rd. Bridge that crosses Mud Creek. At baseflow, the channel at the current knickpoint face is 4.8 m wide, and the average depth at the pressure transducer, which is 20 m upstream of the knickpoint face, is 30 cm. A sheet pile weir with grouted limestone riprap cascades is approximately 50 m upstream of the current knickpoint face. The channel banks along the reach from the bridge through the knickpoint scour hole are between 4 and 5 m high. The scour hole behind the knickpoint face has two levels. The bed elevation drop from the top of the knickpoint face to the first level has an average change of 0.14 m and a maximum change of 0.34 m. The bed elevation drop from the first level to the second level has an average change of 0.66 m and a maximum change greater than 1.01 m. The length of the first level averages 0.68 m.

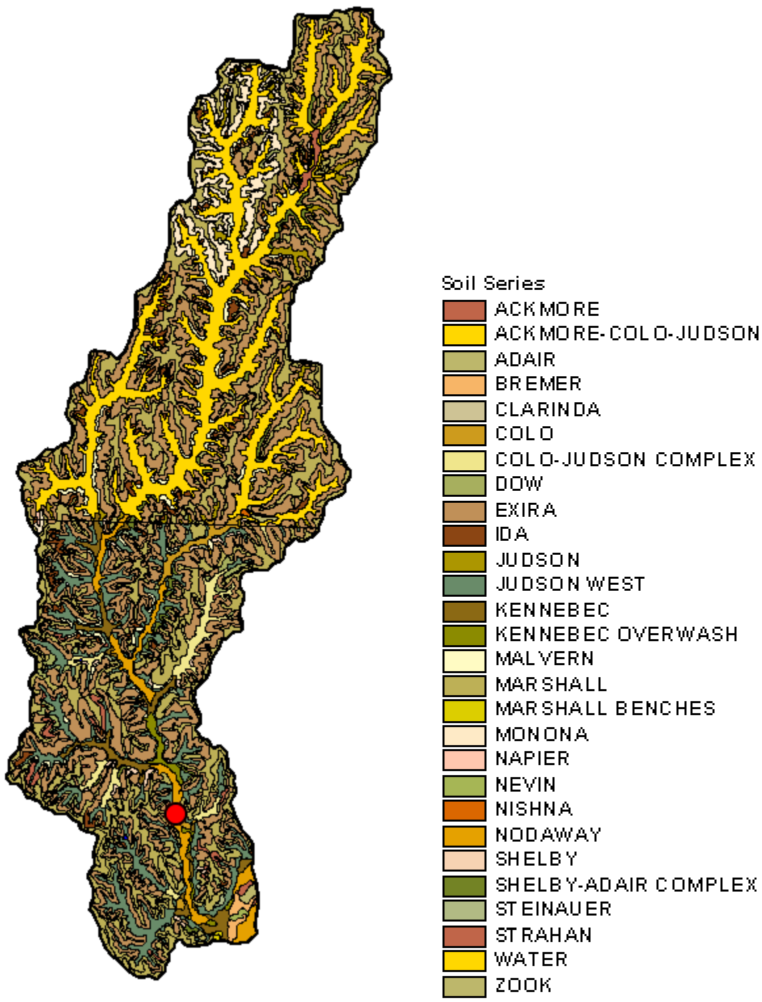


Figure 8. Soils Map. The Mud Creek watershed contains 28 soil series; however, three series cover 72% of the watershed.

2.2 Grain size analysis

Samples of the top 10 cm of both the bank soils and bed sediments were collected along the study reach of Mud Creek (Figure 10). The particle size distributions of these representative samples were determined using standard methods (Singer and Janitzky, 1986). A sub-sample of 50 g was dispersed using a 35.7 g of $(NaPO_3)_6$ per liter of deionized water solution in a ratio of 1 mL of solution: 1 g of sample. The sample was then passed through a 63-µm sieve to remove the sand-sized particles. The filtrate was placed in a 1-L graduated cylinder, stirred, and allowed to settle. A hydrometer was placed in the cylinder and the density of the mixture was periodically recorded to determine the relative proportions of silt and clay. The hydrometer method is based on the settling velocity determined using Stokes Law.

Figure 9. Knickpoint at study site. The knickpoint in Mud Creek below the Elderberry Rd. Bridge was the focal point of this study.

Figure 10. Bed and Bank Sampling. Samples of the stream bed and channel banks were collected for geotechnical analysis.

2.3 Stage – Pressure transducers

A submersible pressure transducer was installed 20 m upstream of the current knickpoint face to monitor water level, or stage, during the study period (Figure 11a). The pressure transducer was mounted in a stilling well 10 cm above the streambed. At this depth, the pressure transducer was submerged during the entire study period. The stilling well was approximately 60 cm from the channel bank amid four fence posts that were sunk into the stream bed to limit the impact of debris flowing downstream during runoff events (Figure 11b). The pressure transducer was connected to a self-contained datalogger, which was mounted atop the bank, through a vented cable (Figure 11c). The vented cable allowed for equilibration with atmospheric pressure. The datalogger recorded the pressure of water above it at hourly intervals. This pressure was linearly related to the stage.

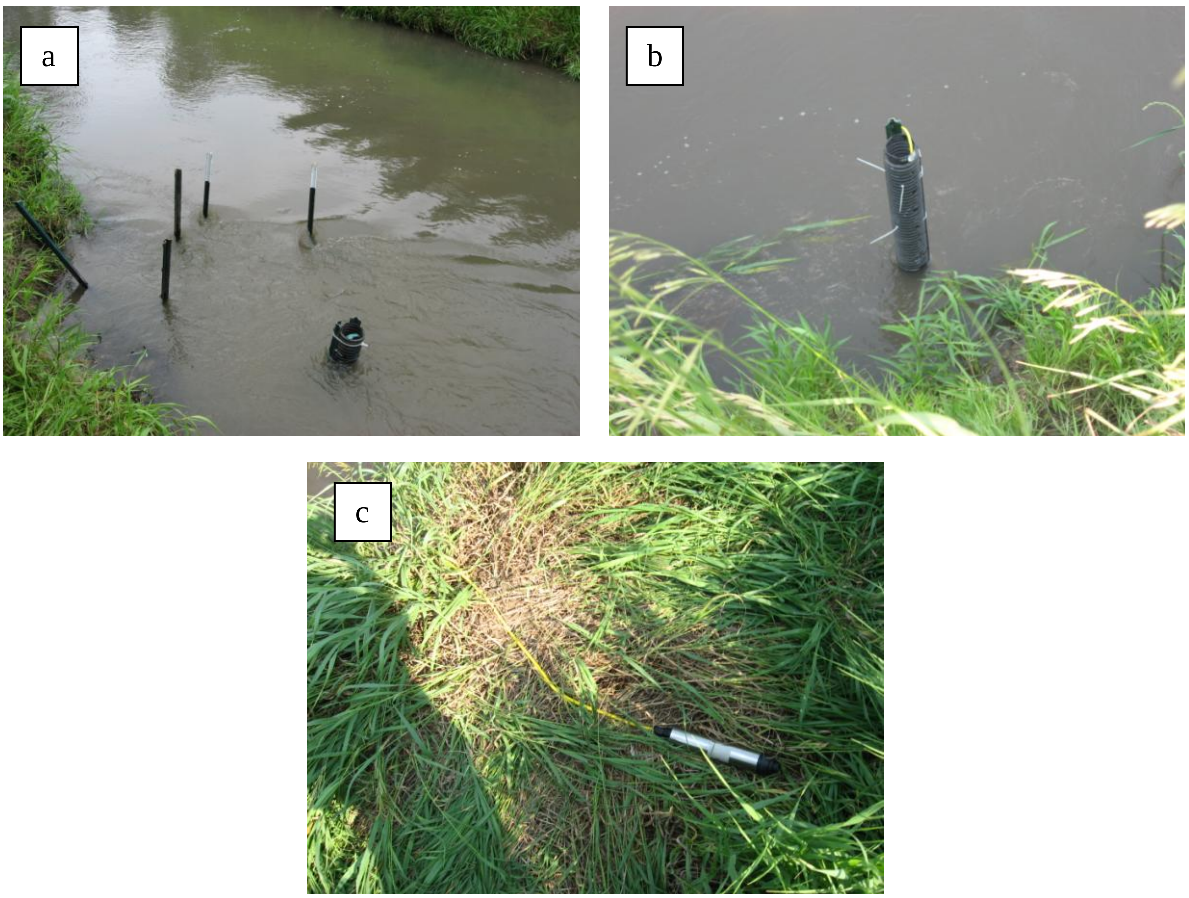


Figure 11. Pressure transducer. (a) Close up of the stilling well. (b) Pressure transducer installed in a stilling well among T-posts. (c) Enclosed datalogger that is attached to the pressure transducer.

2.4 Flow velocity – Rating curves

Flow velocity and discharge at low flows were measured at the knickpoint site using an Acoustic Doppler Velocimeter (ADV) FlowTracker (Figure 12). The ADV FlowTracker was attached to a wading rod to obtain point velocity measurements. These point velocity measurements were summed across a channel transect to determine flow discharges based on standard US Geological Survey methods (Buchanan and Somers, 1969). The ADV FlowTracker has a velocity range: ± 0.001 m/s to 5 m/s (0.003 to 16 ft/s) and an accuracy ±1% of the measured velocity. It transmits to a datalogger attached to the instrument making it suitable for extensive field measurements.

Figure 12. FlowTracker. Velocity measurements using a FlowTracker are needed to develop a stage-discharge rating curve.

At higher flows, Large-Scale Particle Image Velocimetry (LSPIV) was used to measure flow velocities and discharges (Figure 13a). LSPIV measures the free surface velocity based on the concept of pattern recognition used in human vision. Velocity vectors over an area are obtained by estimating displacements of floating fluid-markers using inexpensive video equipment and a geodetic survey to describe the region of interest (Figure 13b). The video images were subsequently digitized and processed using a commercial particle image velocimetry program (LSPIV2), which calculates the 2-D flow field on the water surface as a function of time. In conjunction with bathymetry data, the program estimated the flow discharge.

The evaluated discharges from these two methods can be related to stage from the pressure transducer to develop a flow-rating curve. From the rating curve, discharge can be determined for the whole study period based on the continuous flow record from the pressure transducers.

2.5 Surveys

Bi-annual surveys of the channel topography in the study reach were collected using a total station (Figure 14). These surveys were conducted in early Summer 2007, Fall 2007, Spring 2008, and late Summer 2008. All surveys were referenced to the Elderberry Rd. Bridge and projected in similar planes. Comparisons of these periodic surveys were helpful in determining changes in the knickpoint geometry and overall migration rates during the period of interest. In addition, the surveys provided geodetic information regarding streambed gradients and plunge pool scour depths.

a

b

Figure 13. LSPIV. (a) The LSPIV truck collects video imagery of seeded particles in the stream to determine the free surface velocity. (b) Seeding of the stream with eco-safe mulch for LSPIV measurements.

2.6 Laser

A state-of-the-art laser distance level was mounted above the stream width to measure the distance from a fixed datum to the water surface for an establish area that centered on the knickpoint face (Figure 15a). A 12.19-m long radio antenna truss that spanned the width of the channel was mounted atop a rail system. The top of the rails was 3.96 m above baseflow. The laser (Figure 15b) was suspended from the underside of the truss to another set of rails and was moved across the truss by a pulley system. The laser emitted pulses at a rate of 250 Hz to determine distances. These measurements were averaged every minute. The laser had a resolution of 1 mm and accuracy of 2 cm. The laser was held above established points on a grid over the knickpoint area for two full minutes (Figure 16). Measurements were collected almost daily for three months from June until September 2008. These measurements provided exact positions of the top of knickpoint and scour hole.

Figure 14. Survey of the knickpoint. Bi-annual surveys of the channel morphology were conducted at the knickpoint study site.

2.7 3ST1D

Using the information gathered in the field, the Steep Stream Sediment Transport 1-D model (3ST1D; Papanicolaou et al., 2004) was used to model knickpoint erosion and predict future upstream migration. The model, 3ST1D (Figure 17), is generally used to calculate flow and sediment transport in steep mountain streams and is applicable to unsteady flow conditions that occur over transcritical flow stream reaches (i.e., subcritical to supercritical) such as flow over step-pool sequences or knickpoints. 3ST1D consists of two coupled components, the hydrodynamic and the sediment transport. The flow component in 3ST1D is addressed by solving the unsteady form of the Saint-Venant equations. The Total Variation Diminishing Dissipation (TVD)-MacCormack scheme, which is a shock-capturing scheme capable of rendering the solution oscillation free, is employed to approximate the hydrodynamic solution over the knickpoint face. The sediment component of the model accounts for multifractional sediment transport and incorporates a series of various incipient motion criteria and frictional formulas applicable to cohesive sediment beds (Sanford and Papanicolaou, 2005). In addition, sediment entrainability is estimated based on a state-of-the-art formula that accounts for the bed porosity, turbulent bursting frequency, probability of occurrence of strong episodic turbulent events, and sediment availability in the unit bed area. Thus, 3ST1D is one of the few models that can be used accurately in this study for testing different scenarios. It will prove useful for additional studies at other knickpoints in the state.

For simplification, the numerical simulation of a single knickpoint located within a 120 m stream reach was examined using hypothetical flow events with different magnitudes. The initial and boundary conditions for each case included the flow discharge, Q, (ranging between 0.1 – 50 m^3/s) at the upstream end of the stream reach and the depth, H, (ranging between 0.5 – 2.1 m) at the downstream end of the reach. The three following scenarios were simulated using 3ST1D:

1. The initial channel profile contained a single knickpoint and the channel bed was fixed so that there was no sediment transport or knickpoint migration. This scenario allowed for simulation of the hydraulic conditions (depth and velocity) occurring in the vicinity of the knickpoint.

2. The initial channel profile was flat but the bed sediments were allowed to move. The scenario evaluated the conditions for the development of the knickpoint.

3. The initial channel profile contained a small step on the bed profile representing the frontal face of the knickpoint. This scenario was used to evaluate the propagation of the knickpoint.

a

b

Figure 15. Laser Truss. (a) Measurements of the water surface were conducted at the knickpoint using a laser suspended from a radio antenna truss. (b) Laser level to measure distance from a fixed datum to the water surface.

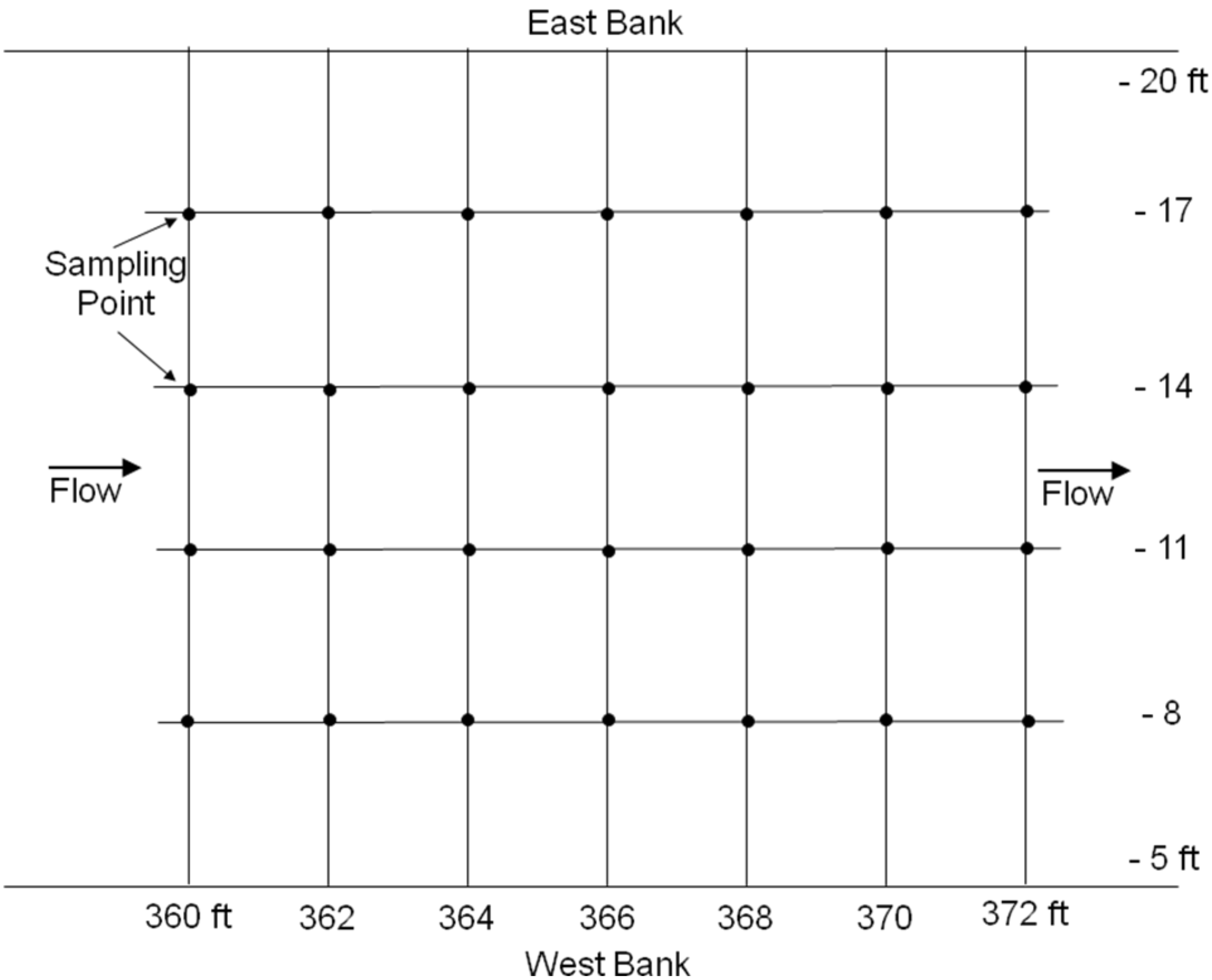


Figure 16. Laser measurement grid. A grid was developed to provide repeatable measurement locations for the laser level suspended over the knickpoint.

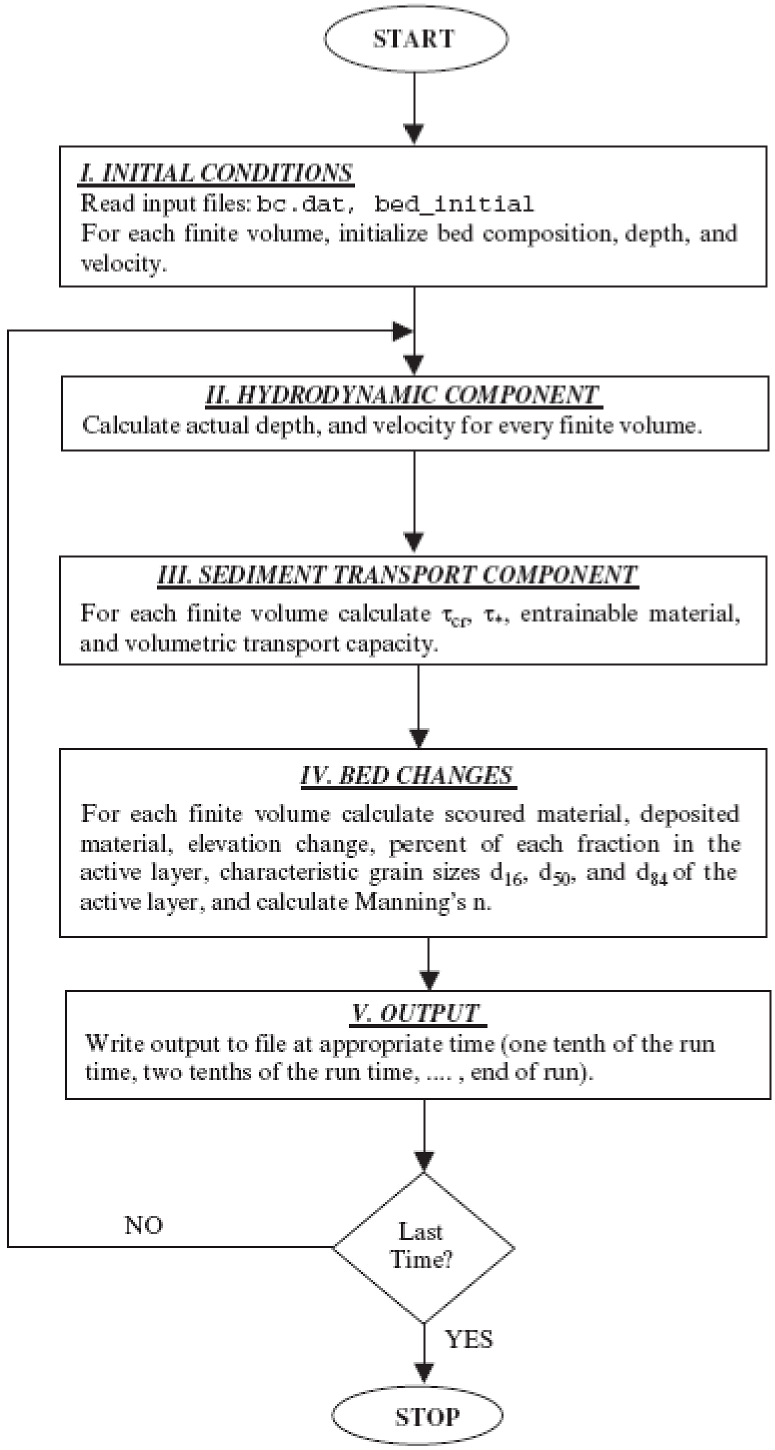


Figure 17. 3ST1D. From Papanicolaou et al. (2004). A flowchart showing the structure of 3ST1D, the model used to evaluate knickpoint formation and propagation.

3. RESULTS

3.1 Particle size analysis

The bed and bank sediments from the knickpoint had slightly different particle size distributions. The bed material had slightly more clay (sand: 5%; silt: 61%; clay: 34%) than the bank sediment (sand: 4%; silt: 71%; clay: 25%). Moreover, the bed material appeared lighter in color than the bank sediment (Figure 18). Both the differences in clay content and color correspond with the differences between the Wisconsin loess and Sangamon paleosol (Ruhe, 1969). Moreover, the actual percentages of clay correspond (loess: 27%, paleosol: 35%). More analysis is needed to confirm the origins of the sediment.

Addition visible evidence for supporting a stratigraphic discontinuity at the knickpoint site can be seen in Figure 18, which shows the different sediments, as well as what appears to be a “fault” between the two layers. These findings appear similar to those in the loess region of Mississippi (Whitten and Patrick, 1981).

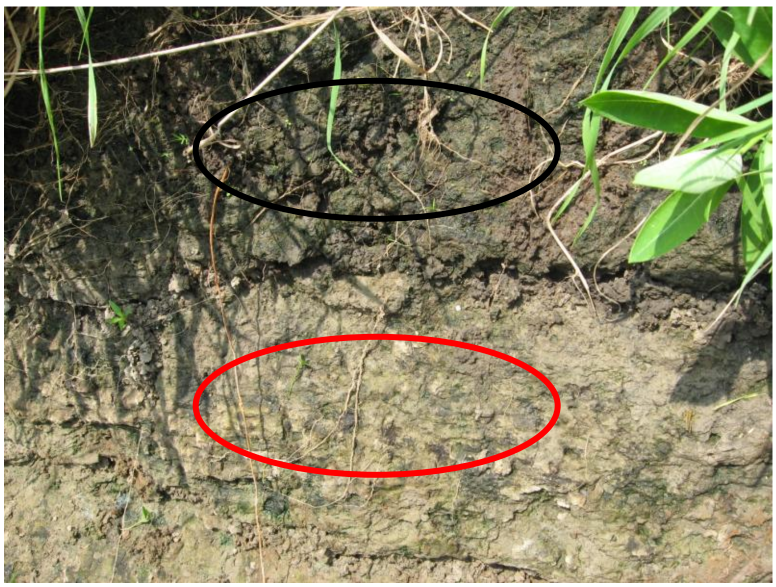


Figure 18. Stratigraphic discontinuity. There appears to be a stratigraphic discontinuity close to the knickpoint with a darker sediment (in the black circle) overlaying a lighter-colored sediment (in the red circle).

3.2 Stage - hydrographs

The total amount of rainfall between June 2007 and November 2007 was 484 mm (Figure 19), which was 37 mm below the annual average amount for this period. Daily precipitation amounts exceeded 25.4 mm on six occasions. The stage hydrograph for the knickpoint reach documented 4 of these runoff events (Figure 19). Another two runoff events occurred in September 2007 when the datalogger was not functioning. The highest recorded stage was 144 cm that resulted from a 63 mm rainfall on Oct. 14, 2007.

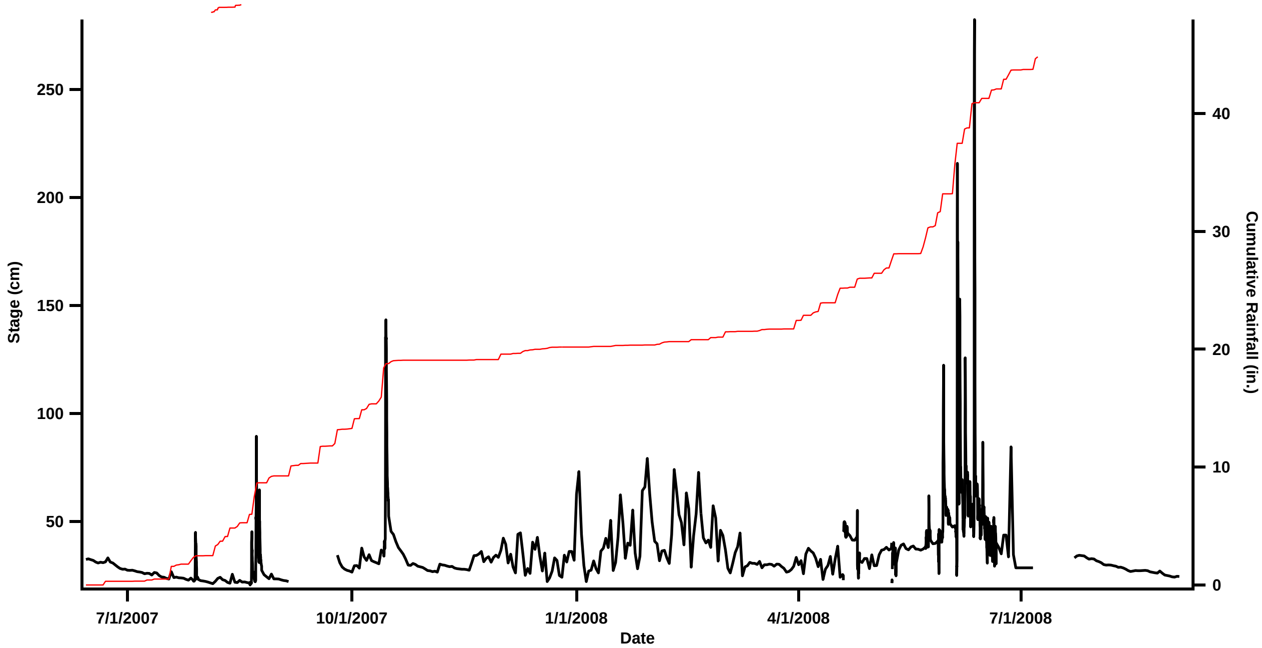


Figure 19. Flow hydrograph. The stage (black line) measured at the installed pressure transducer at the knickpoint study site provided a flow hydrograph for the study period. The cumulative rainfall (red line) is also displayed in the figure.

During the winter months of the study period, precipitation (rainfall + water equivalent of snowfall) amounts totalled 85.9 mm. The stage hydrograph showed much variability during this period due to temperature variations resulting in melting and re-freezing of the snow pack.

During the growing season of 2008 (April – September), the total rainfall amount for the watershed was 648 mm, which was 127 mm above the annual average amount for this period. Daily precipitation amounts exceeded 25.4 mm on six occasions. The stage hydrograph for the knickpoint reach documented 8 runoff events (Figure 19). Another two runoff events occurred in July 2008 when the datalogger was not functioning. The highest recorded stages were 215 cm and 280 cm, which resulted from a series of rain events that produced 250 mm of rainfall over 15 days (May 28 – June 11, 2008).

3.3 Flow velocity – LSPIV, Flowtracker

Two FlowTracker measurements and one LSPIV measurements were conducted at the knickpoint site to determine discharge at the knickpoint site. The stages for the three measurements ranged between 28 and 38 cm and the discharges ranged between 0.56 and 2.08 m^3/s. The resulting rating curve (Figure 20) was developed by plotting the stage vs. discharge and fitting a power function to the data. More data points are needed, especially at higher flows, to produce a more reliable rating curve before it can be used at this site.

3.4 Surveys

Four surveys of the channel morphology were collected during the study period. The first survey was conducted at the beginning of the study period in June 2007 (Figure 21a). At this time, the knickpoint was located at approximately 367 ft. (111 m) from the Elderberry Rd. Bridge, which is equivalent to the -24 ft. contour line on the survey plot (Figure 21a). The black, dashed, vertical lines on the survey plots are simplifications of this initial knickpoint face. The upstream migration of the knickpoint face, to be defined as the -24 ft. contour, was measured from this point.

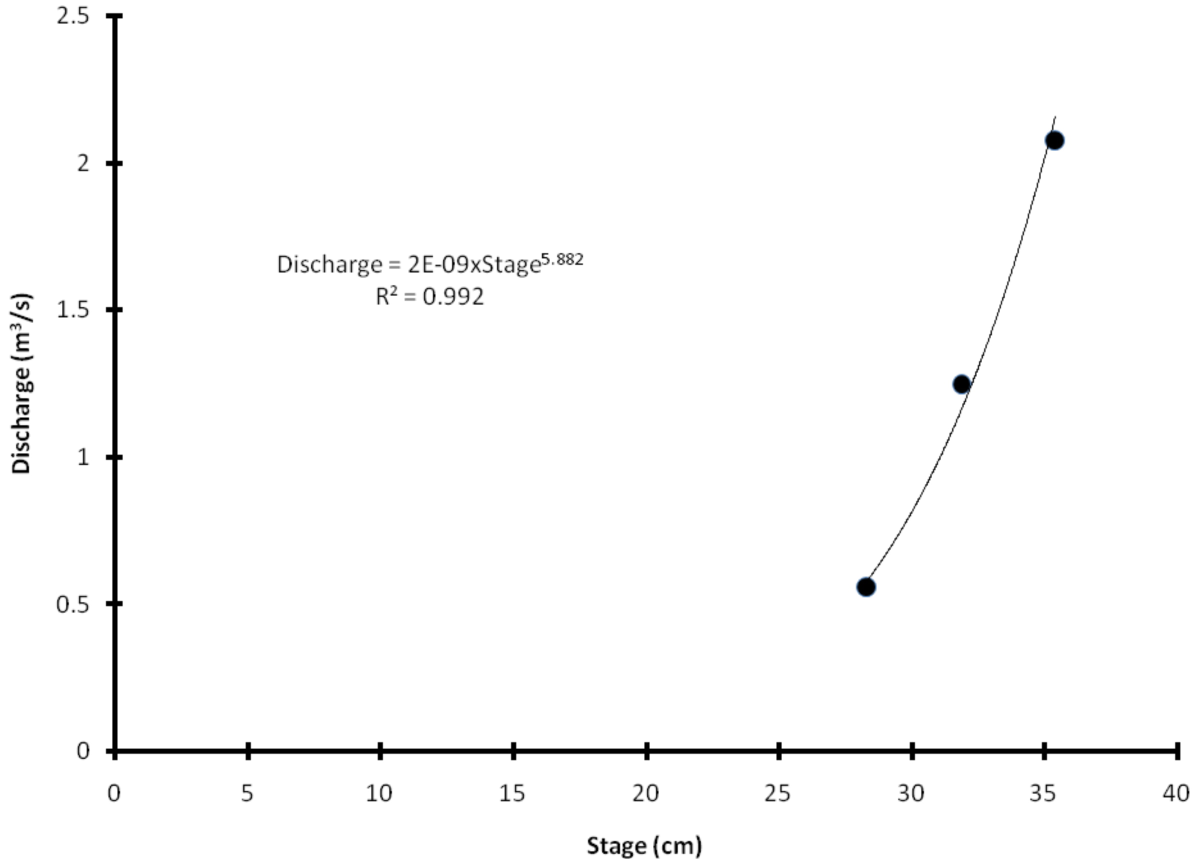


Figure 20. Rating curve. A stage-flow rating curve was developed for this site based on ADV FlowTracker and LSPIV measurements.

The second survey (Figure 21) was conducted in late September 2007. Little change was observed between this survey and the previous survey as seen through similar locations of the -24 ft. contour line. During this period there was no visible movement of the knickpoint face. In support of this finding, there were no major runoff events, which would trigger mass failure of the knickpoint face resulting in upstream migration.

The third survey (Figure 21) was conducted in April 2008 following the winter months when periods of freeze-thaw would weaken the knickpoint face facilitating mass failure. Two noticeable differences were observed between this survey and the previous two surveys. The majority of the knickpoint face (-24 ft. contour) remained in a similar location as in the two previous surveys; however, a small finger-like projection extending upstream was noticeable (see circled region in Figure 21). This projection extended upstream 1.5 m. Using the extent of this projection to determine the annual upstream migration rate, the knickpoint advanced at a rate of 2 m/yr. The second observable difference from this survey was an increase in the size of the scour hole (represented by the -26 ft. contour; see squared area in Figure 21). The downstream length of the scour hole increased from 2.3 m to 4.4 m, while the cross-stream width increased from 2.1 m to 2.7 m between June 2007 and April 2008.

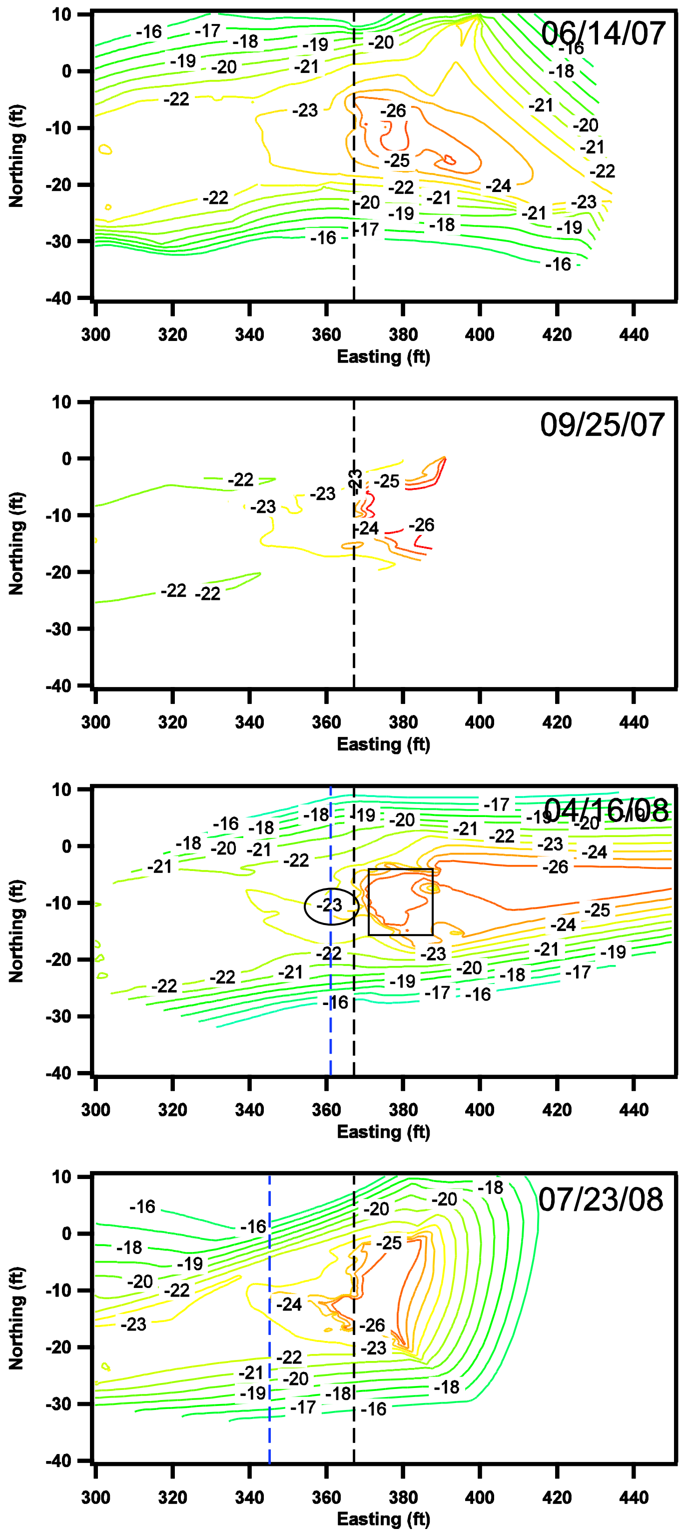


Figure 21. Channel surveys. Bi-annual surveys of the knickpoint show the progression of a finger-like projection (extent of -24 ft. contour line, or position of blue dashed line relative to black dashed line) and an increase in the dimensions of the scour hole (area enclosed by -26 ft. contour line).

The changes that occurred during the winter months continued through Spring and

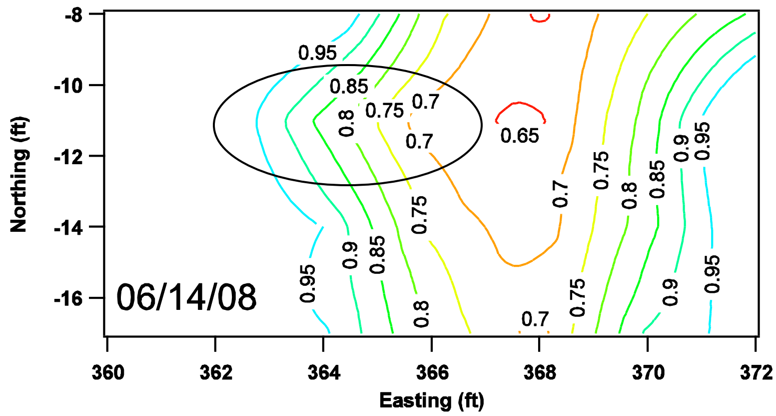
Summer 2008 (Figure 21). The finger-like projection extended further upstream, while the dimensions of the scour hole increased. The projection extended upstream 6.6 m from the initial position of the knickpoint face, suggesting an advancement rate of 5.6 m/yr. Aside from this projection, the remainder of the knickpoint face appeared to remain at its original position. The scour hole dimensions increased to a downstream length of 5.3 m and a cross-channel width of 5.5 m.

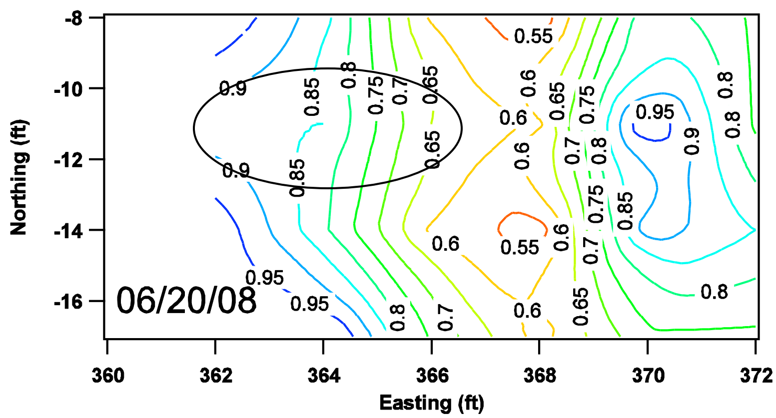
3.5 Laser

Water surface levels were measured using a laser level suspended from a fixed datum over a region centered on the knickpoint. These measurements were collected almost daily between June and September 2008. Contour maps (Appendix 1) similar to those for the surveys were developed to determine if water level can be a surrogate measure of the channel bed to facilitate studies of upstream knickpoint migration. Select maps are presented in the text to demonstrate the utility of the method at representing knickpoint advancement (Figure 22). Contour values are relative depths to a single point on the grid that shared the strongest relationship with the depth at the pressure transducer (Point 362, -11, Figure 16).

The finger-like projection observed in the surveys can be seen in the initial water level contour map from June 14th (Figure 22). The circled area in this figure and all subsequent figures highlight this projection as it advanced. Over this study period, the length of this projection increased 5 m, which was beyond the sampling grid, so knickpoint advancement rates were unobtainable from this method; however, these figures showed well the daily advancements of the projection.

Another feature on these figures, which was useful in determining movement of the knickpoint, was the position of the lowest contour, which represents the lowest water level. In the first two graphs (Figures 22), the center of the lowest contour was located at (368, -11). A 2-ft shift upstream of the position of this lowest contour was noticed between June 20th and June 21st (Figures 22). This shift corresponded with a runoff event from an 18 mm rainfall between June 19th and 20th. It is important to note that large runoff events were observed a few weeks prior to this event with no observable shift in the position of the knickpoint.


06/14/08
Northing (ft)
Easting (ft)
-8
-10
-12
-14
-16
360
362
364
366
368
370
372


06/20/08
Northing (ft)
Easting (ft)
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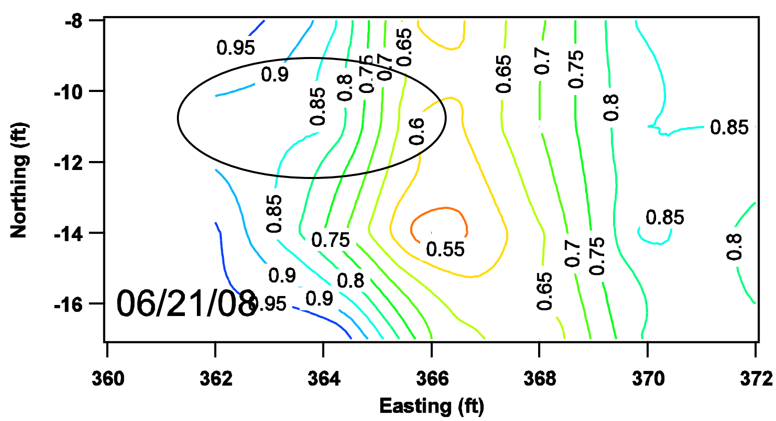
06/21/08
Northing (ft)
Easting (ft)
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-10
-12
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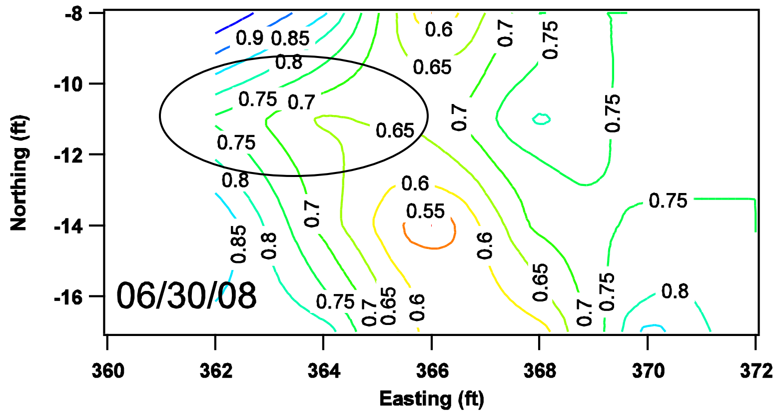
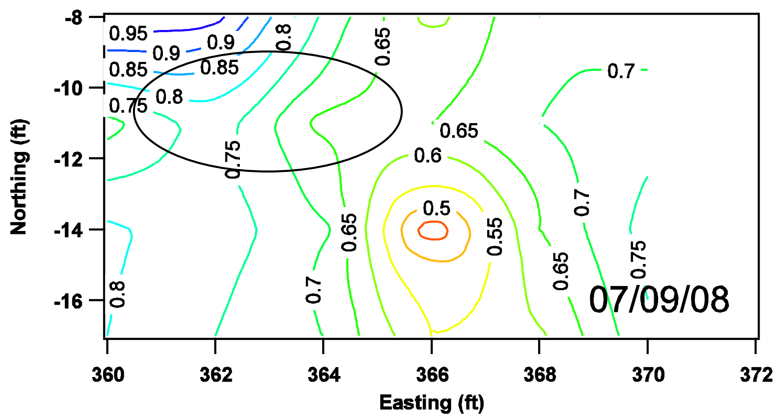
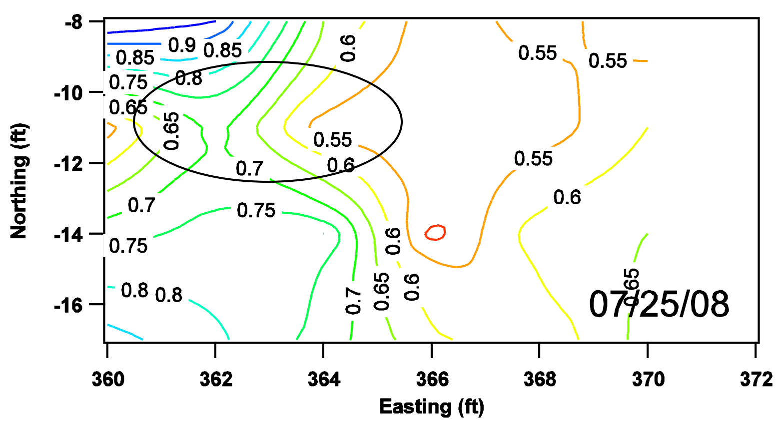
370
372


06/30/08
Northing (ft)
Easting (ft)


07/09/08
Northing (ft)
Easting (ft)


07/25/08
Northing (ft)
Easting (ft)

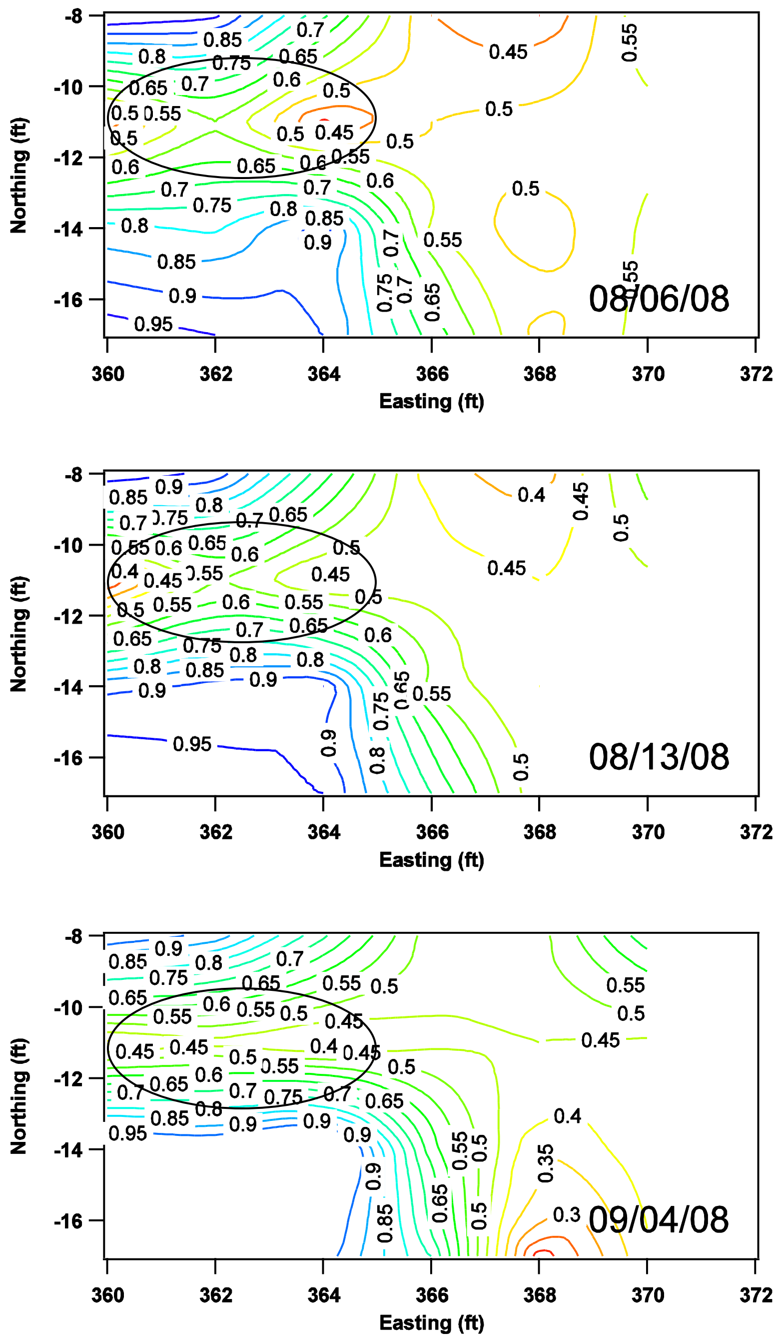


Figure 22. Water level surveys. Select daily measurements of the water level over the knickpoint from a fixed datum show the progression of the knickpoint face.

3.6 3ST1D

Determination of the hydraulic conditions around the knickpoint for case (1), i.e., the fixed bed scenario, allowed for classification of the flow at the knickpoint as vented or unvented for different flow events. Identification of the flow type at the knickpoint was conducted by determining the ratio H1/z, where H1is the water depth over the crest of the knickpoint, obtained from the numerical simulation, and z is the fixed height of the knickpoint face, obtained from the survey maps and sequentially the angle of attack (or impingement angle, θ) of the flow (Figure 23). It has been reported in the literature that when the ratio $H1/z < 1/8$ then vented conditions occur and knickpoint erosion is controlled by the knickpoint geometry and prevailing flow (May, 1989). On the contrary, unvented erosion occurs when the ratio $H1/z > 1/8$. Results from the numerical simulations for the fixed bed conditions, under different flow events, provided the water surface profiles along the whole stream reach and, thus, the flow depths at the crest of the knickpoint. Evaluation of the ratio H1/z indicated that unvented conditions occurred for all the flow events (Table 1). In addition, the angle θ at which the jet strikes the bed was determined, based on the water surface profiles. A plot of the different discharges Q vs. the angles θ was produced (Figure 24), and the results compared favorably with literature reported values (e.g., May, 1989).

Cases (2) and (3) i.e., the moveable bed scenarios, focused on the evolution of the knickpoint. In case (2), a flat bed condition was considered with homogenous bed as the initial bed condition. The bed critical erosional strength was assumed to be 10 Pa, an erosional strength value corresponding to a well compacted cohesive sediment bed (Papanicolaou and Maxwell, 2006). Case (2) simulations were performed for high flow conditions, $Q=10\ m^3/s$ It was found that a scour hole developed within approximately 5,000 sec from the start of the simulations. After a half-day period (~43,000 sec) with a $Q=10\ m^3/s$, the volume of the scour hole increased dramatically and reached equilibrium. The equilibrium scour hole depth was predicted to be roughly 20 cm (Figure 25). If a different critical erosional strengths and Qs were assumed, 3ST1D would have produced scour holes of different volumes. Further, the equilibrium conditions would have been reached at different time periods.

For case (3), a frontal step (mimicking a preformed knickpoint) with z = 1.2 m and a critical erosional strength of 10 Pa was considered as the initial bed configuration during the simulations. A flow of $Q=20\ m^3/s$ was used in these simulations. The TVD shock capturing technique, implemented in the hydrodynamic component of the 3ST1D, allowed the simulation of the evolution of the knickpoint geometric features despite abrupt bed discontinuities introduced as the preformed frontal step. The propagation of the frontal face of the knickpoint was simulated over a period of 10,000 sec. The blue line in Figure 26 showed the upstream migration of the knickpoint. At t=10,000 sec the front face of the knickpoint became vertical supporting the findings in case (1) viz., that flow near the knickpoint triggered the erosion of the knickpoint face.

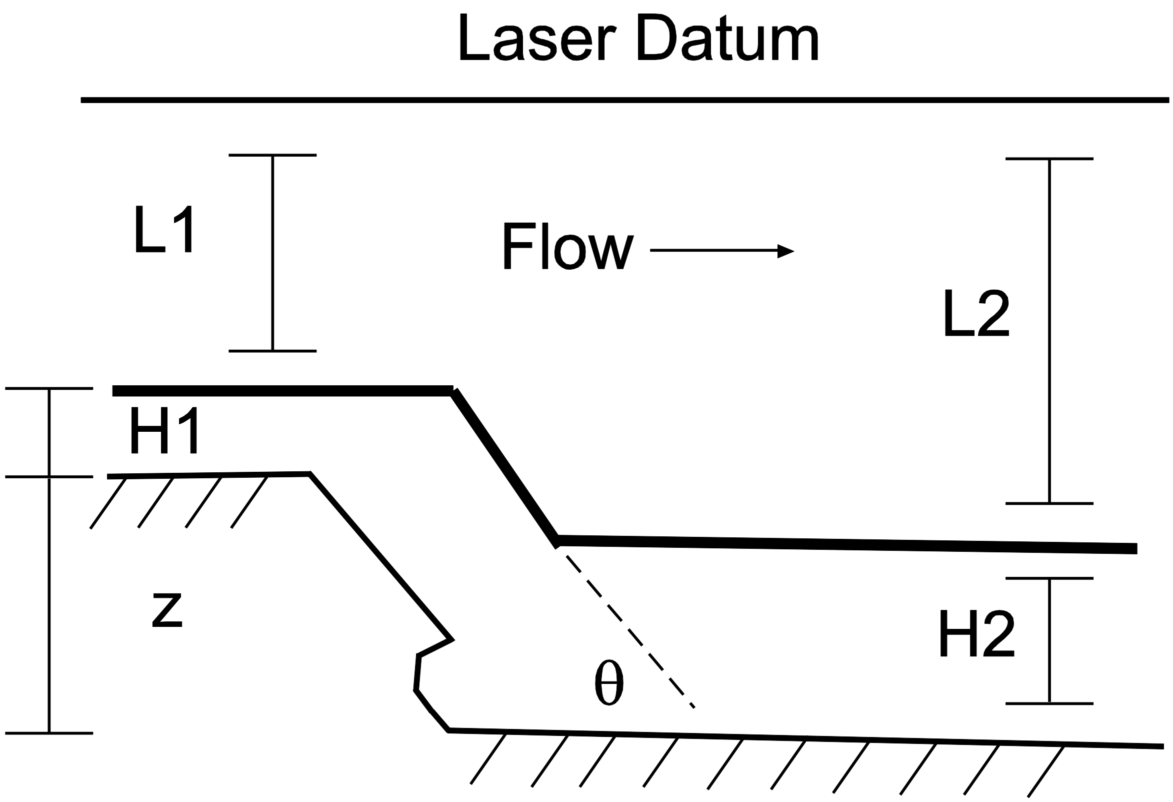


Figure 23. 3ST1D Visulatization. A schematic of the representative knickpoint used for the 3ST1D simulations where H1 and H2 are the depths of flow above and below the knickpoint, respectively. L1 and L2 are the distance of the laser from the fixed datum to the water surface (bold line). The height of the knickpoint is z and q is the impact angle of the impinging jet.

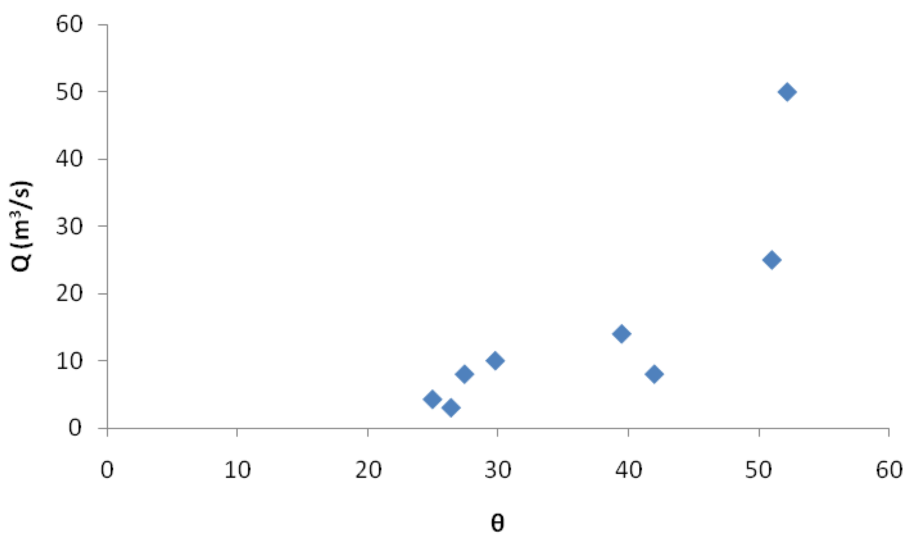


Figure 24. The discharge Q vs. the angle of impact θ.

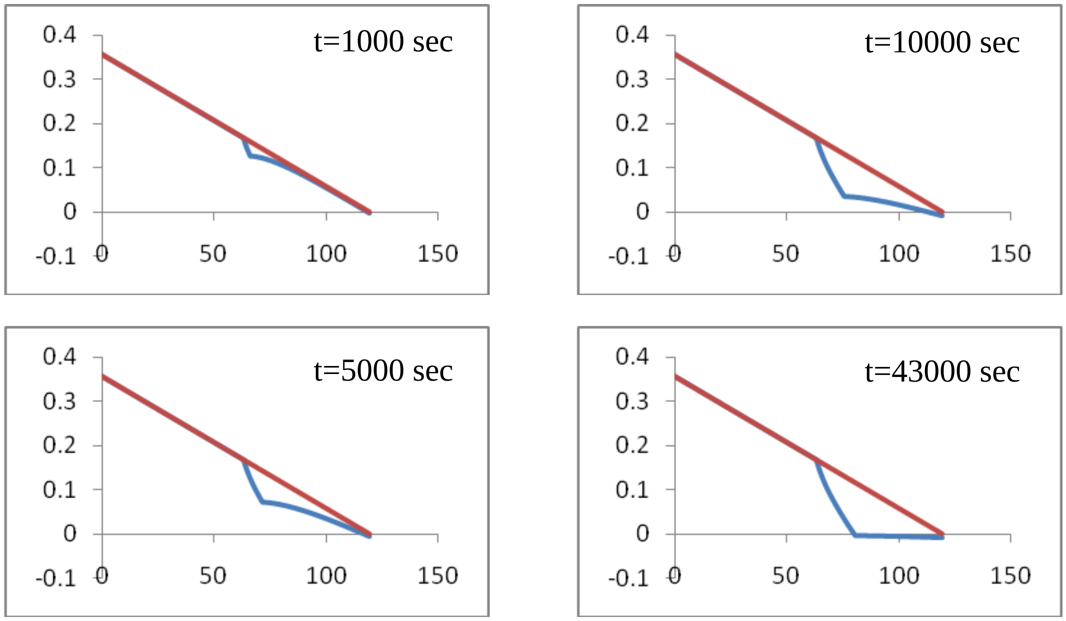


Figure 25. Scour formation downstream of the location of the knickpoint (red line = Initial bed, blue line = Final bed). X-axis is the longitudinal direction (in m) and Y-axis is the elevation (in m).

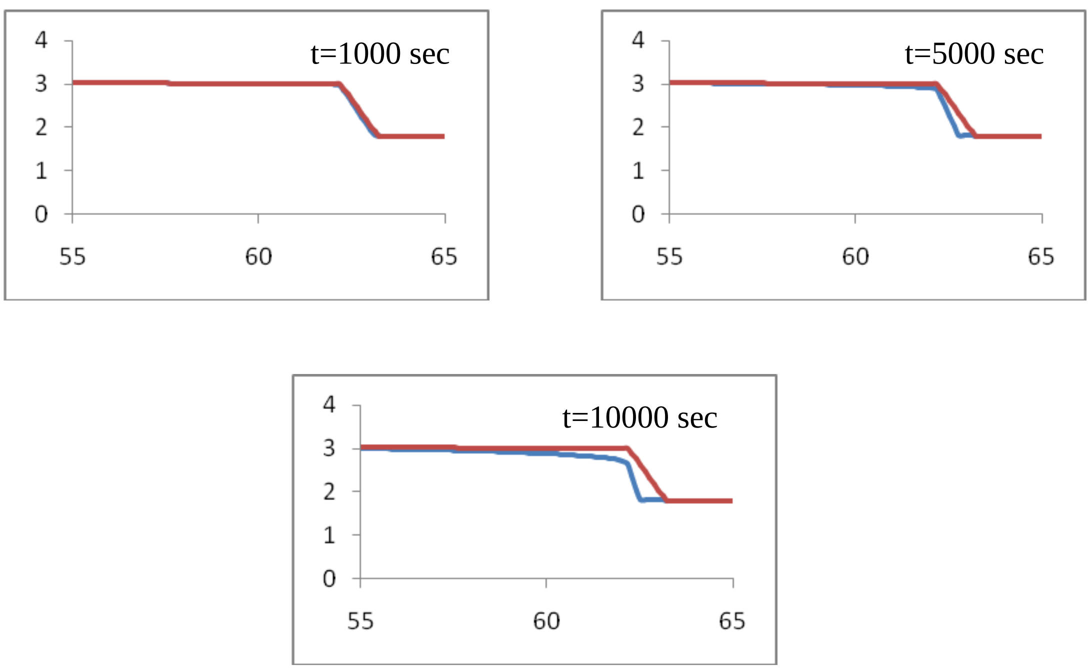


Figure 26. Propagation of the frontal face of the knickpoint (red line = Initial bed, blue line = Final bed). X-axis is the longitudinal direction (in m) and Y-axis is the elevation (in m).

Table 1. Hydraulic conditions for a fixed bed simulation of the knickpoint

Q (m^3/s)	H_1' (m)	H_1 (m)	H_2 (m)	z/H_1	H_1/H_2	H_2/H_1	Case
0.2	0.22	0.4	1.7	3	0.235294	4.25	unvented
0.4	0.32	0.5	1.8	2.4	0.277778	3.6	unvented
0.6	0.51	0.71	2	1.690141	0.355	2.816901	unvented
14	1.03	0.68	0.8	1.764706	0.85	1.176471	unvented
3	0.39	0.25	0.8	4.8	0.3125	3.2	unvented
0.05	0.42	0.61	1.9	1.967213	0.321053	3.114754	unvented
0.2	0.61	0.81	2.1	1.481481	0.385714	2.592593	unvented
8	0.73	0.48	0.5	2.5	0.96	1.041667	unvented
0.1	0.22	0.4	1.7	3	0.235294	4.25	unvented
4.25	0.49	0.31	0.9	3.870968	0.344444	2.903226	unvented
8	0.73	0.48	1	2.5	0.48	2.083333	unvented
3	0.39	0.21	1.7	5.714286	0.123529	8.095238	unvented
1	0.23	0.39	1.7	3.076923	0.229412	4.358974	unvented
0.07	0.22	0.4	1.7	3	0.235294	4.25	unvented
10	0.84	0.55	1	2.181818	0.55	1.818182	unvented
2	0.29	0.16	1.6	7.5	0.1	10	unvented
25	n/a	1.02	0.6	1.176471	n/a	0.588235	unvented
50	n/a	1.5	1.01	0.8	n/a	0.673333	unvented

Notation:

Q (m^3/s) = Flow discharge
H_1' (m) = Depth upstream of the knickpoint (away from the knickpoint)
H_1 (m) = Depth at the knickpoint (at the crest)
H_2 (m) = Depth H2 downstream of the knickpoint
z (m) = Height of the knickpoint fixed for all cases (z = 1.2 m)

3.7 Evaluation protocol - Implementation plan

The main features of inspection form that can be adopted by the Iowa DOT personnel and county engineers when inspecting streams that recently have experienced knickpoint migration necessitates the use of an implementation and inspection plan outlined in Table 2.

Table 2. The main features of inspection form used by the Iowa DOT when inspecting bridges that recently have experienced a major flood flow

Proposed Evaluation Protocol for Knickpoints
Iowa Department of Transportation

Date inspected: ________________________
Date Received in Office: _________________
Survey Team: ____
____

Site Information
Stream name. ____________________________
County. __________________________________
Road. ____________________________________

This report contains
Comments ____ Yes ____ No
Sketches ____ Yes ____ No
Photos ____ Yes ____ No

Place an "X" by all that apply

1. ____ Is there a visible knickpoint?

2. ____ Is there a documentation of the knickpoint location?

3. ____Is there any indication of upstream movement of the knickpoint? How far is the knickpoint from the bridge crossing?

4. ____Is there shifting of the channel alignment or erosion of the stream banks?

5. ____How far is the knickpoint from the sheet piles

6. ____Do scour measurements indicate: (Place an "**X**" by all that apply.)

_____A. scour developed below the bottom of the knickpoint?

_____B. scour is at equilibrium?

_____C. that the streambed has scoured five feet or more below the original

streambed elevation at knickpoint?

Note:

Streambed laser data is to be documented. (sounding measurements may not be possible due to flow bubbling)

A streambed profile via survey should be done on the upstream side of all bridges every two years. If Item #6 is yes, then a profile on the downstream side of the knickpoint should also be done in the scoured area. If the downstream profile also indicates a problem, then laser measurements should be made at the knickpoint crest if possible.

If "No" is the answer to all of the items in the checklist, no further action will be necessary.

If "Yes" is the answer to any items on the checklist, contact the Office for further instructions.

An "*" indicates the item is not visible.

Comments: ___________________________

____

____

____

Completed on ___________________________ By ____

Reviewed by ___________________________________ Date reviewed _________________________

Is a follow-up inspection recommended? _____ Yes _____ No

Comments/Recommendations:____

____

____

____

4. CONCLUSIONS

The severity of channel erosion in the Deep Loess Region of western Iowa is considerable due to channelization of the stream corridor and intensive agriculture, coupled with the highly erodible loess soils. Knickpoints, or discontinuities in bed slope or elevation along the longitudinal stream profile, are common forms of channel degradation in western Iowa. Once a knickpoint has formed it will continue to advance upstream, eroding the channel bed, lowering the base level for tributary streams, and, if unchecked, eventually affecting downstream infrastructure. To date, information regarding knickpoint migration rates in western iowa is lacking. A structured monitoring protocol would assist local government agencies in better understanding the principal factors that cause knickpoint propagation and help estimate the needed response time to control the propagation of a knickpoint after one has been identified.

This study was developed to provide a semi-automated, field-oriented evaluation of a knickpoint on Mud Creek in Mills County, IA using various methods of monitoring to determine the upstream migration rate of the knickpoint. The data collected in the field was then implemented into a one-dimensional, hydrodynamic/ sediment transport model, known as 3ST1D, to predict further migration rates. The goal of these objectives was to provide a reliable method and ultimately a comprehensive and practical manual that will substantially help engineers in monitoring, maintaining, and protecting bridge waterways so as to mitigate or manage scour occurring at the bridge structures.

Monitoring methods included grain size analysis of the bed and bank material from the knickpoint site, stage and flow discharge measurements, bi-annual surveys of the reach from the bridge through the downstream scour hole of the knickpoint, and daily monitoring of water elevations at the knickpoint using a remotely-mounted state-of-the-art laser. It was hypothesized that water level can be a surrogate measure of the channel bed to facilitate studies of upstream knickpoint migration since water level can be used more easily than surveys of the channel bed. A state-of-the-art laser distance level was mounted above the stream width on a radio antenna truss that spanned the width of the channel to measure the distance from a fixed datum to the water surface for an establish area that centered on the knickpoint face. Measurements were collected almost daily of the knickpoint area for three months from June until September 2008.

Results from the channel bed topographical survey showed that although the majority of the knickpoint face did not advance much beyond its original position over the 2-year study period, a finger-like projection advanced upstream at a rate of 5.6 m/yr. This projection extended beyond the area monitored by the laser; however, the laser was able to monitor its development. Another feature of the knickpoint, namely the lowest water level from the fixed datum found in the downstream scour hole, was identified by the laser system. The movement of this feature was noticeable, especially a 2-ft shift upstream following a single 18 mm rainfall between June 19th and 20th, 2008. It is important to note that large runoff events were observed a few weeks prior to this event with no observable shift in the position of the knickpoint. Thus, water level proved reliable as a surrogate measure for knickpoint advancement.

The 3ST1D simulations, which were used to further predict knickpoint movement, proved useful at simulating the development and migration of the knickpoint. Results from the numerical simulations for the fixed bed conditions, under different flow events, provided the water surface profiles along the whole stream reach and, thus, the flow depths at the crest of the knickpoint. This allowed for evaluation of the ratio the depth of flow over the knickpoint to the height of the knickpoint face, which indicated that unvented conditions occurred for all the flow events. The moveable bed scenarios were able to show the development of the scour hole, as well as the upstream migration rate. These simulations showed that flow, which developed unvented conditions, near the knickpoint triggered the erosion of the knickpoint face and facilitated slumping of large volumes propagating knickpoint advancement.

5. REFERENCES

Alonso, C.V. 2002. On the origin of secondary scour associated with migrating knickpoints. In: Simon, A., R.E. Thomas, A.J.C. Collison, and W. Dickerson (eds). *Erodibility of cohesive streambeds in the Yalobusha River system*. Research Report No. 26. USDA-ARS National Sedimentation Laboratory: Oxford, MS.

Alonso, C.V., S.J. Bennett, and O.R. Stein OR. 2002. Predicting head cut erosion and migration in concentrated flows typical of upland areas. *Water Resources Research*. 38(12):39-1 – 39-15.

Baumel, C. 1994. Impact of degrading western Iowa streams on private and public infrastructure costs. In: Hadish, G. (ed). *Stream Stabilization in Western Iowa*., Iowa Department of Transportation Report OT HR-352., Golden Hills Resource Conservation and Development: Oakland, IA; 4-1 - 4-39.

Begin, Z.B., D.F. Meyer, and S.A Schumm. 1980. Knickpoint migration due to baselevel lowering. *Journal of the Waterway Port Coastal and Ocean Engineering Division*. 106:369-388.

Bennett, S.J., and C.V. Alonso. 2006. Turbulent flow and bed pressure within headcut scour holes due to plane reattached jets. *Journal of Hydraulic Research*. 44(4):510-521.

Bennett, S.J., K.M. Robinson, A. Simon, and G.J. Hanson. 2000. Stable knickpoints formed in cohesive sediment. In: Hotchkiss, R.H. and M. Glade (eds). *Proceedings 2000 Joint Conference on Water Resources Engineering and Water Resources Planning & Management,* ASCE: Reston, VA.

Bennett S.J., and J. Casali. 2001. Effect of initial step height on headcut development in upland concentrated flows. *Water Resources Research*. 37(5):1475-1484.

Brush, L.M., and M.G. Wolman. 1960. Knickpoint behavior in non-cohesive material: A laboratory study. *Geological Society of America Bulletin*. 71:59-74.

Buchanan, T.J. and W.P. Somers. 1969. Discharge Measurements at gaging stations. U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 3, Chapter A8. Reston, VA.

Clemence, K.T. 1987. Influence of stratigraphy and structure on knickpoint erosion. Undergraduate Fellow Thesis, Department of Geology, Texas A&M University, College Station, TX.

Daniels, R.B. 1960. Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa. *American Journal of Science*. 258:161-176.

Daniels, R.B., and R.H. Jordan. 1966. Physiographic history and the soils, entrenched stream systems and gullies, Harrison County, Iowa. *U.S. Department of Agriculture Technical Bulletin* 1348.

Frenette, R., and I. Pestov. 2005. Flow and erosive stresses at the base of a headcut. *Journal of Hydraulic Engineering*. 131(2):139-141.

Gardner, T.W. 1983. Experimental study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material. *Geological Society of America Bulletin*. 94(5):664-672.

Grissinger, E.H., and A.J. Bowie. 1984. Materials and site controls on stream bank vegetation. Transactions of the American Society of Agricultural Engineers. 27(6):1829-1835.

Hanson, G.J., K.M. Robinson, K.R. Cook. 1997a. Experimental flume study of headcut migration. In: Wang, S.S.Y., E.J. Langendoen, F.D. Shields, Jr. (eds). *Management of Landscapes Disturbed by Channel Incision, Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. Center for Computational Hydroscience and Engineering: University of Mississippi, pp.497-502.

Hanson, G.J., K.M. Robinson, K.R. Cook. 1997b. Headcut migration analysis of a compacted soil. *Transactions of the American Society of Agricultural Engineers*. 40(2):355-361.

Hanson, G.J., K.M. Robinson, K.R. Cook. 2001. Prediction of headcut migration using a deterministic approach. *Transactions of the American Society of Agricultural Engineers*. 44(3):525-531.

Holland, W.N., and G. Pickup. 1976. Flume study of knickpoint development in stratified sediment. *Geological Society of America Bulletin*. 87:76-82.

Lee, H.Y., and S.T. Hwang.1994. Migration of a backward-facing step. *Journal of Hydraulic Engineering*. 120(6):693-705.

May, J.H. 1989. Report 4: Geologic and hydrodynamic controls on the mechanics of knickpoint migration. In *Geotechnical aspects of rock erosion in emergency spillway channels*. US Army Engineer Waterways Experiment Station: Vicksburg, MS.

Nixon, J.R. 1982. Soil Survey of Mills County, Iowa. US Department of Agriculture - Soil Conservation Service.

Papanicolaou, A.N., A. Bdour, and E. Wicklein. 2004. One-dimensional hydrodynamic/sediment transport model applicable to steep mountain streams. *Journal of Hydraulic Research*. 42(4):257-275.

Parker, G., and N. Izumi. 2000. Purely erosional cyclic and solitary steps created by flow over a cohesive bed. *Journal of Fluid Mechanics*. 419:203-238.

Rajaratnam, N., and K. Subramanya. 1968. Plane turbulent reattached wall jets. *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers*. 94:95-112.

Robinson, K.M. 1989. Hydraulic stresses on an overfall boundary. *Transactions of the American Society of Agricultural Engineers*. 32(4):1269-1274.

Robinson, K.M. 1992. Predicting stress and pressure at an overfall. *Transactions of the American Society of Agricultural Engineers*. 35(2):561-569.

Robinson, K.M., and G.J. Hanson. 1995. Large-scale headcut erosion testing. *Transactions of the American Society of Agricultural Engineers*. 38(2):429-434.

Robinson, K.M., and G.J. Hanson. 1996a. Influence of backwater on headcut advance. In*: Proceedings, North American Water & Environment Congress*. ASCE: Anaheim, CA.

Robinson, K.M., and G.J. Hanson. 1996b. Gully headcut advance. *Transactions of the American Society of Agricultural Engineers*. 39(1):33-38.

Robinson, K.M., and G.J. Hanson. 2001. Headcut erosion research. *Proceedings of the 7th Federal Interagency Sedimentation Conference*, Reno, NV.

Robinson, K.M., K.R. Cook, and G.J. Hanson. 2000. Velocity field measurements at an overfall. *Transactions of the American Society of Agricultural Engineers*. 43(3):665-670.

Ruhe, R.V. 1956. Geomorphic surfaces and the nature of soils. *Soil Science*. 82:441-445.

Ruhe, R.V. 1969.Quaternary Landscapes in Iowa. Iowa State University Press. Ames, IA. 255 p.

Sanford, J., and A.N. Papanicolaou. 2005. Watershed processes related to gully formation. World Water and Environmental Resources Congress, EWRI, ASCE, May 15-19, 2005.

Schumm S.A. 1973. Geomorphic thresholds and complex response of drainage system, fluvial geomorphology. In: Morisawa, M. (ed). *Proceedings, Fourth Annual Geomorphology Summit*. Binghamton, NY. Pp. 299-310.

Simon, A. 1992. Energy, time, and channel evolution in catastrophically disturbed fluvial systems. In: Phillips, J.D., and W.H. Renwick (eds). *Geomorphic Systems*. *Geomorphology*. 5(3-5):345-372.

Simon, A., and A.J.C. Collison. 2001. Pore-water pressure effects on the detachment of cohesive streambeds: seepage forces and matric suction. *Earth Surface Processes and Landforms*. 26:1421-1442. DOI: 10.1002/esp.287.

Simon, A., and M. Rinaldi. 2000. Channel instability in the loess area of the Midwestern United States. *Journal of the American Water Resources Association*. 36(1):133-150.

Simon, A. and R.E. Thomas. 2002. Processes and forms of an unstable alluvial system with resistant, cohesive streambeds. *Earth Surface Processes and Landforms*. 27:699-718.

Simon, A., S. Bennett, and M.W. Griffith. 2000. Knickpoint erosion and migration in cohesive streambeds. In: Hotchkiss, R.H. and M. Glade (eds). *Proceedings 2000 Joint Conference on Water Resources Engineering and Water Resources Planning & Management*, ASCE: Reston, VA.

Simon, A., R.E. Thomas, A.J.C. Collison, and W. Dickerson. 2002. Erodibility of cohesive streambeds in the Yalobusha River system. *Research Report No.* 26. USDA-ARS National Sedimentation Laboratory: Oxford, MS.

Singer, M.J., and P. Janitzki. 1986. Field and laboratory procedures used in a soil chronosequence study. *US Geological Survey Bulliten 1648*. Washington, D.C.

Stein, O.R., P.Y. Julien, and C.V. Alonso. 1997. Headward advancement of incised channels. In: Wang, S.S.Y., E.J. Langendoen, F.D. Shields, Jr. (eds). *Management of Landscapes Disturbed by Channel Incision, Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. Center for Computational Hydroscience and Engineering: University of Mississippi, pp. 497-502.

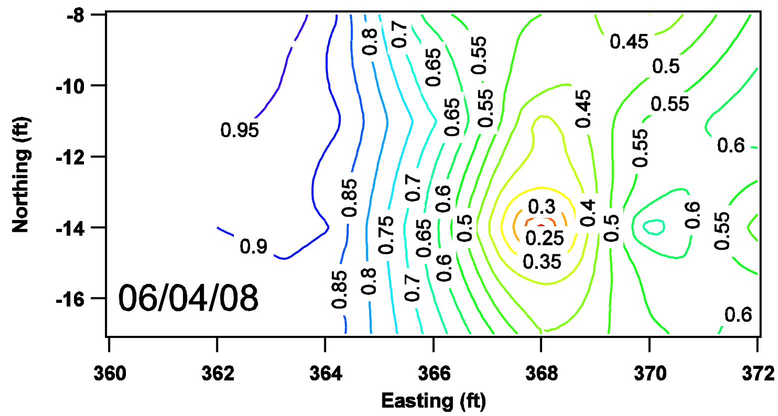
Stein, O.R., and D.A. LaTray. 2002. Experiments and modeling of headcut migration in stratified soils. *Water Resources Research*. 38(12):20-1 - 20-12.

Thomas, R.E., A.J.C. Collison, and A. Simon. 2001. Mechanisms and rates of knickpoint migration in cohesive streambeds: Hydraulic shear and mass failure. In: Hayes, D.F. (ed). *Designing Successful Stream and Wetland Restoration Projects, Proceedings of the 2001 Wetlands Engineering and River Restoration Conference,* ASCE: Reston, VA.

Whitten, C.B. and D.M. Patrick. 1981. Engineering geology and geomorphology of stream bank erosion: Report 2, Yazoo Basin Uplands Mississippi. Technical Report GL-79-7. Geotechnical Laboratory, US Army Corp of Engineers Waterways Experiment Station, Vicksburg, MS.

6. APPENDICES

APPENDIX 1:
Water level measurements over the knickpoint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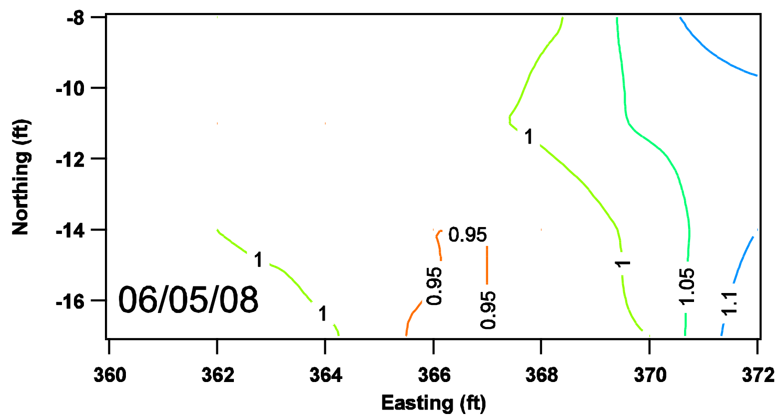
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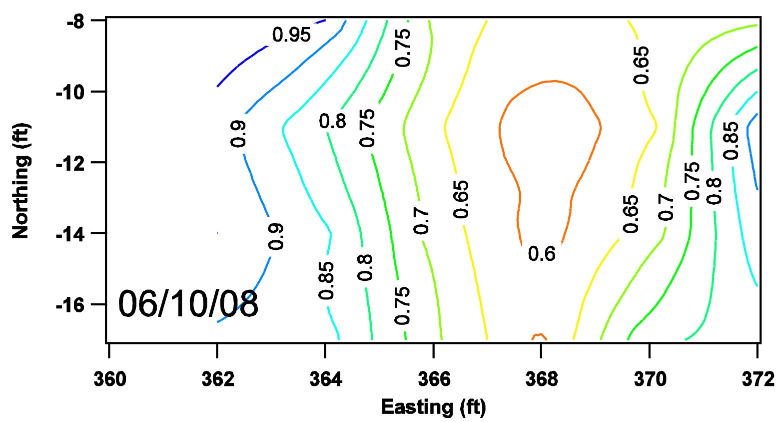
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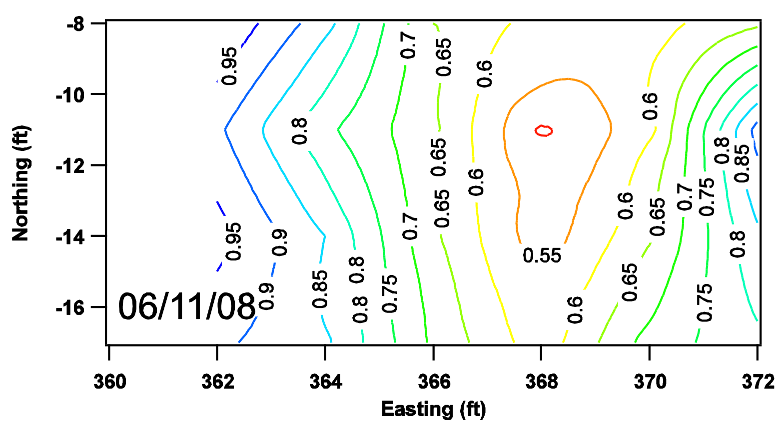
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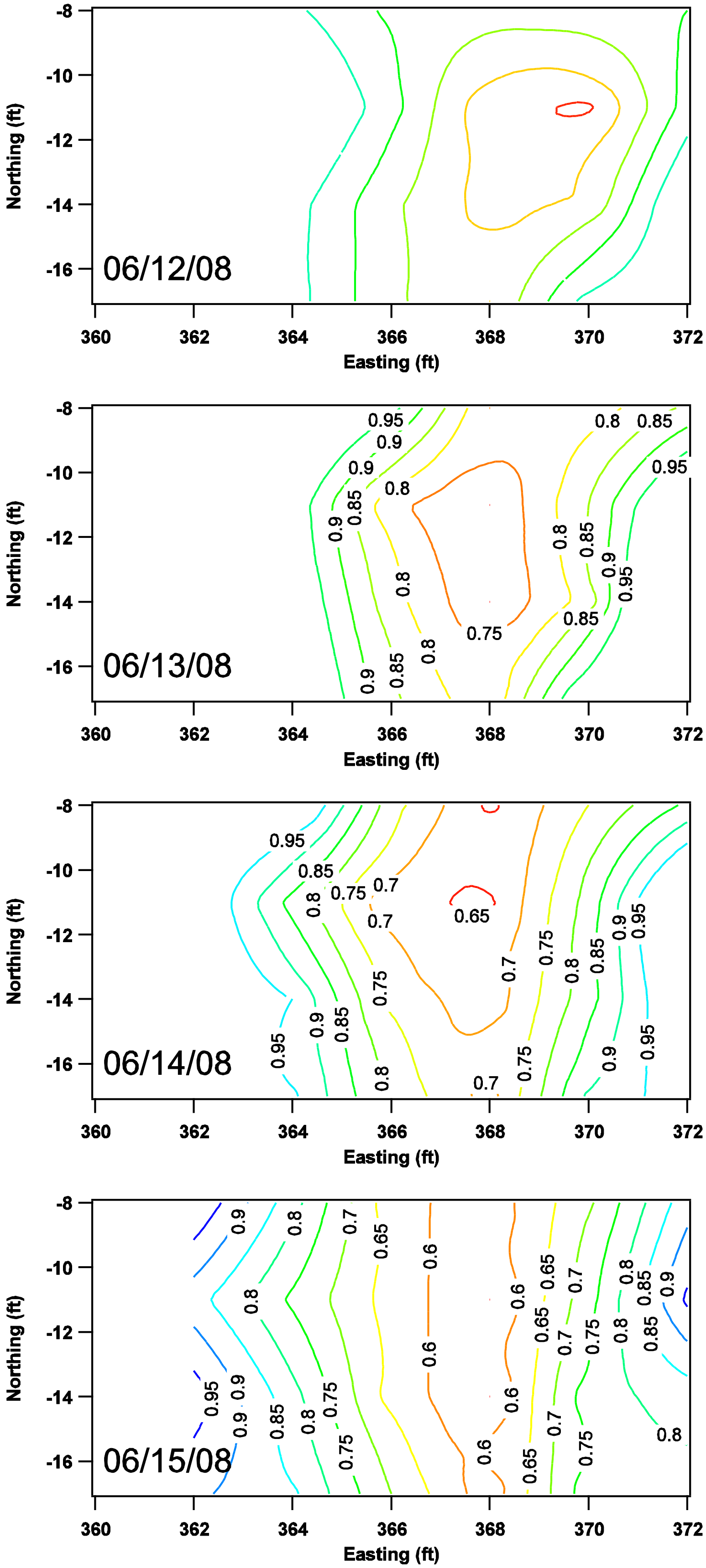
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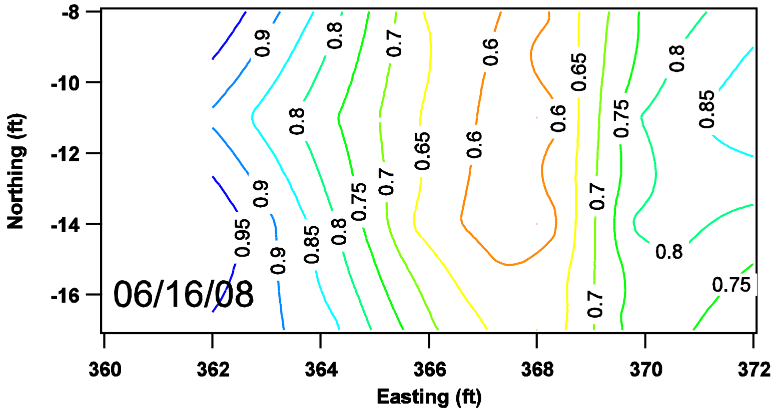
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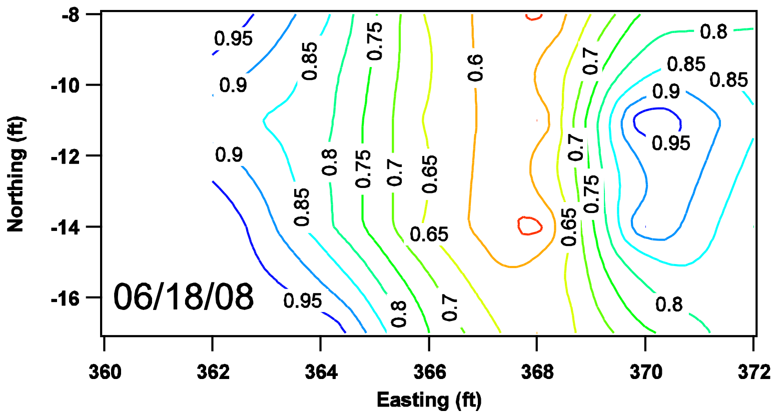
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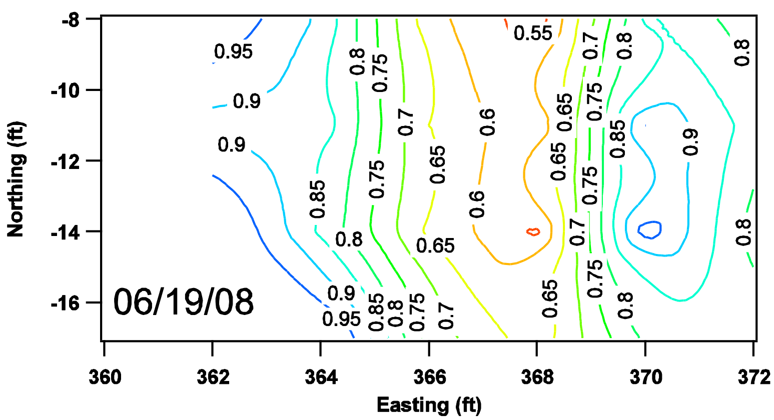
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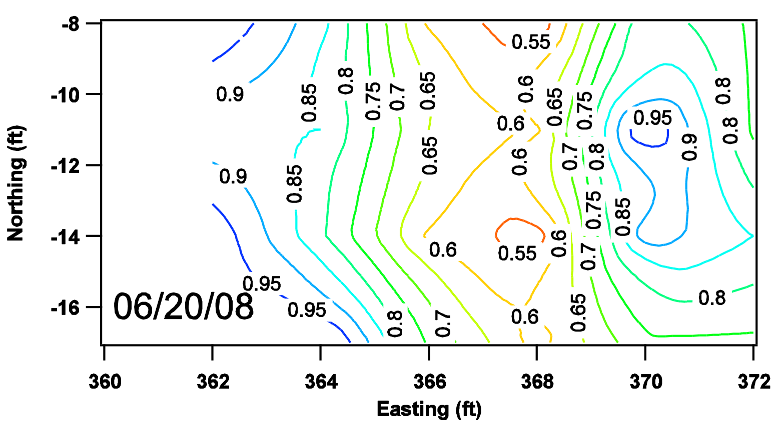
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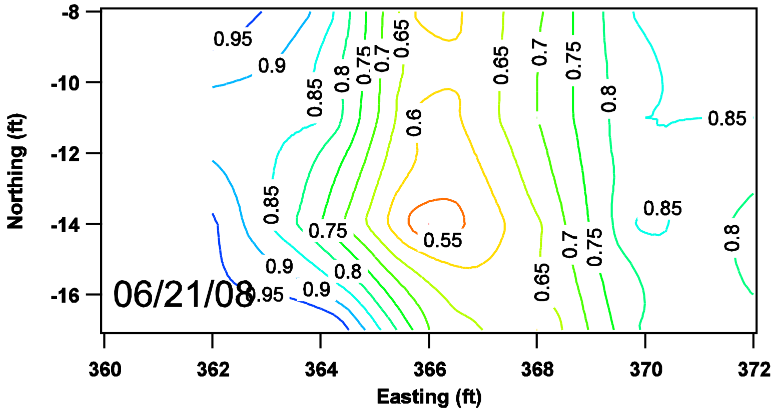
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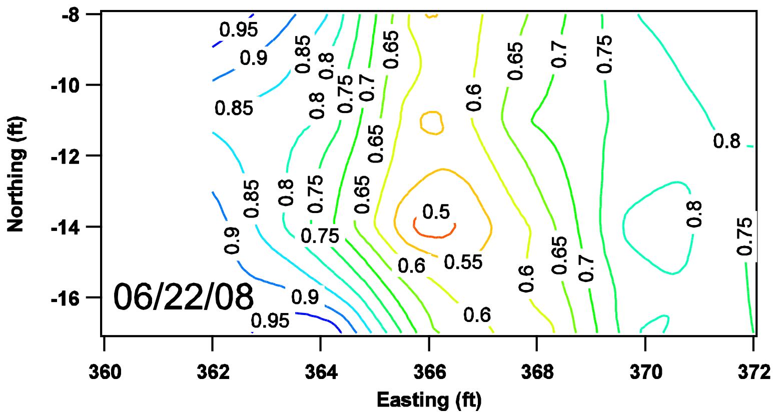
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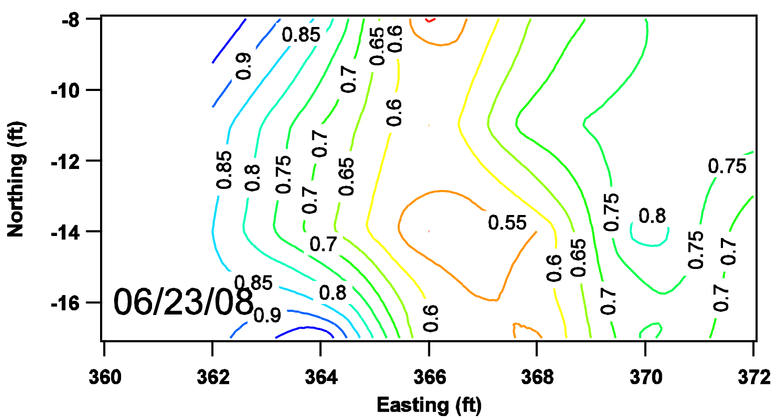
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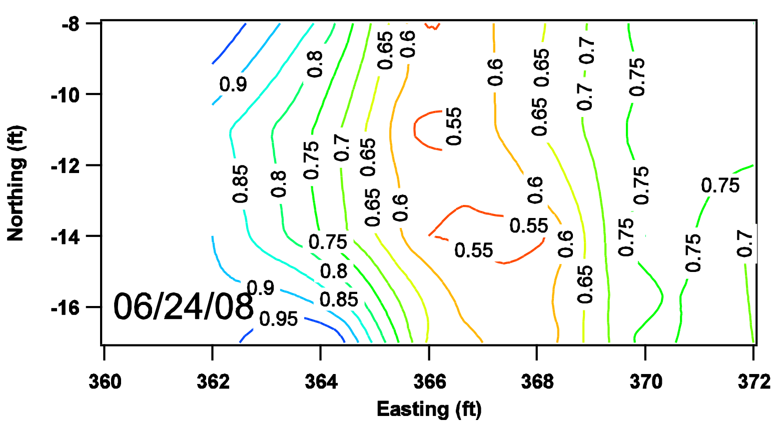
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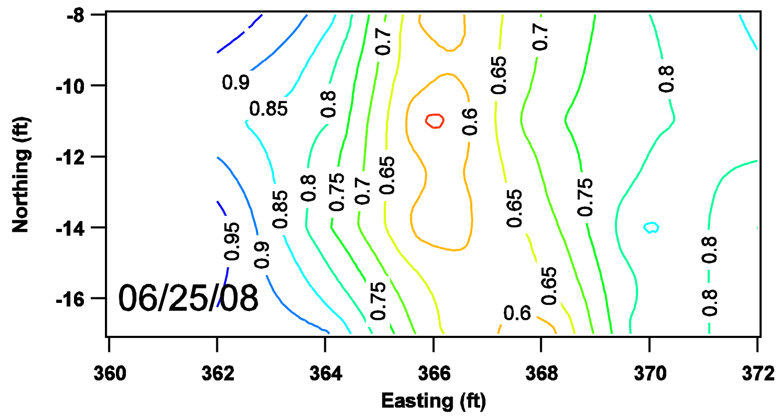

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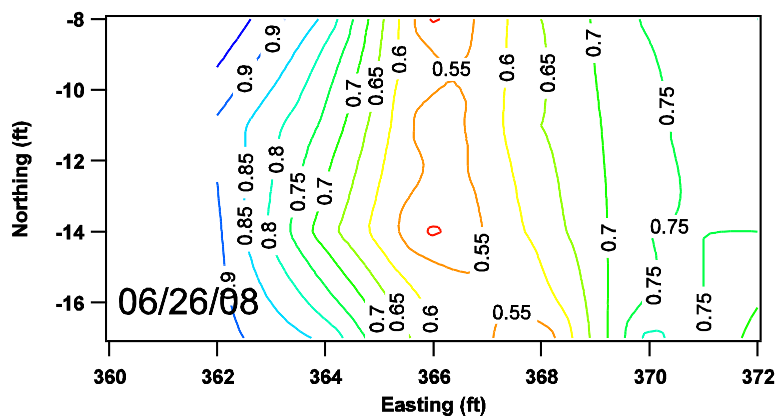

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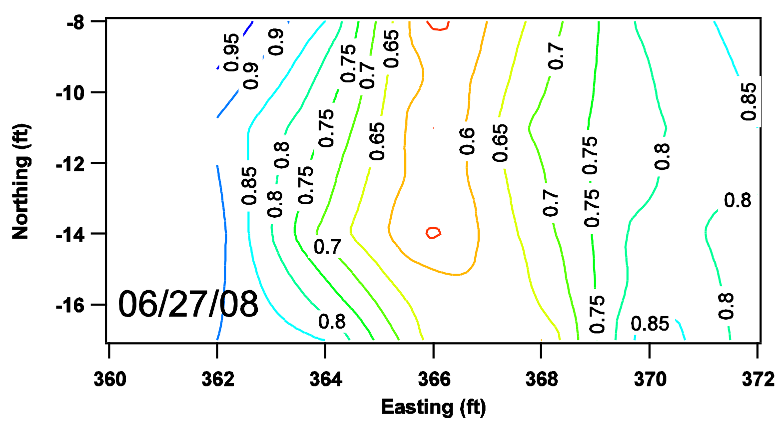

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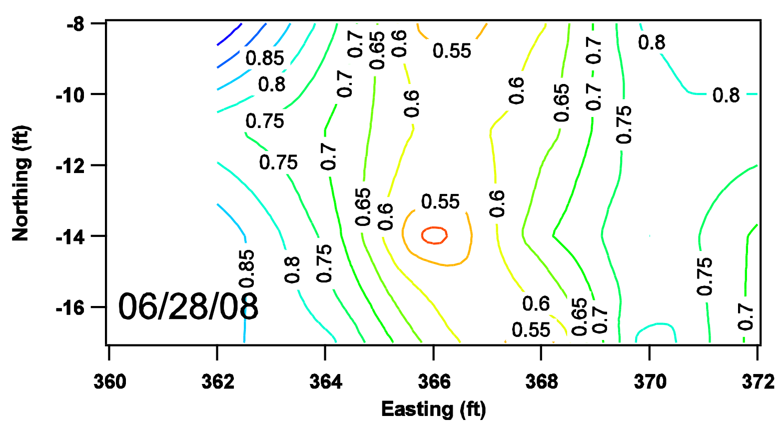

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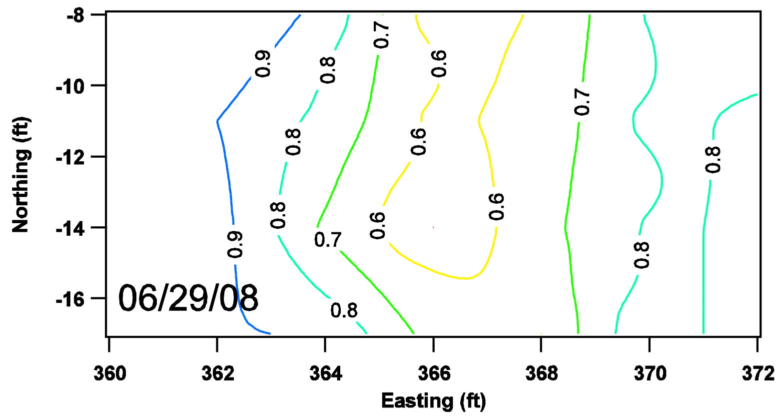
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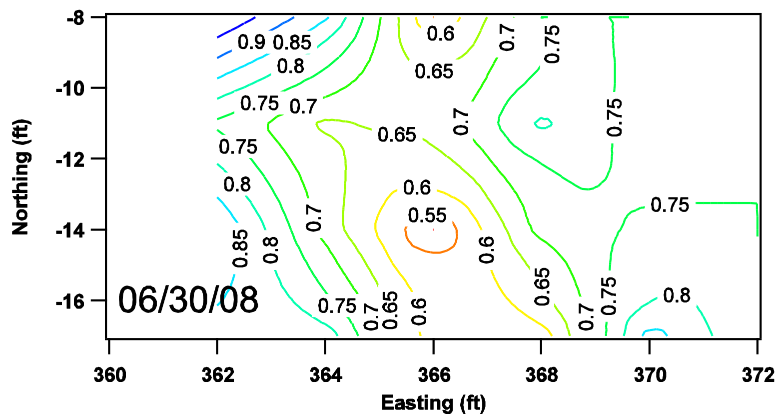
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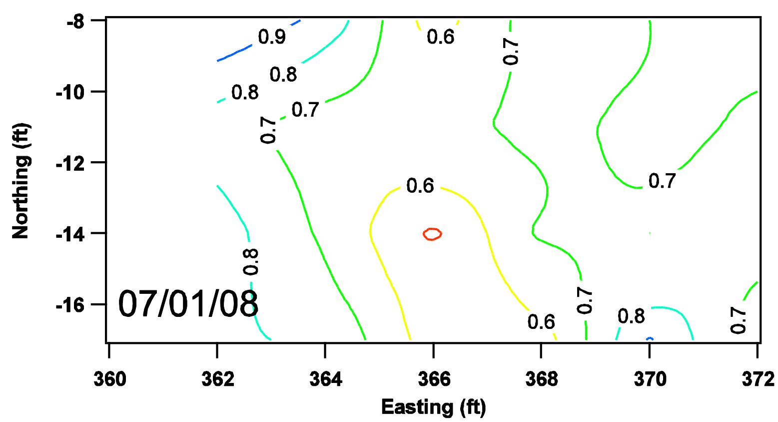
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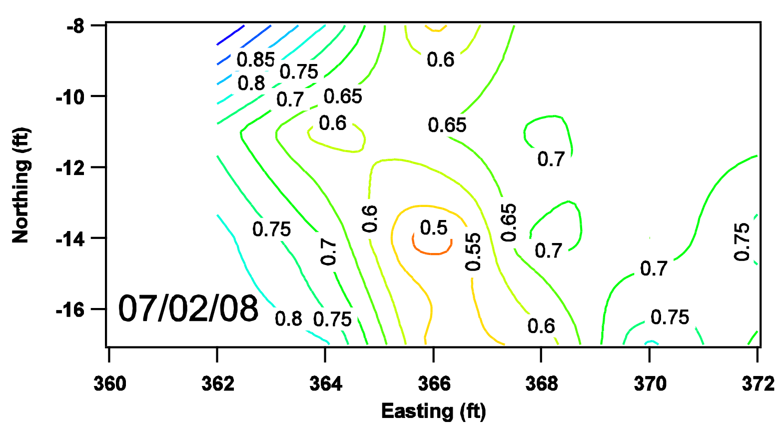
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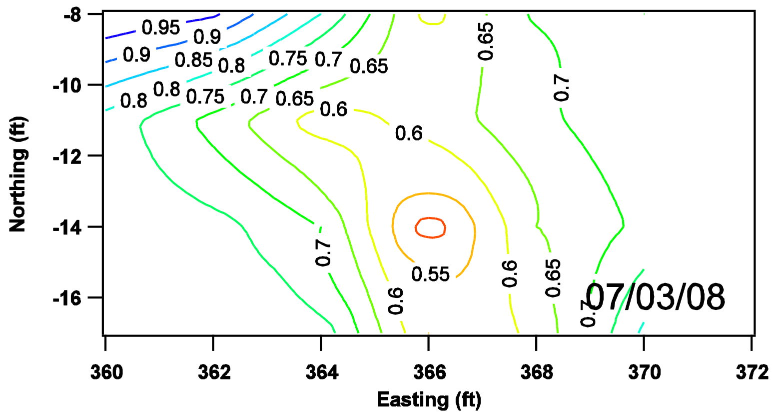
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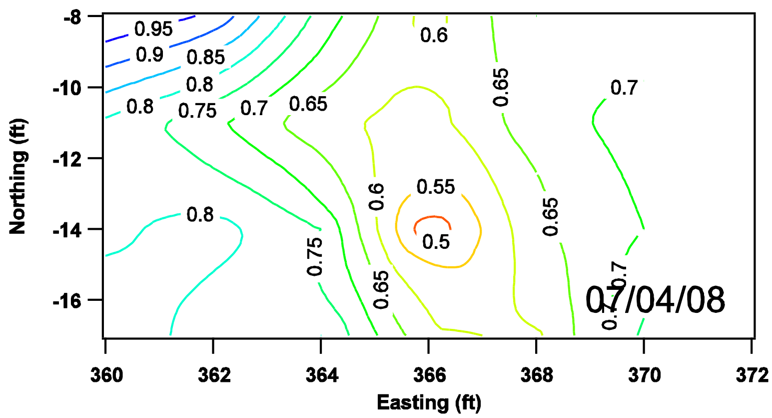
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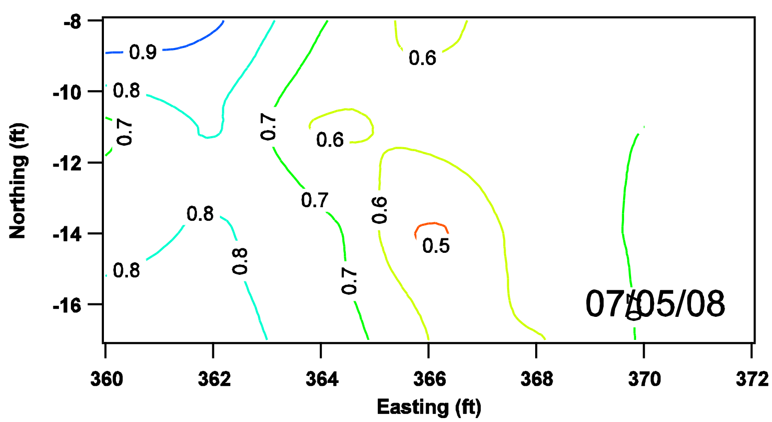
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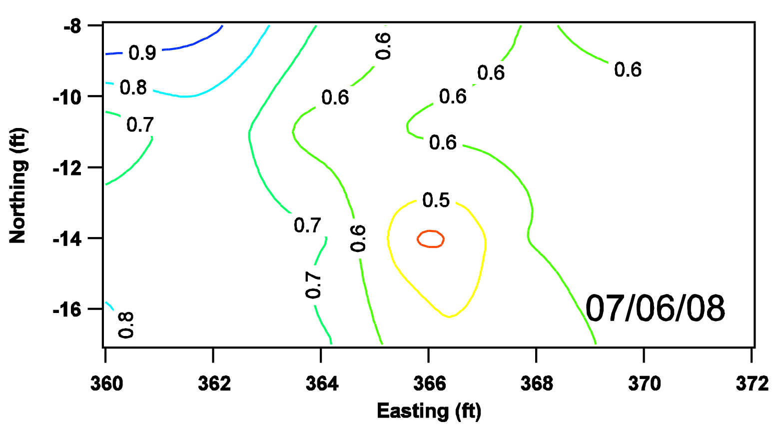
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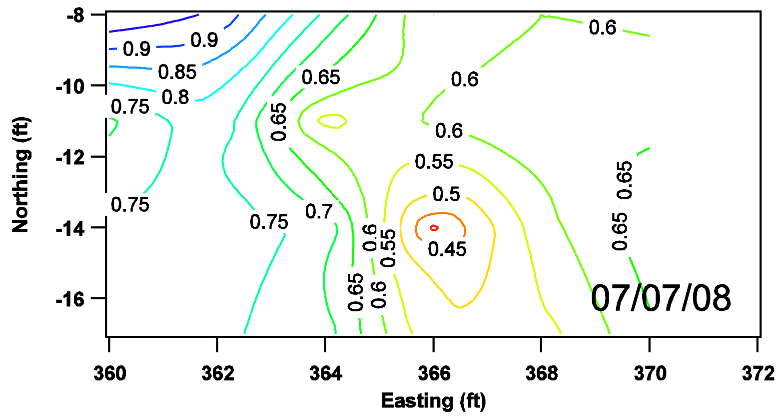
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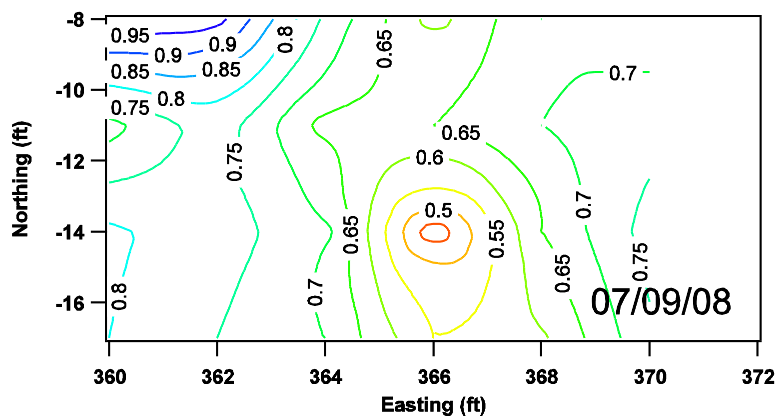
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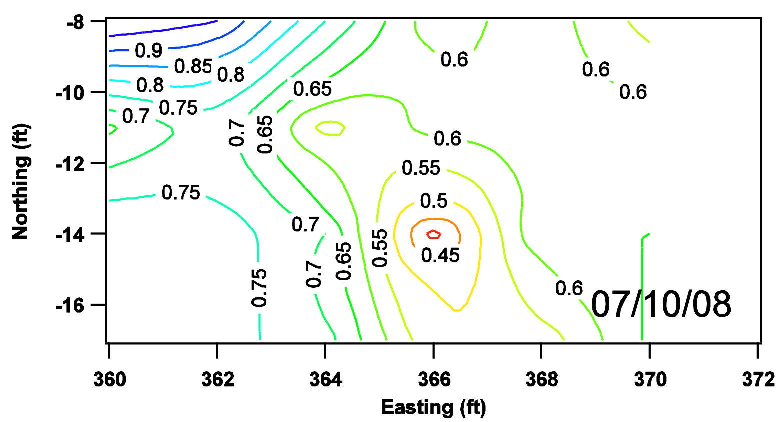
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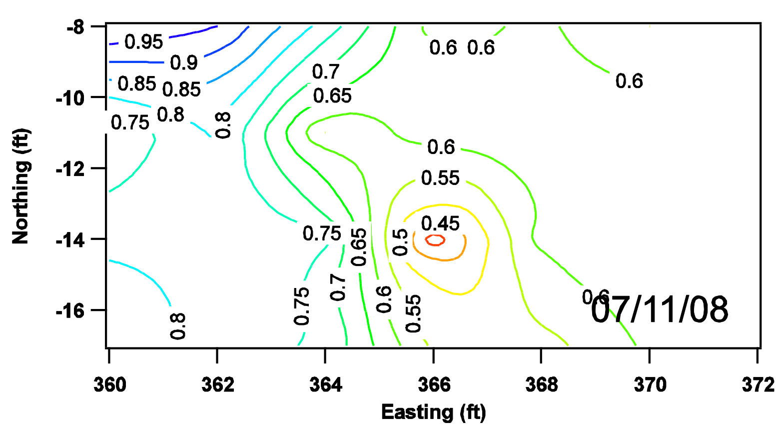
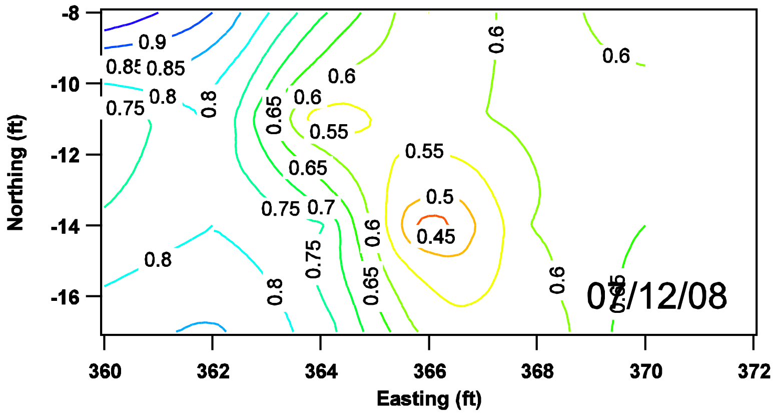

Northing (ft)
Easting (ft)
-8
-10
-12
-14
-16
360
362
364
366
368
370
372
07/11/08


07/12/08
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Easting (ft)
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-10
-12
-14
-16
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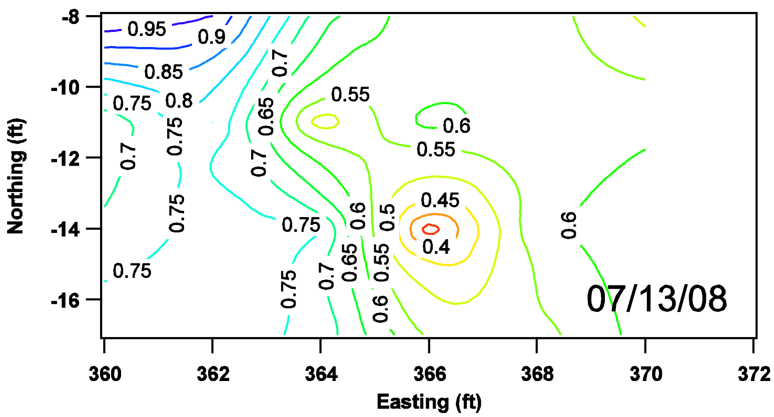
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Easting (ft)
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-10
-12
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-16
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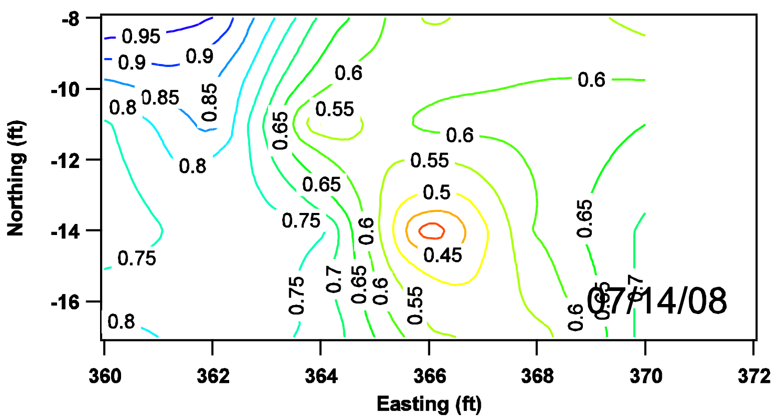
07/14/08
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Easting (ft)
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-12
-14
-16
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362
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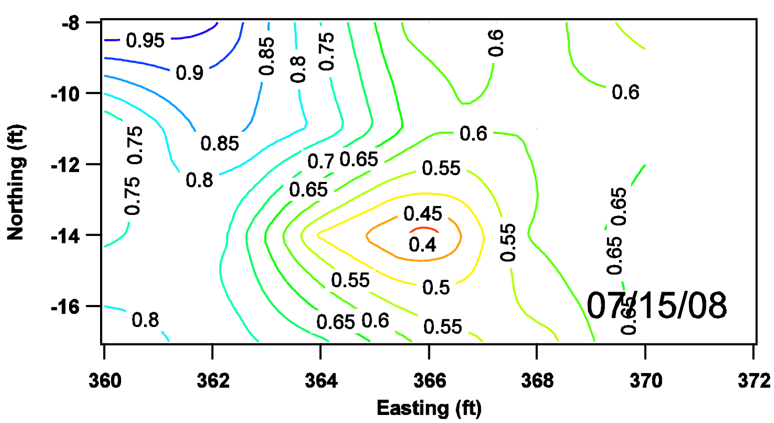
366
368
370
372


07/15/08
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Easting (ft)
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-10
-12
-14
-16
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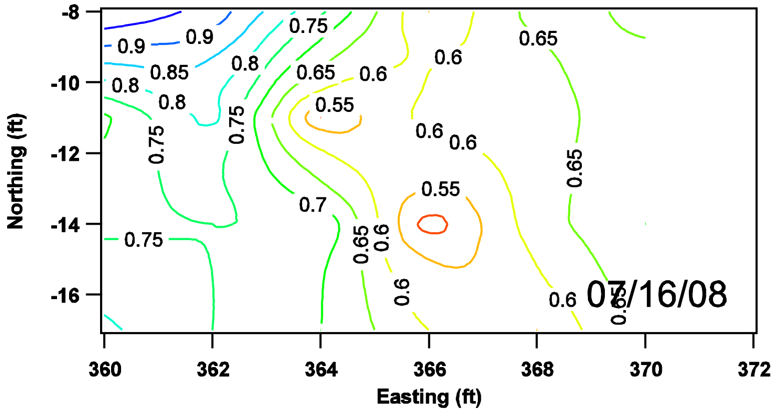
366
368
370
372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Easting (ft)
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-12
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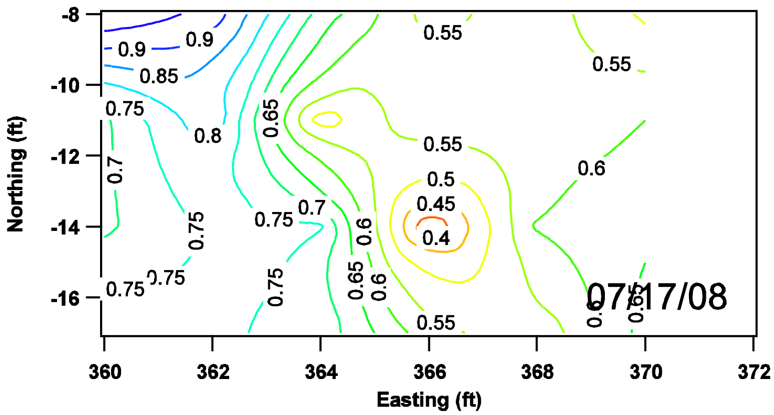
-16
360
362
364
366
368
370
372
07/16/08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Easting (ft)
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-10
-12
-14
-16
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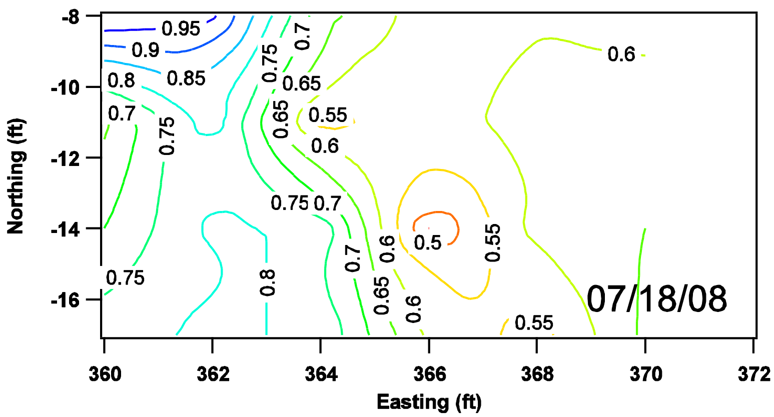
362
364
366
368
370
372
07/17/08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Easting (ft)
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360
362
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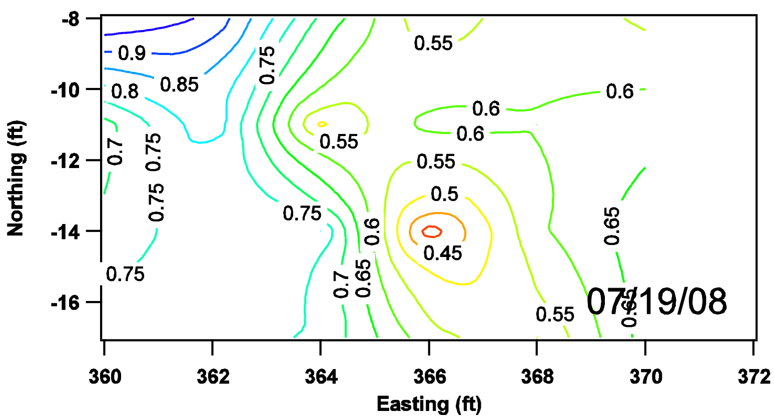
372
07/18/08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Easting (ft)
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-10
-12
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-16
360
362
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366
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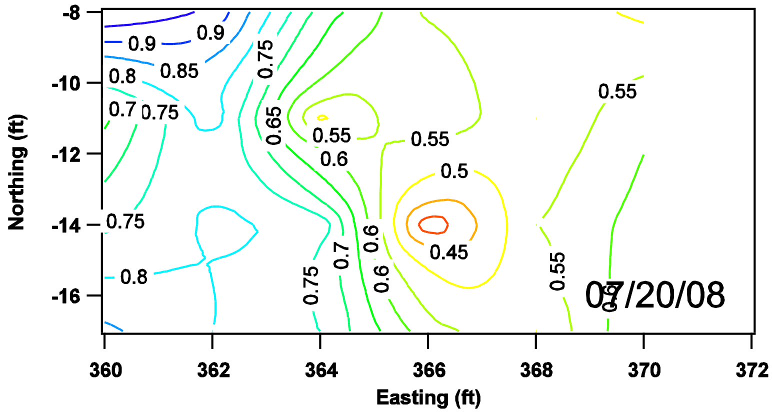
370
372
07/19/08



Northing (ft)
Easting (ft)
-8
-10
-12
-14
-16
360
362
364
366
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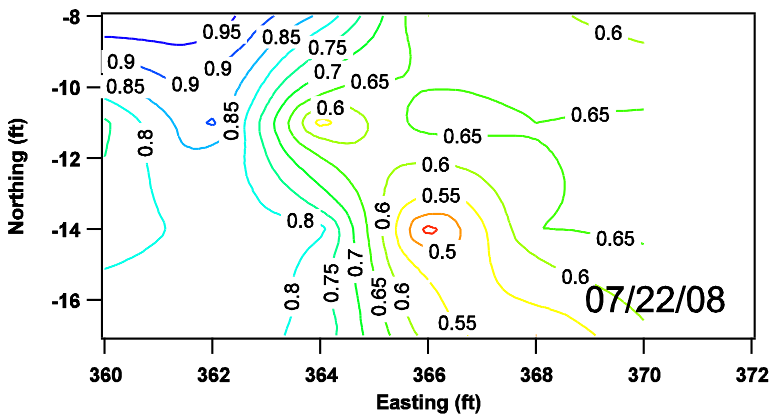
372
07/20/08



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Easting (ft)
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-10
-12
-14
-16
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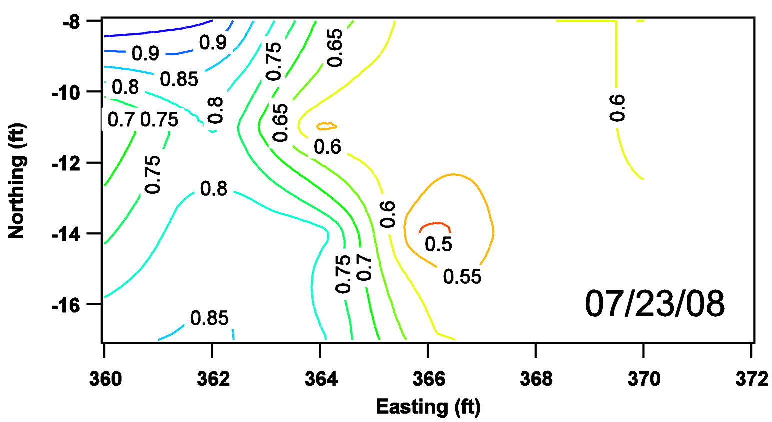
362
364
366
368
370
372
07/22/08



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Easting (ft)
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-10
-12
-14
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362
364
366
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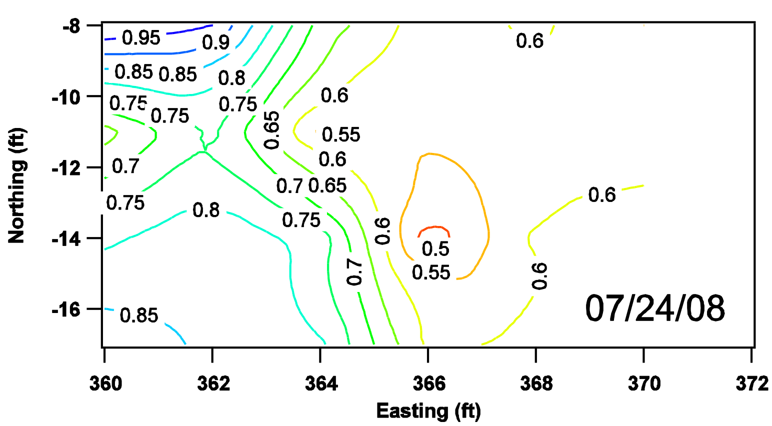
370
372
07/23/08



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Easting (ft)
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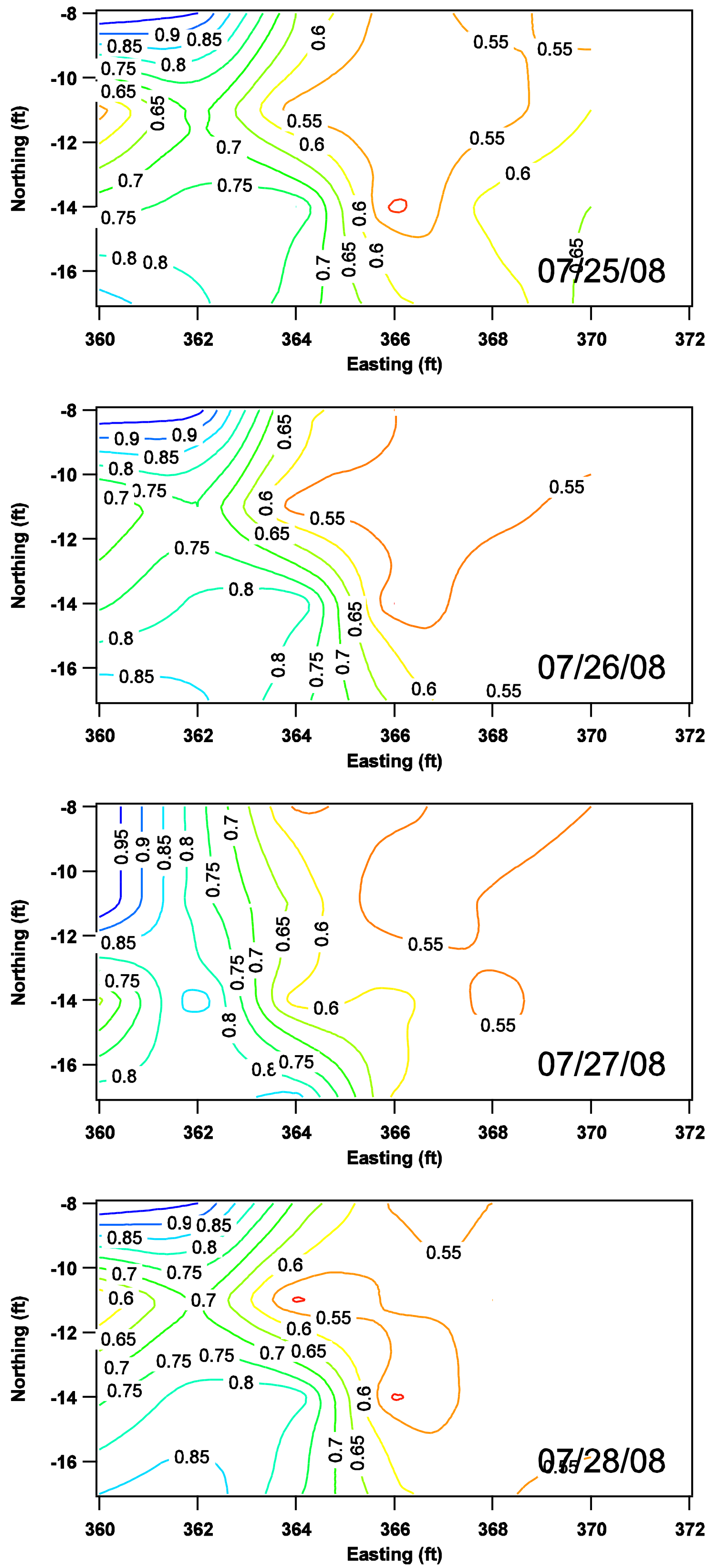
-10
-12
-14
-16
360
362
364
366
368
370
372
07/24/08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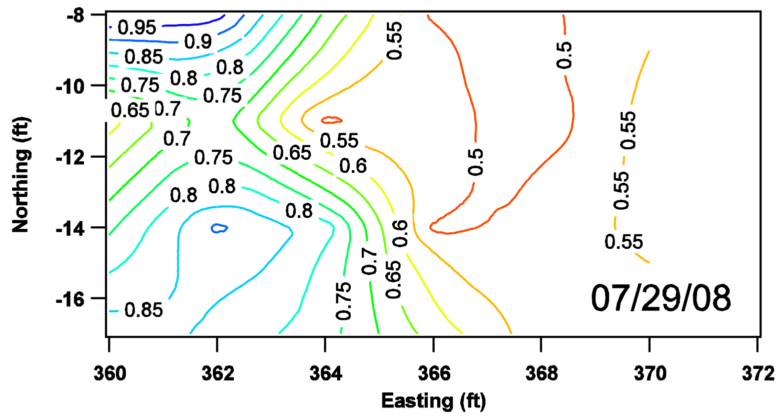
Easting (ft)
07/25/08
07/26/08
07/27/08
07/28/08


07/29/08
Northing (ft)
Easting (ft)
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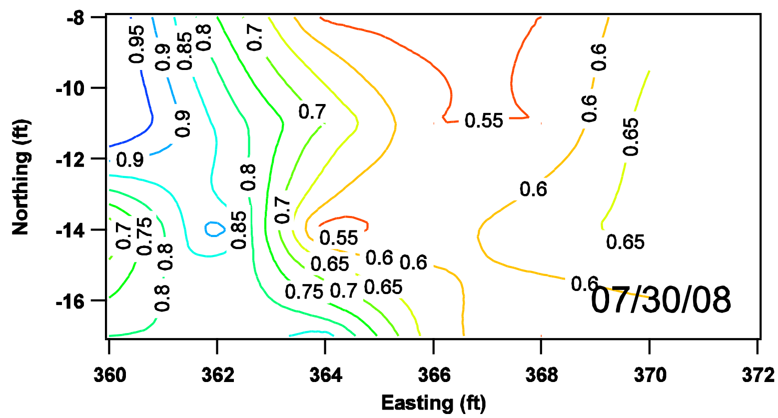
07/30/08
Northing (ft)
Easting (ft)
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-10
-12
-14
-16
360
362
364
366
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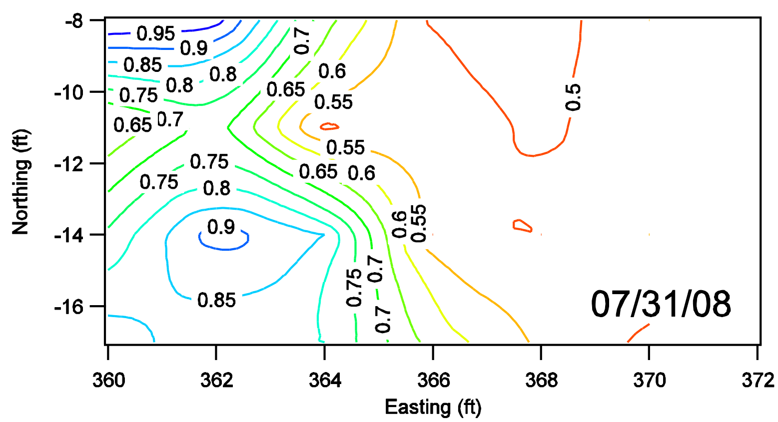
372


07/31/08
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Easting (ft)
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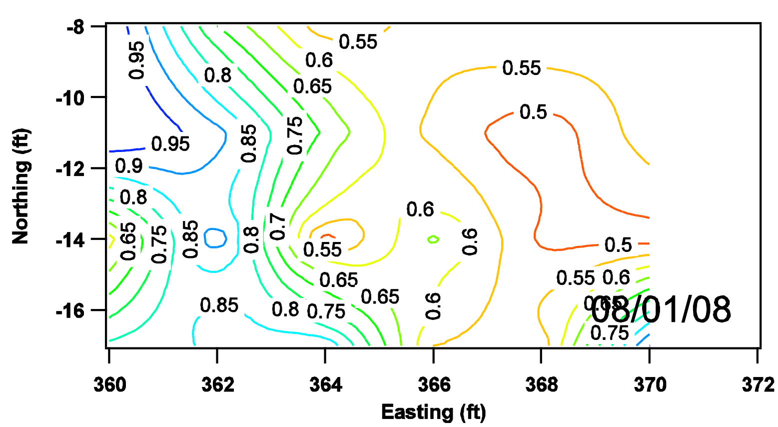
08/01/08
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Easting (ft)
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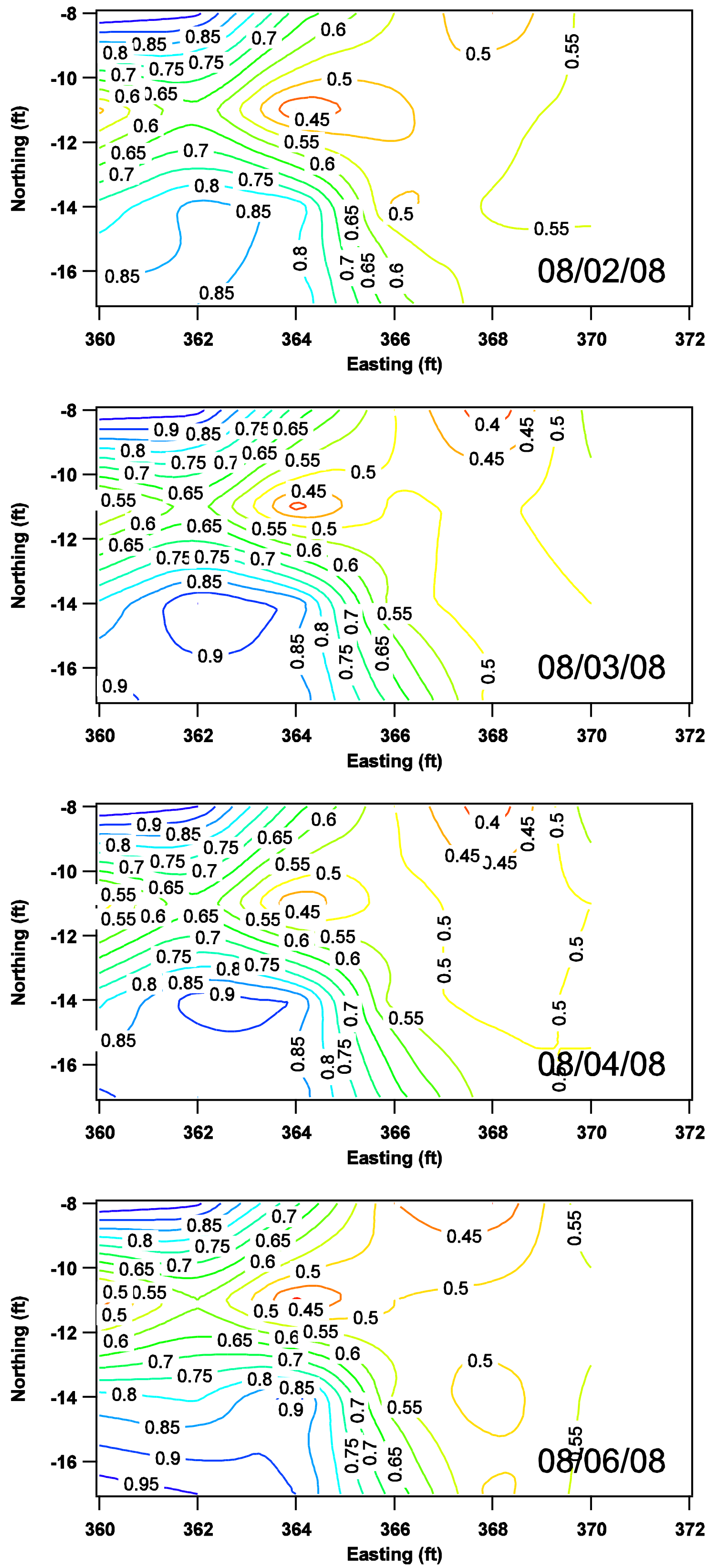
372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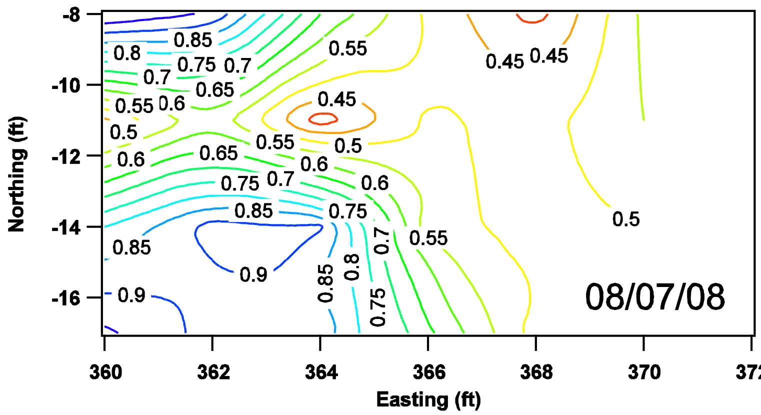
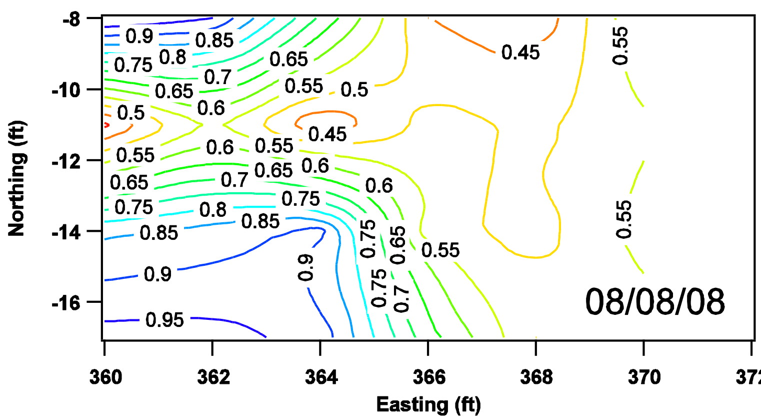
Easting (ft)
08/02/08
08/03/08
08/04/08
08/06/08



08/07/08
Northing (ft)
Easting (ft)



08/08/08
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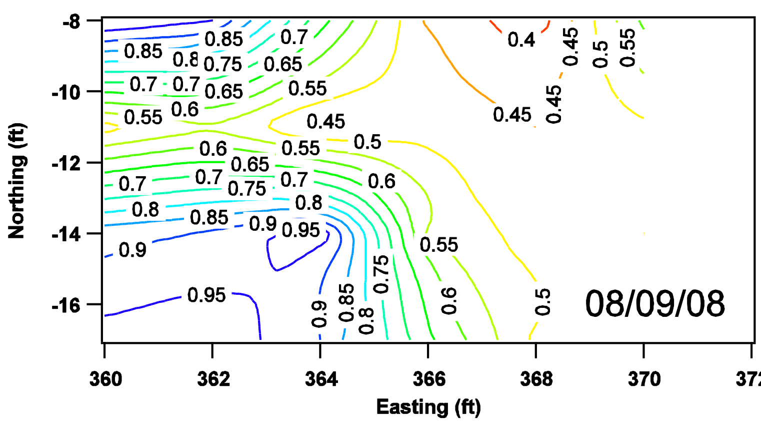
Easting (ft)



08/09/08
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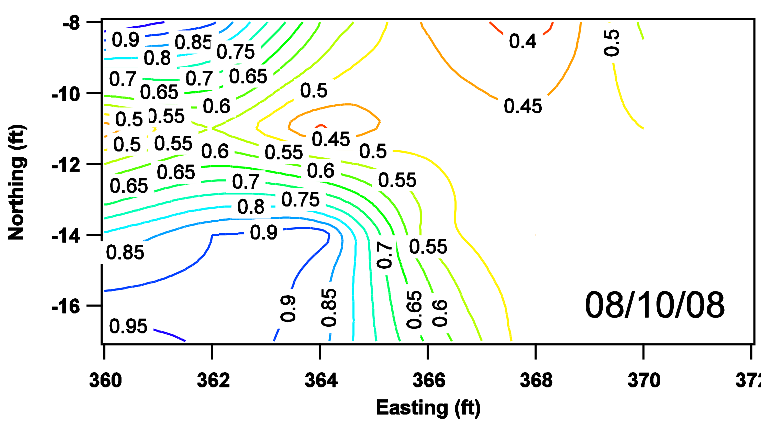
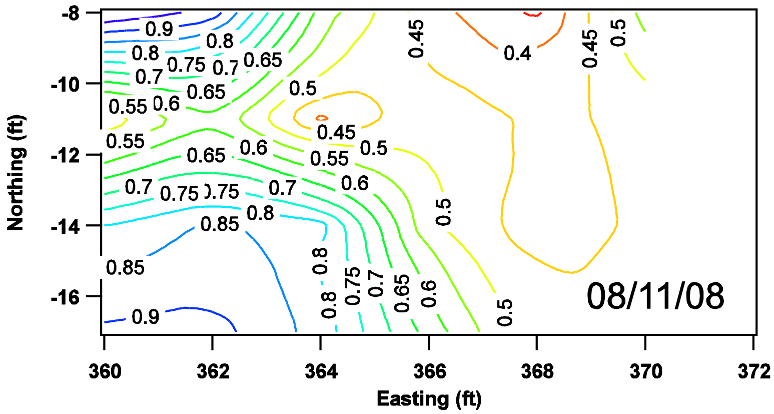
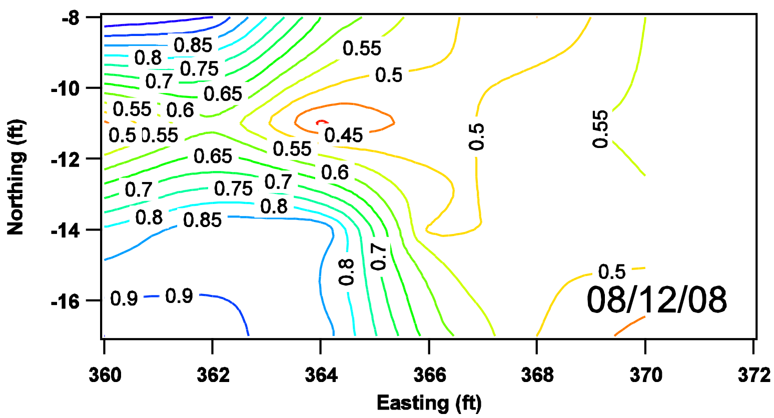
Easting (ft)



08/10/08
Northing (ft)
Easting (ft)


Northing (ft)
Easting (ft)
08/11/08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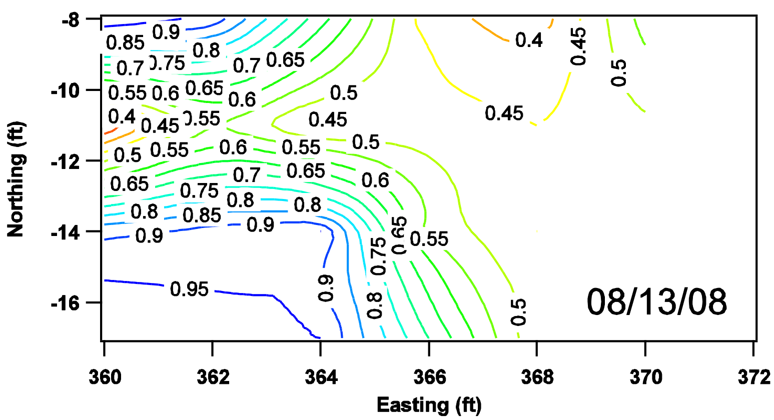
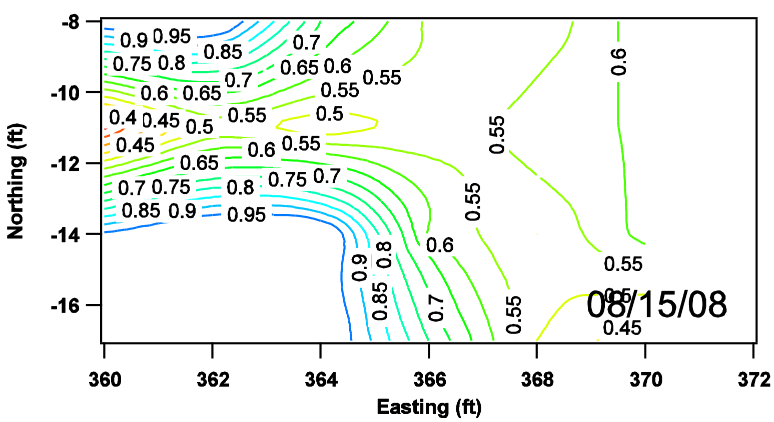
Easting (ft)
08/12/08


Northing (ft)
Easting (ft)
08/13/08


Northing (ft)
Easting (ft)
08/15/08

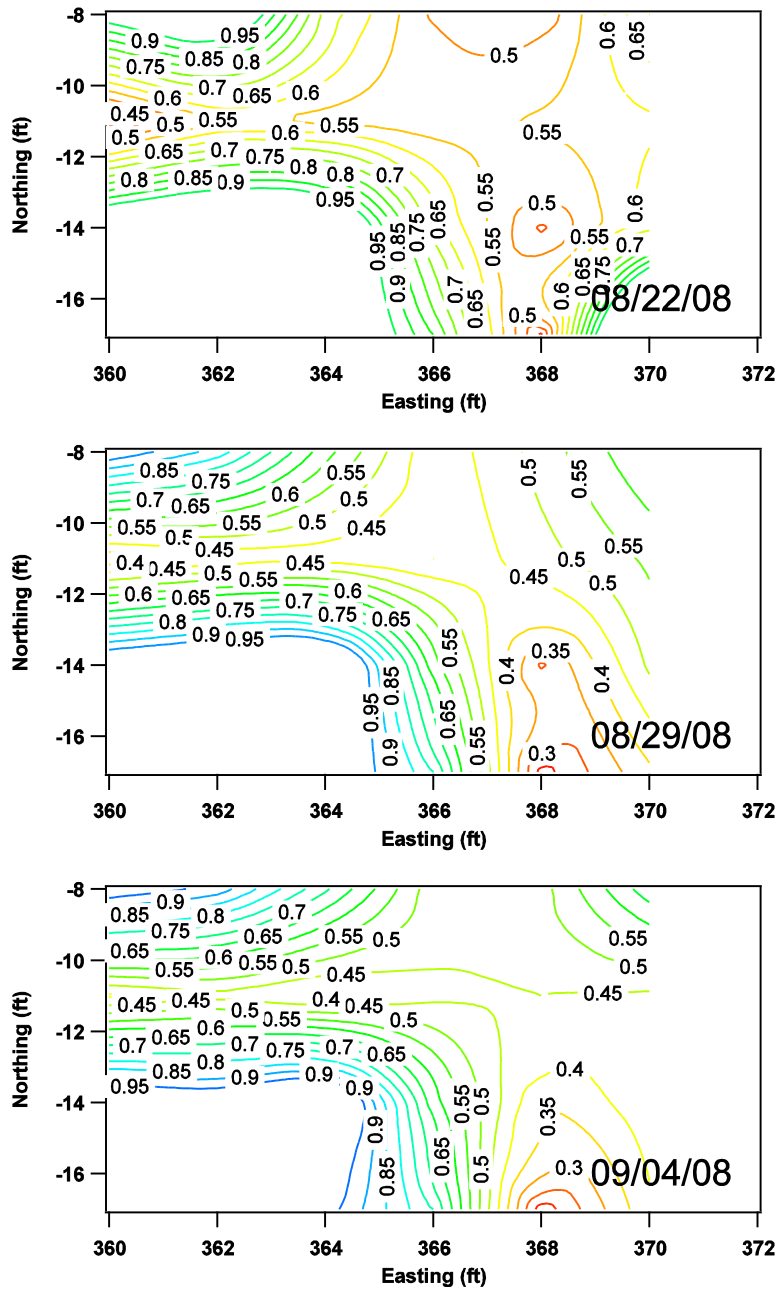


Figure 22. Water level surveys. Daily measurements of the water level over the knickpoint from a fixed datum show the progression of the knickpoint face.