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Geomorphic History of the Grand River and Grand River Valley: Natural and Anthropomorphic Hydraulic Controls

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Abstract

Preliminary investigation into the feasibility and benefits of removing 5 low head dams located on the Grand River, in the city of Grand Rapids, Michigan, is currently underway. The anthropomorphic hydraulic controls (dams), constructed in the late 1800's, were built at the location of several bedrock exposures which served as natural hydraulic controls. Prior to dam construction, an abrupt change in river gradient at these exposures resulted in the rapids for which Grand Rapids is named. Evaluation of several alternatives for restoring more natural flow and sediment dynamics in the Grand Rapids reach is part of the removal effort.

This study provides a detailed explanation of the geomorphic setting and history of the entire Grand River, including new mapping and sediment data for five natural hydraulic controls that were identified during preliminary investigation of the region. These controls were confirmed through bathymetric mapping of a ~13 kilometer reach upstream of Grand Rapids between Ada and Lowell, Michigan. A 135 meter long and roughly 30 meter wide exposure of boulder-rich fluvial sediment was identified 5 kilometers upstream of Ada, Michigan. The exposure trends generally N-S and contains fine sand to large boulders. The surface of the exposure possesses a D_{50} of 87.6 mm and a D_{10} and D_{90} of and 12.2 mm and 1,302 mm, respectively. The subsurface of this deposit has a D_{50} of 14.8 mm and a D_{10} and D_{90} of 7.3 mm and 95.5 mm, respectively. The top of the deposit is not flat. Surveying indicates the elevation of the top of the deposit varies by up to a meter. This exposure provides unique substrate and habitat uncommon in the Grand River, which is primarily a sand and silt dominated river. Further mapping and sampling of this exposure may provide data which will allow this reach to be used as an analogue for restoration efforts in Grand Rapids.

The Grand River Valley (GRV), through which the lower Grand River flows, is significantly larger than the modern floodplain. Previous research has suggested that the GRV was formed, since the last glacial maximum (LGM), by glacial outwash travelling from the Huron Basin to Glacial Lake Chicago (in the Lake Michigan Basin). Mapping and analysis of approximately 40,000 water wells adjacent to the Grand River Valley revealed: 1) a bedrock channel, presumably occupied by the ancestral Grand River; 2) evidence for a Grand River outlet north of the modern location which predates the LGM; and 3) a N-S trending area of thick alluvium and boulder occurrence which may represent valley fill of the pre-LGM bedrock valley.

Introduction

Crossing eighteen counties and extending 404 kilometers, the Grand River (GR) is Michigan's longest river. It begins in northern Hillsdale County, Michigan, and flows through the cities of Jackson, Lansing, Ionia, Lowell, Ada, and Grand Rapids to its mouth in Grand Haven, Michigan (Fig. 1.). The Grand River watershed (GRW) encompasses a total drainage area of over 14,245 km^2 (5,500 mi^2), comprising 13% of the entire Lake Michigan drainage basin, making it Michigan's second largest (USACE, 2007). This watershed is composed of four sub-watersheds: the Upper Grand, Maple, Thornapple, and Lower Grand watersheds. Contained in these are the GR's major tributaries: the Thornapple, Rogue, Flat, and Maple Rivers. Downstream of its confluence with the Maple River (near Saginaw Bay), the modern GR is not responsible for shaping the valley in which it flows, characterizing it an under-fit stream. Here, the GR enters a feature known as the Grand River Valley (GRV) (Fig. 1). The GR follows this valley from its confluence with the Maple River to its outlet at Grand Haven, MI.

The GRV begins near the town of Maple Rapids, MI where it extends west to Grand Haven, MI. This valley is characterized in most regions by the presence of broad valley floors, deeply incised ravines, and relict flood terraces (Bretz, 1952; Eschman and Farrand, 1970; Robards, 1980). It is described as possessing a nearly uniform width of roughly 1.6 kilometers (Kehew, 1993; Leverett and Taylor, 1915). Earlier work suggests that the GRV was cut when it served as the main outlet for glacial meltwater in the Huron and Erie Basins during the Late Wisconsinan glacial period (Bretz, 1952; Kehew, 1993; Leverett and Taylor, 1915). The GRV glacial drainage system carried meltwater drainage from glacial lakes in the Huron and Erie basins west, across the "thumb" of Michigan (near Saginaw, Michigan), where it discharged into a glacial Lake Michigan (Bretz, 1951a; Bretz, 1951b; Bretz, 1952; Bretz, 1959; Bretz, 1964; Bretz, 1966, 1969; Eschman, 1980; Eschman and Farrand, 1970; Farrand and Eschman, 1974; Hough, 1966; Kehew, 1993; Robards, 1980). The gradient of the modern GR downstream of its confluence with the GRV (the "Lower Grand") is reported to be significantly different than its gradient upstream of the GRV confluence ("the Upper Grand") (Eschman and Farrand, 1970; Leverett and Taylor, 1915).

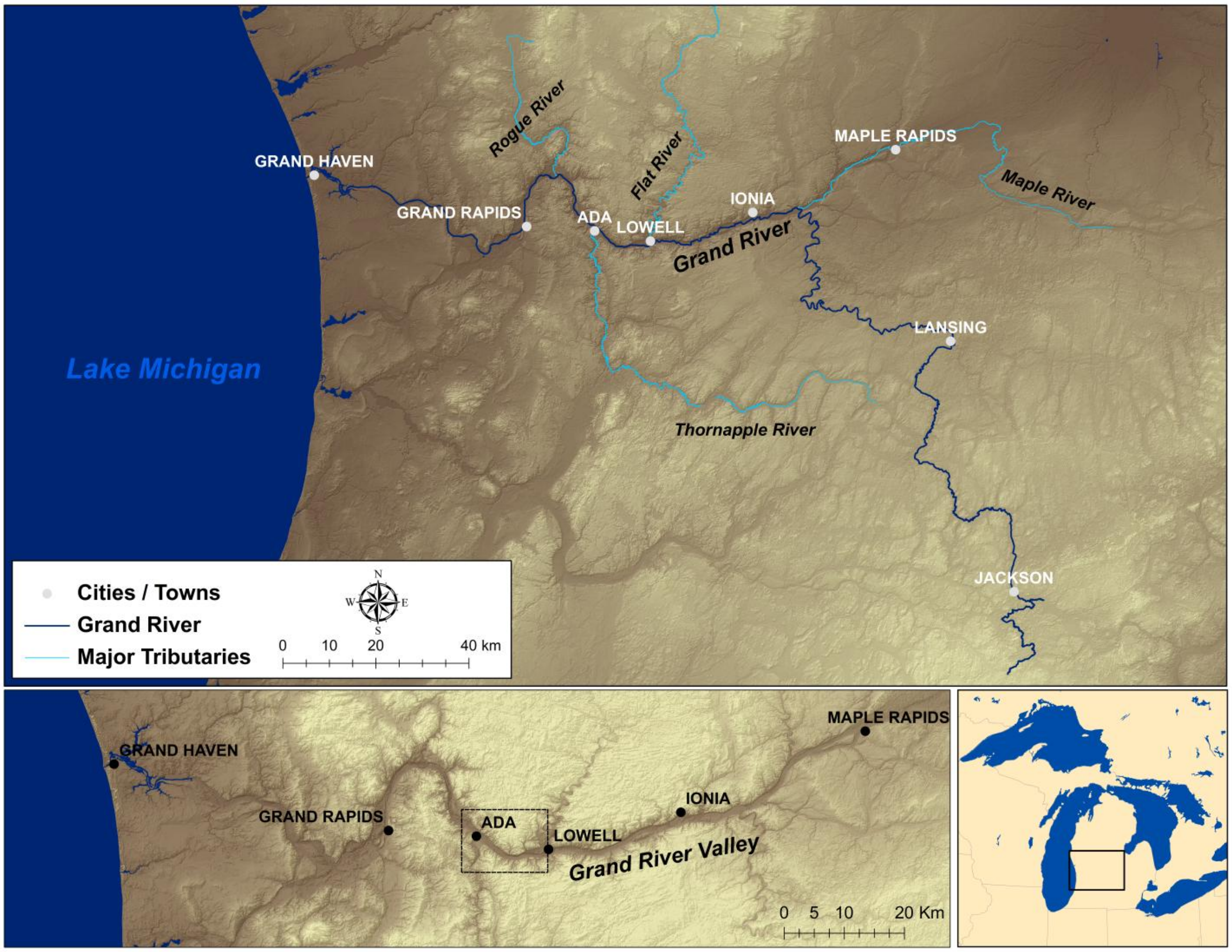

Fig. 1. The modern Grand River (top) and Grand River Valley (bottom left). The location of our primary study reach (through which bathymetric and sediment data was collected) is represented on the bottom left as a dashed box.

Stream gradients (longitudinal-stream profiles) of alluvial river channels reflect a balance between sediment transport and bed erosion (Lane, 1955; Mackin, 1948). Changes of baselevel or sediment supply and transport will cause the channel to adjust to achieve the gradient which best optimizes these conditions (Crosby and Whipple, 2006). Channel adjustment to allow equilibration of these variables is not synchronous throughout a basin, but rather propagates upstream through the main river channel (Howard, 1994; Tucker and Slingerland, 1994). The establishment of equilibrium conditions can be prevented by hard points in the form of bedrock exposures, or alluvium which is too large to transport by available stream power. Channel alteration occurs at a mobile boundary, which develops between adjusting portions of the channel and portions which retain their relict, unaltered form. This fluvial portion of the transitory boundary between adjusting and relict topography is defined as a knickpoint (Crosby and Whipple, 2006). Knickpoints are most often visible in topographic profiles as an abrupt change in river gradient. Both natural and anthropomorphic structures affect the formation, migration rate, and magnitude of knickpoint migration and sediment transport through rivers (Wampler et al., 2007). Although a wide-range of naturally occurring natural hydraulic controls exist (see Costa and Schuster, 1988), some common natural hydraulic controls of interest to this study include: 1) bedrock; and 2) glaciofluvial derived alluvium too large to transport with available stream power.

Elevated bedrock obstructions in the river bed, or bedrock sills, can dramatically affect the rate at which equilibrium gradient is achieved following base level change. The modern GR is a sand and silt dominated river. Bedrock controls are rare, however, a sill composed of Bay Port Limestone and Michigan Formation dolostone occurs in the channel bottom through the city of Grand Rapids, Michigan. Knickpoint migration rate and magnitude at bedrock controlled river reaches, such as that through Grand Rapids, is a function of stream power, sediment size, sediment supply, and bedrock resistance (Crosby and Whipple, 2006; Gardner, 1983; Gasparini et al., 2006; Miller, 1991; Seidl and Dietrich, 1993; Sklar and Dietrich, 1998; Snyder et al., 2003). These variables control the rate of incision into bedrock, thus controlling the knickpoint migration rate and the rate at which an equilibrium gradient is achieved.

Glaciofluvial deposits derived from tills and moraines in both active and post-glacial landscapes can act as natural hydraulic controls. A total of fifteen moraines are reported to be present along the

GRV; 11 are recessional moraines of the Saginaw lobe, and five are recessional or lateral moraines of the Lake Michigan lobe (Eschman and Farrand, 1970). Glacial meltwater can become trapped behind a moraine, forming a natural dam. Referred to as "moraine dams", these structures are commonly steep-sided and have width-to-height ratios varying between 0.1-0.2 (Clague and Evans, 2000). Breaching of moraine dams can result in catastrophic outburst flooding of glacial meltwater impounded behind the dams. This occurrence has been well documented in both modern and ancient glacial landscapes (Baker and Bunker, 1985; Bretz, 1969; Cenderelli and Wohl, 2003; Clague and Evans, 2000; Hewitt, 1982; Richardson and Reynolds, 2000; Vuichard and Zimmermann, 1987).The magnitude and rate at which discharge is released following a moraine dam breach is a function of till composition, triggering event (e.g. landslide, icefall, rainfall), and volume of impounded water (Costa and Schuster, 1988). Boulder armor can form at the outflow channel of moraine dams composed of boulder-rich till. This affects outflow channel incision following dam failure. The Cumberland Glacier in Vancouver, British Columbia provided an example of such an occurrence. Nostetuko Lake, impounded behind a moraine dam built by the glacier, catastrophically discharged down the Nostetuko River when an ice avalanche caused dam failure (Blown and Church, 1985). Channel adjustment to the abrupt change in base level ceased when a boulder armor paved the outlet channel floor.

The most prominent and widespread anthropomorphic hydraulic controls acting on contemporary river systems are constructed dams. More than 75,000 anthropogenic dams greater than or equal to 2 meters in height impound portions of most watersheds worldwide (Graf, 2006). A total of 228 dams are present within the Grand River watershed (Hanshue and Harrington, 2011). Dams dramatically alter river response to baselevel change (Graf, 2006; Leopold, 1992; Leopold and Bull, 1979). Baselevel lowering in a dam-controlled river system only affects the downstream portion of the river. The upstream portion experiences a "slack-water" effect, causing sediment infilling upstream as the channel adjusts to the decrease in slope. The opposite effect occurs downstream of dams.

Downstream reaches typically become deeply incised due to a sediment deficit below the dam (Kondolf, 1994; Schmidt and Wilcock, 2008).

Preliminary investigation into the feasibility and benefits of removing 5 low head dams located on the Grand River in the city of Grand Rapids, Michigan is currently underway. These dams are the only major anthropomorphic hydraulic controls active in the Lower Grand Basin of the Grand River. Proponents of the dam removal project hope to restore the natural rapids (for which the city is named) that once occupied the channel downstream of these controls. Historically, the rapids are described as “not of the nature of an abrupt leap or drop, but have a nearly uniform descent for the distance of a little more than a mile, amounting to a fall of about eighteen feet, over a limestone bed…”(Baxter, 1891).The limestone bed is mapped as part of both the Bayport Limestone and Michigan Formation and is roughly 300 million years old. This bedrock exposure, to our knowledge, is the only previously described natural hydraulic control within the Lower Grand Basin, as well as one of only three known locations in which bedrock is exposed along the entire river (Eschman and Farrand, 1970).

This study investigates natural hydraulic controls not previously mapped or described upstream of Grand Rapids, MI. Five areas of what appear to be bedrock or cemented gravel exposures were identified in the Grand River between Ada and Lowell, MI using Google Earth aerial imagery (Fig. 2). Near this location, a 135 meter long outcrop of fluvial sand, gravel, and boulders was identified 5 kilometers upstream of Ada, MI. Detailed geologic, bathymetric, and sediment data was collected and analyzed along this reach (Fig. 1) to confirm the existence of and to characterize these exposures. Our research questions include: 1) What natural hydraulic controls exist along our study reach and what influence do these have on the flow dynamics and sediment transport of the modern and ancient Grand River?; 2) Can subsurface lithology data (water well data) be used to infer shallow bedrock locations which may influence Grand River and Grand River Valley morphology and sediment transport?; 3) Can the modern and ancient Grand River and Grand River Valley gradient (long profile) be explained by known hydraulic controls and geomorphic history?; and 4) Will the removal of existing dams in Grand Rapids result in hydraulic parameters and geomorphic features similar to other reaches with natural hydraulic controls?

Fig. 2. Potential outcropping substrate identified during preliminary aerial photography investigation (outlined in red).

2. Geomorphic history of the Grand River and Grand River Valley

Glacial Grand River and Grand River Valley

The GRV has been described as one of the most spectacular and deeply incised glacial drainage features in North America (Leverett and Taylor, 1915). As previously mentioned, during the Late Wisconsinan glacial advances (Woodfordian substage; between 35 and 10 Ka), the valley operated as the primary connecting channel between glacial lakes in the Michigan, Huron, and Erie basins when ice blocked the passage way between the Huron and Michigan basins (present day Mackinac Straits) (Colman et al., 1994; Eschman and Karrow, 1985; Kehew, 1993; Larson and Schaetzl, 2001). The GRV is located where two large lobes of the Laurentide ice sheet, the Saginaw Lobe (SL) and the Lake Michigan Lobe (LML), advanced toward one another (Fig. 3). As these lobes of the Laurentide ice sheet receded, large proglacial lakes formed in the southern Great Lakes basin between areas of higher topography in Illinois and Ohio to the south and the ice margin to the north (Larson and Schaetzl, 2001; Teller, 1987). The most influential of these on the morphology of the GRV were glacial lake Maumee (14ka), Saginaw (~14-12.8ka), Whittlesey (~13 -12.7ka), and Warren (~12.5 – 12.2ka) in the Huron and Erie Basins, and glacial Lake Chicago (~14-11.6Ka) in the Lake Michigan Basin (Bretz, 1951a; Bretz, 1951b; Bretz, 1952; Bretz, 1959; Colman et al., 1994; Eschman and Farrand, 1970; Eschman and Karrow, 1985; Farrand and Eschman, 1974; Hansel and Mickelson, 1988; Hough, 1966; Kehew, 1993; Leverett and Taylor, 1915). Glacial meltwater contained in the proglacial lakes in the Huron and Erie Basins is reported to have drained west, through the GRV, into Glacial Lake Chicago. Each of these proglacial lakes had various prominent lake levels, or phases, correlating with the retreat and/or advance of various lobes of the Laurentide Ice Sheet or the opening/closing of proglacial lake outlets. As the main connector between the Hurон and Erie Basins in the East and the Lake Michigan basin in the west, the GRV has figured prominently in studies correlating Late Wisconsinan proglacial lake phases.

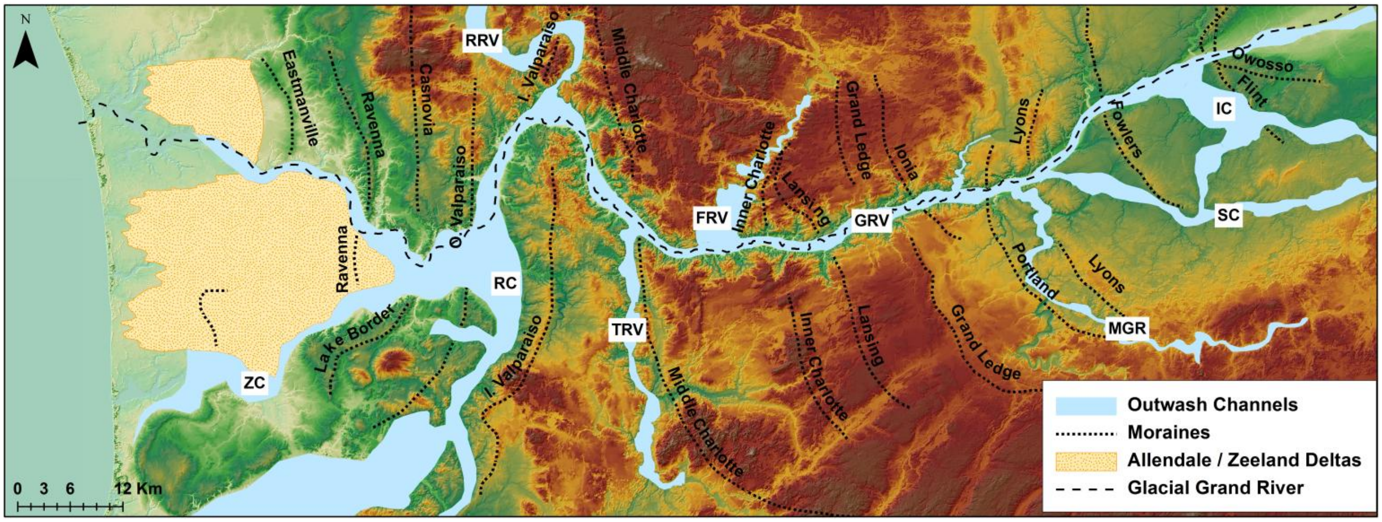

Fig. 3. Important geomorphic features along the GRV: the Zeeland Channel (ZC), the Ross Channel (RC), the Rogue River Valley (RC), the Thornapple River Valley (TRV), the Flat River Valley (FRV), the Grand River Valley (GRV), the Modern Grand River (MGR) outwash channel, Stoney Creek (SC), and the Imlay Channel (IC). Map modified from Eschman and Farrand (1970).

2.2 Previous Work on the GRV

Previous investigation into the origin and geomorphology of the Grand River Valley include the work of Leverett and Taylor (1915), Bretz (Bretz, 1951a; Bretz, 1951b; Bretz, 1952; Bretz, 1959; Bretz, 1964), Hough (1966), Eschman and Farrand (1970), Farrand and Eschman (1974), Robards (1980), Kehew (1993), and Larson et al. (1994).

Leverett and Taylor (1915) were the first researchers to formally define the GRV as the connecting channel for which drainage from proglacial lakes in the Huron and Erie Basins emptied into the Lake Michigan Basin. They hypothesized that the formation of the GRV was entirely a product of lake and base-level changes at the river mouth as the Saginaw lobe and Lake Michigan lobes of the Laurentide ice sheet retreated northward. Leverett and Taylor (1915) do not believe that the GRV was the result of modification of a major pre-existing topographic low, but postulate that it originally followed a “shallow, ill-defined depression” on the surface of glacial drift (Leverett and Taylor, 1915). They propose that the creation of the main channel (and hence the river valley) began when proglacial meltwater from glacial Lake Maumee II discharged across the “thumb” region of Michigan. Incision of this channel (the GRV) occurred during progressively lower phases of Lake Chicago. This incision was sped up by additional meltwater discharge from tributary meltwater channels of ice-marginal streams.

Bretz (1952) described the geomorphic history of the GRV in three episodes: 1) the erosion of the main channel; 2) meltwater discharge during the building of a series of moraines; and 3) incision of the GRV during discharge from succeeding proglacial lakes in the Huron and Erie Basins (Bretz, 1952). Bretz (1952) argues for the existence of a pre-glacial valley extending along the course of the GRV (contradicting Leverett and Taylor’s interpretation). In the early stages of his second episode, interlobate drainage between the Saginaw and Lake Michigan lobes (near the modern day Rogue River) passed through the Grand Rapids area, draining southwesterly through the Ross and Jamestown channels between the Valparaiso moraines into the modern Kalamazoo River Valley (Fig. 2.). Retreat of the Saginaw Lobe extended the GRV east as the Glacial Grand River experienced headward erosion through recessional moraines. Bretz (1952) postulates that the excavation of the main channel and the building of the Allendale Delta occurred during this time. The third episode explained by Bretz (1952) involves proglacial lake discharge through the GRV. He attributes various terrace surfaces along the GRV to represent equilibrium gradients graded to succeeding lake levels. His interpretation of the timing of lake discharges down the GRV, specifically that of Lake Warren, was challenged by some (Hough, 1966), however subsequent terrace correlation generally supports Bretz's interpretations regarding lake discharge chronology through the GRV (Eschman and Farrand, 1970; Farrand and Eschman, 1974; Robards, 1980).

It has been suggested that one or more glacial-lake outburst floods discharged from lakes Maumee (I, II, and III) and Whittlesey in the Huron Basin, through the GRV, into the Lake Michigan Basin (Eschman and Karrow, 1985; Kehew, 1993; Kozlowski et al., 2005). The present depth of the GRV below glacial Lake Saginaw, boulder lag at the Grand River Valley entrance, streamlined landforms (islands) and bedrock exposures in the valley bottom are all cited as geomorphic evidence for glacial-lake outburst floods through the GRV (Kehew, 1993). This is contrary to the proposal that base-level lowering at the outlet of the Glacial Grand River (Leverett and Taylor, 1915) caused channel floor incision, but supports Bretz's conclusion that increased discharge of meltwater caused channel down-cutting into the valley floor.

2.3 Unanswered Questions

Previous reports have mentioned bedrock exposures along the GRV (Bretz, 1952; Kehew, 1993; Robards, 1980). However, to our knowledge, the extent to which these exposures influence the gradient of the modern GR, and previously influenced the Glacial GR has not been investigated. Bretz (1959) calculated a gradient of 0.00014 (0.75 feet / mile) for the Glacial GR. However, this is may be an oversimplification. Other work suggests that the gradient of the GRV from Maple Rapids, MI to Grand Rapids, MI averages 0.00012 (0.625 feet / mile), but increases abruptly to 0.00021 (1.1 feet / mile) from Grand Rapids to Eastmanville, MI, and flattens out to 0.00014 (0.74 feet / mile) for the final 21 kilometers of its length (Eschman and Farrand, 1970). A large bedrock sill (described above) exists in the bed of the GR in Grand Rapids, MI. This exposure has restricted the incision to the downstream portion of the stream. Furthermore, while the existence of “boulder fields” on the valley floor and in relict terraces has been documented (Bretz, 1952; Kehew, 1993; Leverett and Taylor, 1915), the origin of these deposits and effect that these had on channel adjustment following base level change has not yet been provided. Could these boulder fields have functioned as natural hydraulic controls similar to that which existed at the Chicago outlet (Bretz, 1964; Eschman and Karrow, 1985; Kehew, 1993)? What is the distribution of these boulder-rich deposits beneath the bed of the modern Grand River? Do these deposits provide unique habitat previously not mapped or described?

3. Methods

In an attempt to answer the above questions, investigation into the geologic, sedimentologic, and topographic characteristics of the GR and GRV was made. A topographic profile spanning the entire extent of the river was created to identify existing knickpoints. Bedrock topography through Kent and Ottawa counties was investigated for shallow bedrock or bedrock exposures in the river which may act as, or influence the accumulation of, natural hydraulic controls (boulder-rich alluvium). A geographic information system (GIS) was used to map sediment characteristics of the GR and GRV through Kent and Ottawa counties using drill-hole and field data. Detailed bathymetric digital elevation models (DEM) were created along two reaches of the Grand River through Kent County to better characterize potential natural hydraulic controls contained within them. Along one of these reaches, an outcrop of boulder-rich alluvial sediment was identified. This outcrop was mapped and sediment data was collected to investigate the origin of this deposit and its influence on flow dynamics and sediment transport in the modern GR.

3.1 Longitudinal Profile

A longitudinal profile, which displays water surface elevation (WSE) as a function of distance, was generated using ArcMap 10 (ESRI; Redlands, California) GIS. This was created using Digital Elevation Models (DEMs) to represent water surface elevation (WSE), a linear-referenced river centerline, and point features along the centerline. These data and features were used to measure geographic (x, y), elevation (z), and distance (m) attributes at equally spaced points along the river.

10-meter resolution DEMs spanning the entire course of the river were obtained from the National Elevation Dataset (NED) prepared by the United States Geological Survey (USGS)(Gesch et al., 2002; USGS, 2006). Dataset coordinates were projected to the North American Datum of 1983 geographic coordinate system with a World Geodetic System 1984 (WGS84) projected coordinate system. Elevations contained in the dataset were referenced to the North American Vertical Datum of 1988 (NAVD88). DEMs were downloaded by “tiles”, each tile spanning 1 degree of latitude and longitude (1x1). Individual tiles were mosaicked together in ArcMap 10 to create a seamless dataset of the entire study area.

A river centerline was digitized to represent linear distance along the GR for use in the topographic profile. The centerline extended from the mouth of the GR in Grand Haven, MI to its headwaters in Jackson County, MI. A polyline shapefile, which bound each of the banks of the GR, was downloaded from the Michigan Geographic Data Library (MiGDL)(DTMB, 2002). The bounding polyline was collapsed into a single, central line, representing the geometric center of the river using an automated method in ArcMap 10. The centerline was visually inspected for errors and was corrected where it was determined to deviate from the center of the river. Linear-referencing was performed on the centerline. This attributed measurement values, or “m-values”, to the centerline and provided an automated means of measuring the distance of features from the beginning of the line.

Equally spaced points, 500 meters apart, were created along the river centerline. Using an automated method in ArcMap 10, the distance from the beginning (mouth) of the centerline was attributed to each point. A similar automated method was used in the same GIS to attribute each point with elevation values (z-values) corresponding to its geographic location. These attributes were then delineated and tabulated to graphically represent WSE as a function of distance from the mouth of the GR.

3.2 Bathymetric Data

As previously stated, preliminary investigation of the Grand River using Google Earth aerial imagery suggested the presence of outcropping substrate between Ada and Lowell, MI (Fig. 2). To investigate these phenomena, detailed river bathymetry was collected along this reach. This data was used to create a 3D representation of river bed elevation along the reach in order to identify the type and extent of existing natural hydraulic controls. Bathymetric data was collected using a consumer grade chart plotter and a motor boat. Information contained in the data included geographic information (x, y coordinates) and depths (z-values) at points recorded in set intervals. These data were interpolated using ArcMap 10 to create a DEM of river bottom elevation.

A Garmin GPSMAP 441s chartplotter with a Transom-Mount Dual-Frequency 50/200 kHz transducer was used to collect both geographic coordinates and water depths at various points along the river. The chartplotter was fixed to the motorboat in a fashion that minimized the error between GPS and depth measurements. The chartplotter (which contained the GPS) was located approximately 0.5 meters from the transducer. GPS error ranged from ~2.4-3.0 meters. Error in depth measurements is unknown, but believed to be small, as the transducer was placed approximately 3 centimeters below the water's surface (enough to allow normal pitch and roll of the boat while keeping the transducer submerged). At intervals between 4-5 seconds, a point was recorded by the chartplotter. Each point was attributed with the geographic coordinates of the location at which it was recorded and the depth at that location. A traversing, "zigzag" pattern was utilized to ensure thorough coverage of the river bottom. A total of 15,815 data points were collected on 3 different days along the reach from Ada to Lowell.

Raw location and depth data for each point was extracted from the chartplotter and compiled and tabulated for further use. In order to transform water depth measurements at each point to river bed elevation (RBE) measurements, the data was first imported into ArcMap 10. Linear distance from the mouth of the GR, along the river centerline (created for use in the topographic profile, see section 3.1), was attributed to each point. Depths were converted to bed elevation using known datum elevation and water depth for a USGS river gage located in Ada, MI. The depth attribute of each point was transformed to RBE using trigonometric relationships between water surface elevation (WSE), the slope of the water's surface, and linear distance:

$$River\ Bed\ Elevation\ (RBE) = [(Dist_{Ada} \times WSS_{Ada\ to\ Lowell}) + WSE_{Ada}] - Depth$$

Where:

$Dist_{Ada}$ = Distance from each point to the USGS gage in Ada, MI (meters)

$WSS_{Ada\ to\ Lowell}$ = Average slope of the water's surface from Ada, MI to Lowell, MI (calculated from USGS gage measurements at both locations)

WSE_{Ada} = Average water surface elevation (meters) on the date and duration of data collection (obtained from USGS gage at Ada, MI)

$Depth$ = Water depth at each point (in meters)

Upon transformation of river depth to RBE at each measured point, RBE at non-measured locations was interpolated using an Inverse Distance Weighting (IDW) technique in ArcMap 10. The final topographic surface was exported in raster format with a pixel resolution of 2 meters (the average distance between measured points).

In addition to the bathymetric data described above, survey data for the Grand River through the city of Grand Rapids, Michigan was obtained from the Grand Rapids Whitewater Group (www.grandrapidswhitewater.org). The data provided included sediment lithology information and elevation contours. Elevation contours were used to create a DEM of the river bed using an automated method in ArcMap 10 GIS.

3.3 Boulder-rich alluvium characterization

An outcrop of boulder-rich alluvial sediment was identified 5.0 kilometers upstream of Ada during bathymetric data collection (Fig 2). Recognizing its occurrence as both unique substrate and a potential hydraulic control, further characterization of this exposure was performed. Characterization of sediment size and distribution was performed using a Trimble R7 survey grade GPS, Topcon Total Station surveying, Wolman Pebble Counts, field observations, and standard sieving methods.

The Trimble R7 GPS was used to establish 3 control points upon which our survey was based. The Topcon Total Station was used to map outcrop distribution. Mapped parameters included: 1) the extent of the exposed portion of the outcrop; 2) the extent of submerged boulder-rich alluvium in water shallow enough to wade; and 3) elevations of exposed, submerged, and buried boulder-rich alluvial sediment deposits. Locations were recorded in a Universal Transverse Mercator (UTM) geographic coordinate system (Zone 16) projected to WGS84. Elevations were referenced to NAVD88. The location and elevation of the exposed boulder-rich alluvium were collected by walking the perimeter of the exposure and recording points approximately every 2 meters. The same method was used to record elevation and extent of the submerged boulders. A cross section of the channel was also taken across the northern extent of the deposit. In the region between exposed portions of the deposit, where no visible outcropping of alluvium occurred, a series of 5 boreholes were excavated (approximately 3 meters apart) to determine the depth at which this deposit occurred in the subsurface (if at all).

A series of Wolman Pebble Counts were also completed on the boulder-rich alluvium deposit (Bunte and Abt, 2001). Three, 20 meter transects were established at its western edge. Clasts were sampled at 0.25 meter intervals along each of these transects (80 per transect) for a total of 240 counts. Grain sizes were measured using a USGS 0.50 phi interval gravelometer. Upon completion of the Wolman survey, grain size measurements were analyzed using the GRADISTAT program to obtain sediment statistics (Blott and Pye, 2001).

For further sediment analysis, a ~36 kg bulk sample of sediment was taken from the boulder-rich alluvium deposit. This sample was obtained from an excavated hole, approximately 0.5 meters in depth, near the bank of river at the location of the exposed deposit. This was performed to minimize organic substrate contamination from the surface of the outcrop (e.g. mussel shells) and to obtain a representative sample of the substrate that was unaltered by the modern river. Clasts larger than ~128 mm were excluded. The sample was dried at 105°C for approximately 24 hours. It was then disaggregated and its bulk weight was recorded. Upon disaggregation, the sample divided into two size fractions, ± 6.35 mm. The (-) 6.35 mm sub-sample was sieved at 0.50 phi size fractions using USGS standard sieves and a ROTAP shaker. Each set of sieves was placed in the ROTAP for a minimum of fifteen minutes. The (+) 6.35 mm sub-sample was measured manually with a gravelometer and separated into 0.50 phi size fractions. The weight of each size fraction for both sub-samples (± 6.35 mm) was recorded and input into the GRADISTAT program for the generation of grain size statistics (Blott and Pye, 2001).

3.4 Well Log Analysis

Bedrock topography, sediment thickness, boulder occurrence, and alluvial sediment thickness maps of Kent and Ottawa Counties (extending through the Thornapple and Lower Grand Watersheds) were created to investigate both the existence of natural hydraulic controls in the river bed as well as geologic/sedimentological characteristics of the Grand River Valley. Maps were created using data obtained from approximately 40,000 water well log records. Well logs were obtained in shapefile form from the MiGDL (DTMB, 2002). Data contained in the well logs included the geographic coordinates of each well, the stratigraphy of each well, and the lithology, depth, and thickness of each sequence of the stratigraphy.

The lithologic sequences of each well were tabulated and summarized using a lithologic classification system (Table 1). This was performed to minimize the variance between lithologic sequences described in the well logs and to highlight bedrock exposures, and alluvial thickness not attributable to glacial tills. Lithology was summarized in six classes: Boulders, Alluvium, Clay Alluvium, Organics, Soil, and Bedrock (Table 1). Depth and thickness attributes relating to the three classes of interest (alluvium, boulders, and bedrock) were compiled in a separate table. The total thickness of alluvial sediment at each well was summarized by combining the individual thicknesses of each sequence classified as “alluvium” in Table 1. The boulder class was summarized by minimum depth of each recorded occurrence. For the bedrock class, the minimum depth at which bedrock was recorded in the well log (minimum depth to bedrock) was compiled and attributed to each well. In addition to the attributes mentioned above, each table (boulder occurrence, alluvial thickness, and bedrock depth) contained a unique well identifier as well as the geographic coordinates of each well.

The summarized log records for each class (alluvium thickness, and boulder and bedrock occurrences) were imported into ArcMap 10, where the location each well was represented by a point feature. In order to transform bedrock depth to bedrock elevation for use in the creation of a bedrock topography map, the elevation of each well was extracted from the NED DEM described in section 3.1. Well-head elevations were subtracted from the depth at which bedrock, of any lithology, was first described (minimum depth to bedrock) to produce a minimum bedrock elevation at each well. Both the bedrock elevation and alluvium thickness at each well were interpolated using an inverse distance weighting (IDW) technique to predict bedrock elevation and alluvium thickness at non-measured locations. Each prediction map was exported in raster format with a pixel size (104m) that correlated with half of the mean distance between wells (280m).

The sediment thickness map was created following the completion of the bedrock elevation (topography) map. Sediment thicknesses were calculated by subtraction of the land surface elevation (obtained from the NED DEM) from the bedrock elevation.

Table 1. Reclassification of water well-log lithology descriptions. The “delete” class was not included in the well-log analysis. This class represents difficult to interpret or inaccurate lithologic sequence descriptions encountered in the original log.

	Re-Classification						
	Alluvium	Bedrock	Boulders	Clay Alluvium	Organics	Soil	Delete
Original Lithology Description	Cobbles	Dolomite	Boulders	Clay	Coal	Loam	Debris
	Conglomerate	Dolomite & Limestone		Clay & Boulders	Peat	Muck	Granite
	Gravel	Gypsum		Clay & Cobbles		Mud	Interval Not Sampled
	Gravel & Boulders	Limestone		Clay & Gravel		Topsoil	Iron Formation
	Gravel & Cobbles	Limestone & Dolomite		Clay & Sand			Lithology Unknown
	Gravel & Sand	Limestone & Sandstone		Clay & Silt			No Lithology Information
	Gravel & Silt	Limestone & Shale		Clay & Stones			No Log
	Gravel & Stones	Marl		Clay Gravel Sand			Quartz
	Gravel Sand Clay	Sandstone		Clay Gravel Silt			Quartzite
	Sand	Sandstone & Limestone		Clay Gravel Stones			See Comments
	Sand & Boulders	Sandstone & Shale		Clay Sand Gravel			Slate
	Sand & Cobbles	Shale		Clay Sand Silt			Unidentified Consolidated Fm
	Sand & Gravel	Shale & Coal		Clay Silt Gravel			Unknown
	Sand & Silt	Shale & Limestone		Clay Silt Sand			Void
	Sand & Stones	Shale & Sandstone		Gravel & Clay			Hardpan
	Sand Gravel Silt	Shale Sandstone Limestone		Gravel Clay Sand			
	Sand Silt Gravel			Sand & Clay			
	Silt			Sand Clay Gravel			
	Silt & Gravel			Sand Clay Silt			
	Silt & Sand			Sand Gravel Clay			
	Silt & Stones			Sand Silt Clay			
	Silt Sand Gravel			Silt & Clay			
	Stones			Silt Gravel Clay			
				Silt Sand Clay			

4. Results and interpretation

4.1 Longitudinal Profile

Examination of the longitudinal profile suggests the presence of four reaches with different river gradients along the GR (Fig. 4; Table 2). These reaches are: 1) the Upper Grand River; 2) the transition zone from the Upper to Lower Grand River; 3) the Lower Grand River (through which part of the Glacial Grand flowed); and 4) the relict channel of the Glacial Grand, no longer occupied by the modern Grand River.

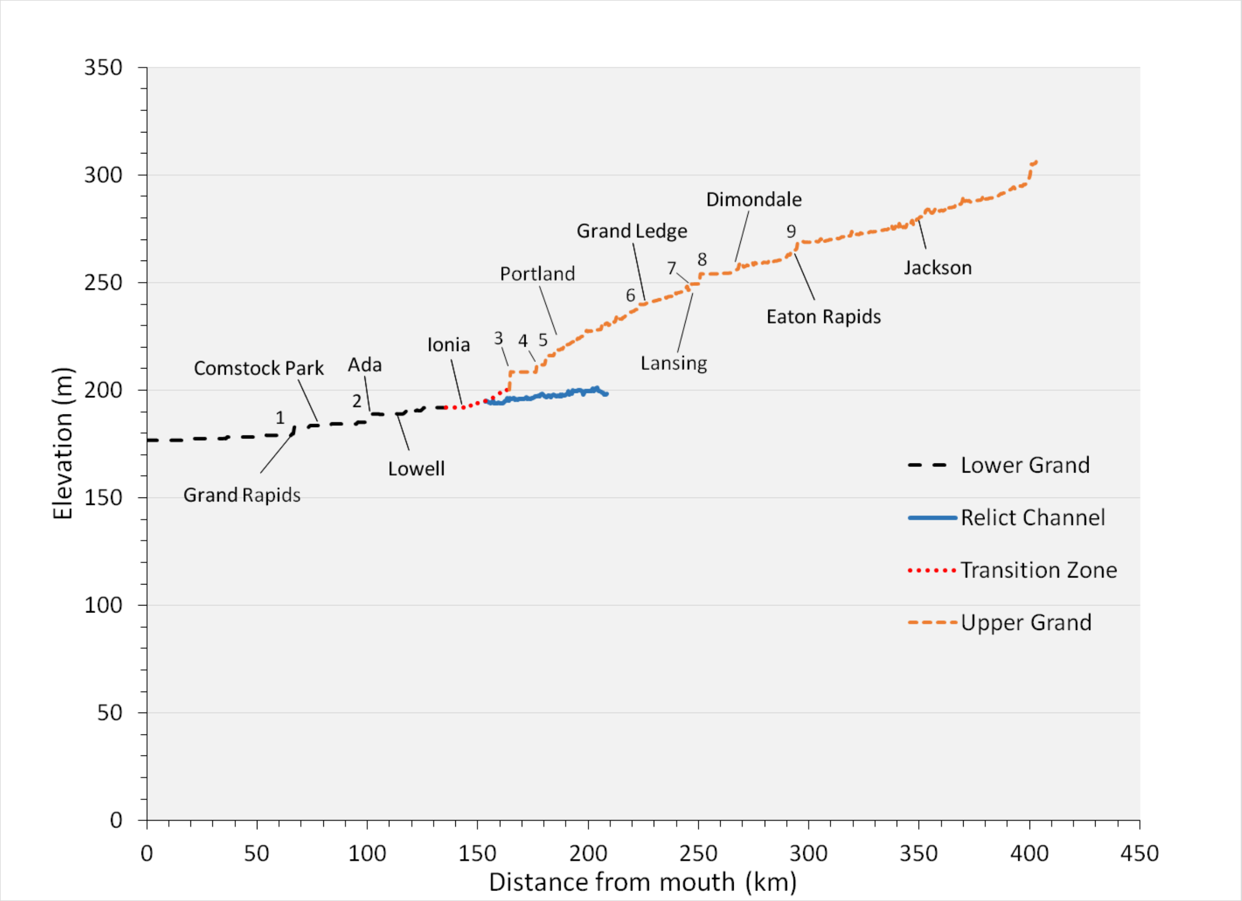

Fig. 4. Longitudinal profile through the modern and glacial Grand River. Channels are divided into four distinct categories (different colored lines) based on gradient morphology. Major knickpoints are numbered 1-9.

Table 2. Elevation rise, channel length, and slope of morphologically distinct channels in the Grand River.

Channel	Rise (m)	Run (km)	Slope (m/m)	Slope (ft/mi)
Lower Grand	15.9	135.1	0.00012	0.62
Transition Zone	8.2	28.8	0.00028	1.50
Relict Channel	6.22	20.4	0.00011	0.60
Upper Grand	107.4	241.1	0.00045	2.35
Modern River	130.8	404.5	0.00032	1.71

4.1.1 Upper Grand River Reach

The Upper Grand River reach exhibited the steepest slope (0.00045 (2.35 feet/mile)). This section of the GR served as a tributary when the GRV was an active meltwater channel (Leverett and Taylor, 1915). The largest change in river gradient occurs at a series of knickpoints near the confluence of the Upper and Lower Grand sections (knickpoints 5-3, Fig. 4; Table 3). The first of the three prominent knickpoints (knickpoint 5) appears as a drop of 4.06 meters over a distance of 4.00 km (0.0010 slope). It does not appear to correspond to any known anthropomorphic structure. Visual examination of this location via aerial imagery does not provide any conclusive evidence regarding its origin or morphology. We interpret this knickpoint to be the product of channel adjustment following dam construction. The last two knickpoints along the Upper Grand (Knickpoint 3-4) occur at the Portland City and Weber Dams, respectively. The knickpoint at the Weber dam exhibits the largest change in gradient of all knickpoints identified through the three different reaches. This knickpoint displays a slope of 0.0166.

4.1.2 Transition Reach

The abandonment of the Glacial Grand as a proglacial lake outlet in the Huron Basin marked the establishment of the modern course of the GR (Leverett and Taylor, 1915). The transition reach between the Upper and Lower GR sections exhibits this change in course, displaying a slope intermediate between the Upper and Lower sections (0.00028 (1.50 feet/mile)). It appears that this section of the river graded the Upper Grand (which again, historically served as a major tributary to the Glacial Grand River) to the Lower Grand following the stoppage of eastern meltwater discharge (approximately 12 ka; Eschman and Farrand, 1970) (Fig. 4). There does not appear to be any knickpoints along this section.

4.1.3 Lower Grand River Reach

The profile of the Lower Grand River, which flows through the GRV and was used as a glacial drainage pathway, suggests a shallow slope of 0.00012 (0.621 feet/mile). Two major knickpoints appear along this section. The first (knickpoint 2) occurs near Ada, Michigan and drops 3.76 meters over the course of 500 meters. This abrupt change in gradient does not correspond to any known current or historic anthropogenic control. Examination of this location via aerial imagery does not provide any conclusive evidence regarding its origin or morphology. The second knickpoint on the profile (knickpoint 1) corresponds with both known natural and anthropomorphic hydraulic controls. This knickpoint is located at the 6th street dam(s) in Grand Rapids, MI. As previously described, this dam was constructed directly downstream of a natural bedrock control (limestone sill).

4.1.4 Glacial and Modern Grand River Gradient

The gradient of the entire river from headwaters to mouth was 0.00032 (1.71 feet/mile). A longitudinal profile extending through the relict channel of the Grand River (i.e. the Glacial Grand River) suggests a gradient of 0.00014 (0.75 feet/mile). This gradient agrees with previously reported slopes of 0.00014 (0.74-0.75 feet/mile) for the ancient river channel (Bretz, 1959; Eschman and Farrand, 1970).

Table 3. Identification of numbered knickpoints in Fig. 4. Hydraulic drops of each knickpoint are compared to the height of the anthropomorphic hydraulic controls (where applicable).

Knickpoint	Location	Rise (m)	Dam Height(m)	Slope (m/m)
1	6th street dam	3.81	~3.96	0.0025
2	Near Ada, MI	3.76	N/A	0.0025
3	Weber Dam	8.31	10.05	0.0166
4	Portland City Dam	3.36	3.35	0.0067
5	Near Portland, MI	4.06	N/A	0.0010
6	Fitzgerald Dam	1.75	~1.53	0.0035
7	North Lansing Dam	2.53	~2.43	0.0051
8	Moores Park Dam	4.63	4.57	0.0093
9	Smithville Dam	3.01	3.96	0.0060

4.2 Bathymetric Data

The DEM produced as a result of bathymetric mapping from Lowell, MI to Ada, MI (Fig. 5b) had an average root mean square error (RMSE) of 0.27 meters between measured elevations. The bathymetric DEM suggests an average slope of 0.00021 (1.11 feet/mile) for the surveyed reach. This is larger than the overall slope of the Lower Grand River section (in which this reach of river is contained). The maximum RBE recorded was 185.93 meters. The minimum RBE, 181.53 meters, was documented in a deep hole just east of the M-21 bridge-crossing in Ada, Michigan. Of the 5 outcroppings of substrate identified on aerial photos, 3 correspond to RBE highs on the DEM (Fig. 5b, Fig. 6). The maximum RBE at these locations average 0.16 meters (0.53 feet) higher than the average RBE along the entire reach surveyed. Due to the unusually high river stage at the time of the bathymetric data collection, river-bed substrate samples were not retrieved. Further characterization of bottom substrate at these locations is needed in order to identify the specific type and extent of hydraulic control present.

Bathymetric survey data through the city of Grand Rapids, MI was used to produce a DEM of the river bed (Fig. 5a). Elevation along this section ranged from a maximum of 190 meters (623ft) to a minimum of 177 meters (581 feet) above mean sea level (amsl). The long profile suggests slope an order of magnitude larger (0.0014 (7.42 feet/mile)) than that shown by the surveyed reach between Ada and Lowell, MI (Fig. 7). The 6th street dam appears on the profile as a 2.07 meter (6.80 foot) drop in elevation. The limestone sill present behind the dam (described earlier) is interpreted to be shown on the long-stream profile as a 1.6 km long-section of significantly higher topography.

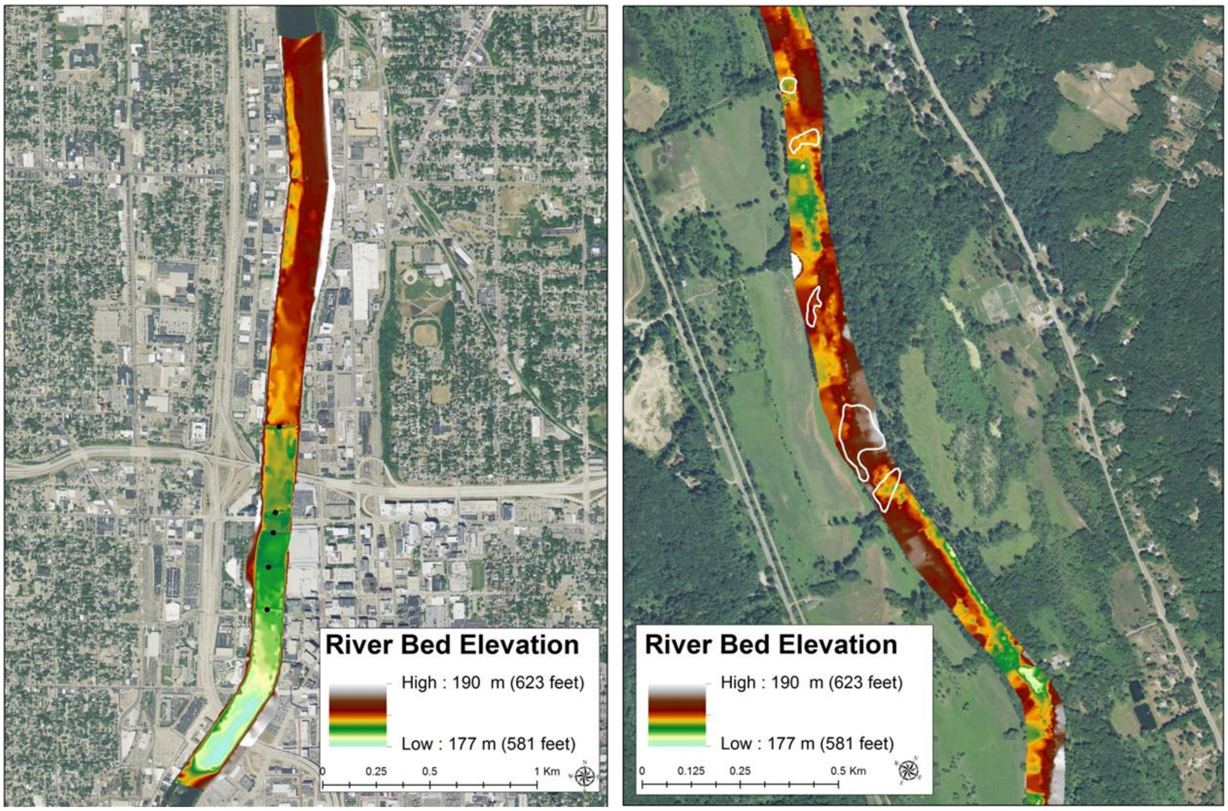

Fig. 5. Bathymetric DEMs produced for A) Grand Rapids (black dots represent dams); and B) This study (white outlines represent potential exposed substrate). River-bed elevation data for the city of Grand Rapids was provided by Grand Rapids Whitewater (GRW; www.grandrapidswhitewater.org).

Based on the slope of the river through the surveyed reach (0.00021) and the elevation of the structures identified above the river bed (maximum elevations average 0.16 meters higher than the average RBE), we do not interpret the mapped river bed “highs” between Ada and Lowell, MI to influence sediment transport and flow dynamics to the extent that the limestone sill present in Grand

Rapids, MI does (Figs. 6-7). However, the collection of substrate samples at these locations, and expanded bathymetric mapping, may show that these controls have a larger influence than interpreted from the current slope and elevation data alone. It is also possible that if removal of the 6th street dam results in a modest lowering (0.25-0.5m) of the WSE near Ada, MI, additional natural controls could be exposed.

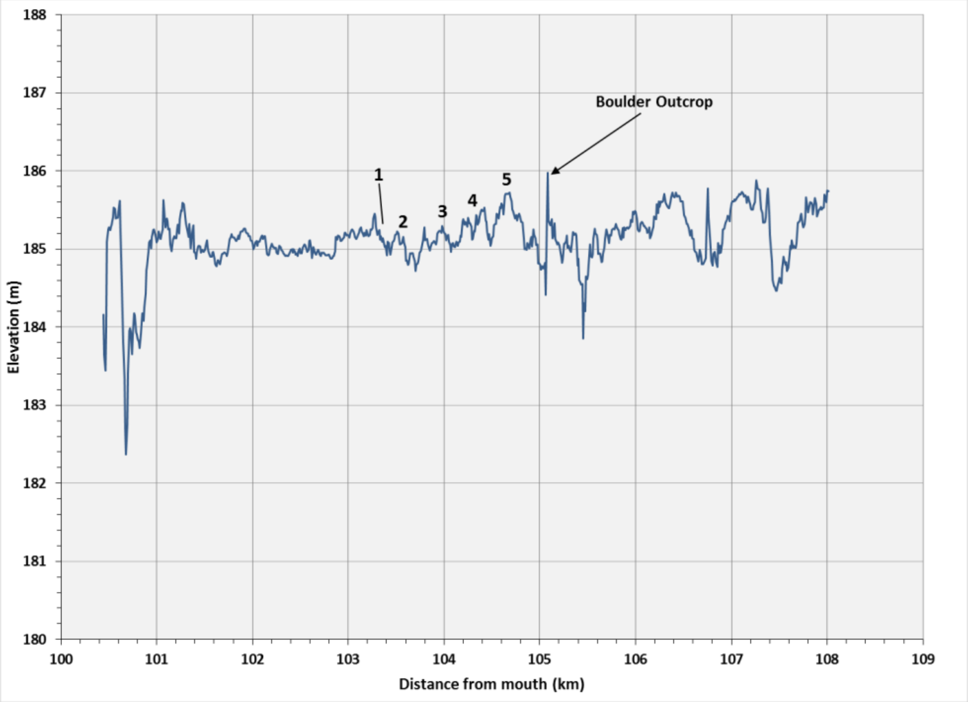

Fig. 6. Long-stream profile of RBE from Ada to Lowell, MI. Elevation data was taken from this study's bathymetric DEM. Potential outcrops identified on Google Earth aerial imagery are labeled 1-5 from west to east (see Figs. 5 & 2).

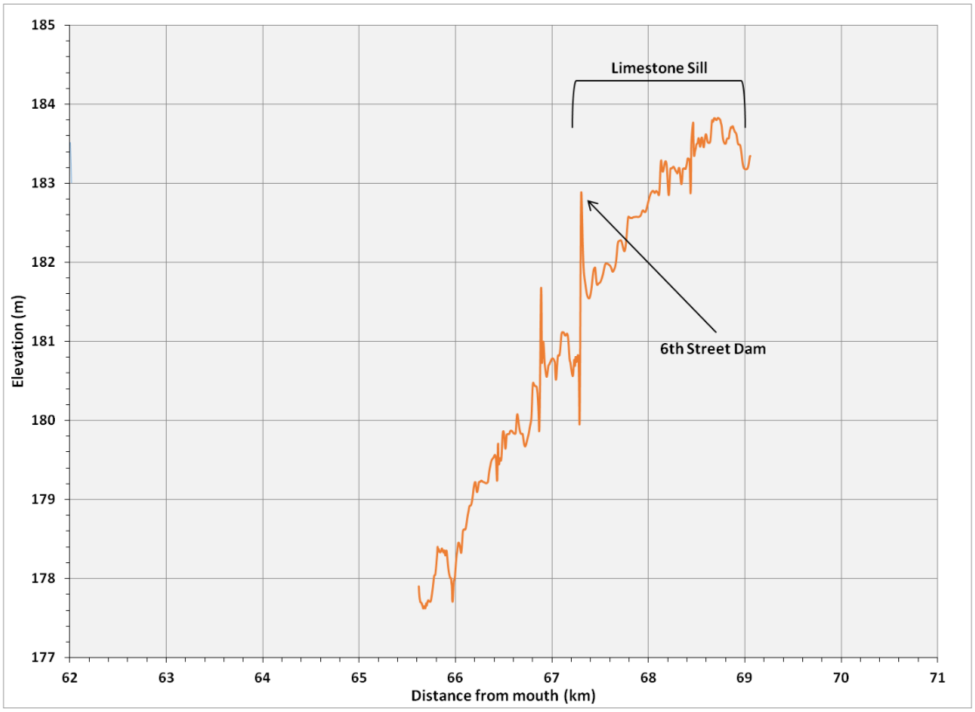

Fig. 7. Long-stream profile of RBE through Grand Rapids, MI using the bathymetric DEM produced from GRW elevation contours.

4.3 Boulder-rich alluvium characterization

4.3.1 Mapping

The mapped extent of the unexposed and exposed boulder-rich alluvium extends roughly 35 meters into the channel from the rivers northern bank (Figs. 8-9). The exposed portion of the deposit occurs in a series of three distinct clusters. These clusters orient parallel to the river for 1.25 km, and average 38 meters apart. Buried or submerged portions of the deposit were recorded up to 11 meters away from the exposed boulders, but the full extent of the boulder-rich alluvium is not known. The elevation of top of the deposit varies by roughly 1 meter, its minimum and maximum elevations being 185.2 and 186.2 meters, respectively (B-B'; Fig. 8). A cross-section spanning the entire channel and extending through the northern portion of the deposit (A-A'; Fig.8), suggests the boulder-rich alluvium occurrence is lower in elevation, was eroded, or was never present in the thalweg of the river channel (Fig.10).

Fig. 8. Boulder-rich alluvium exposure identified 5 kilometers upstream from Ada, MI.

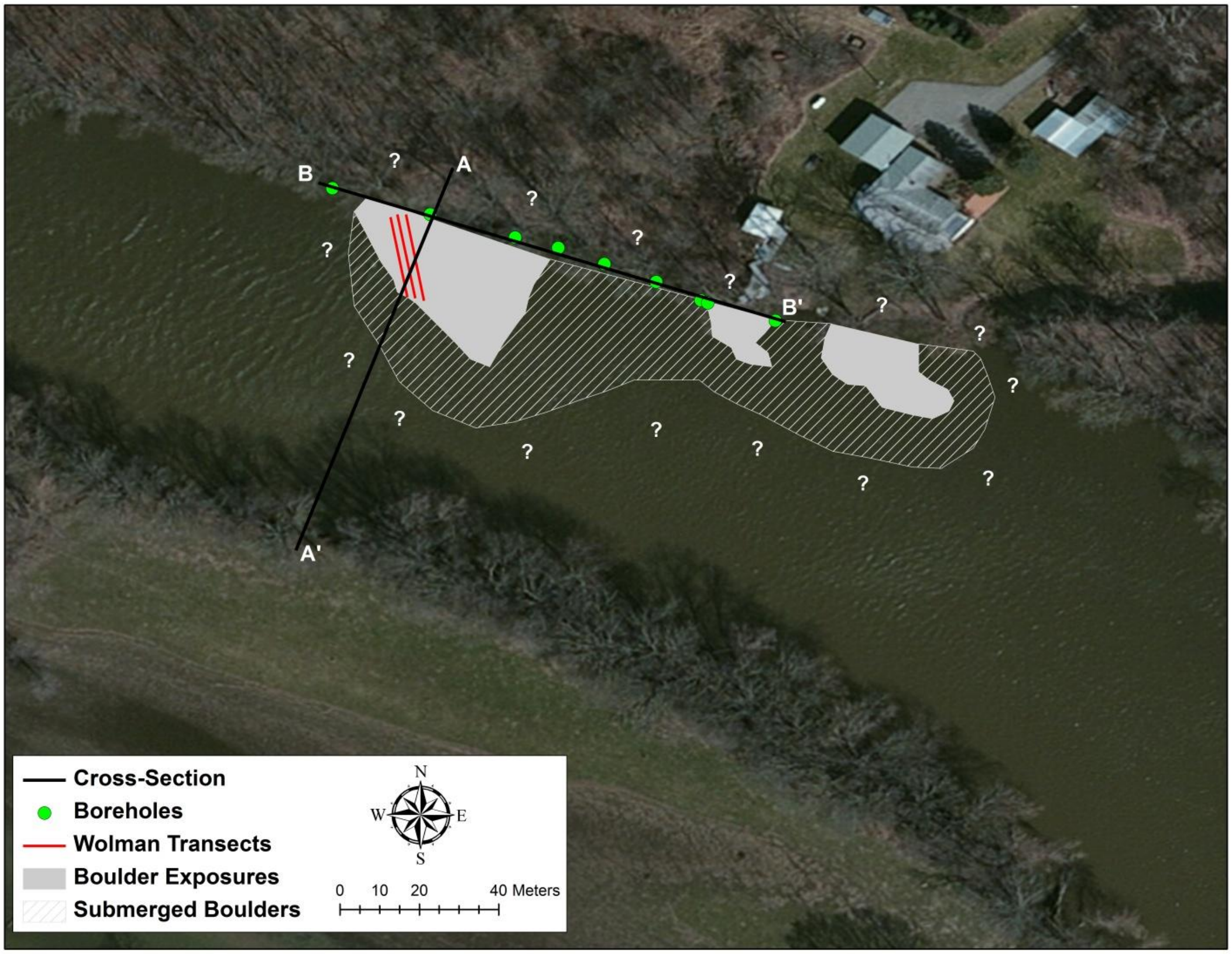

Fig. 9. Map showing the location and extent of the boulder-rich alluvium deposit and survey data used to characterize it. It is not known how far this deposit extends outside of the mapped area, as represented by question marks on the map

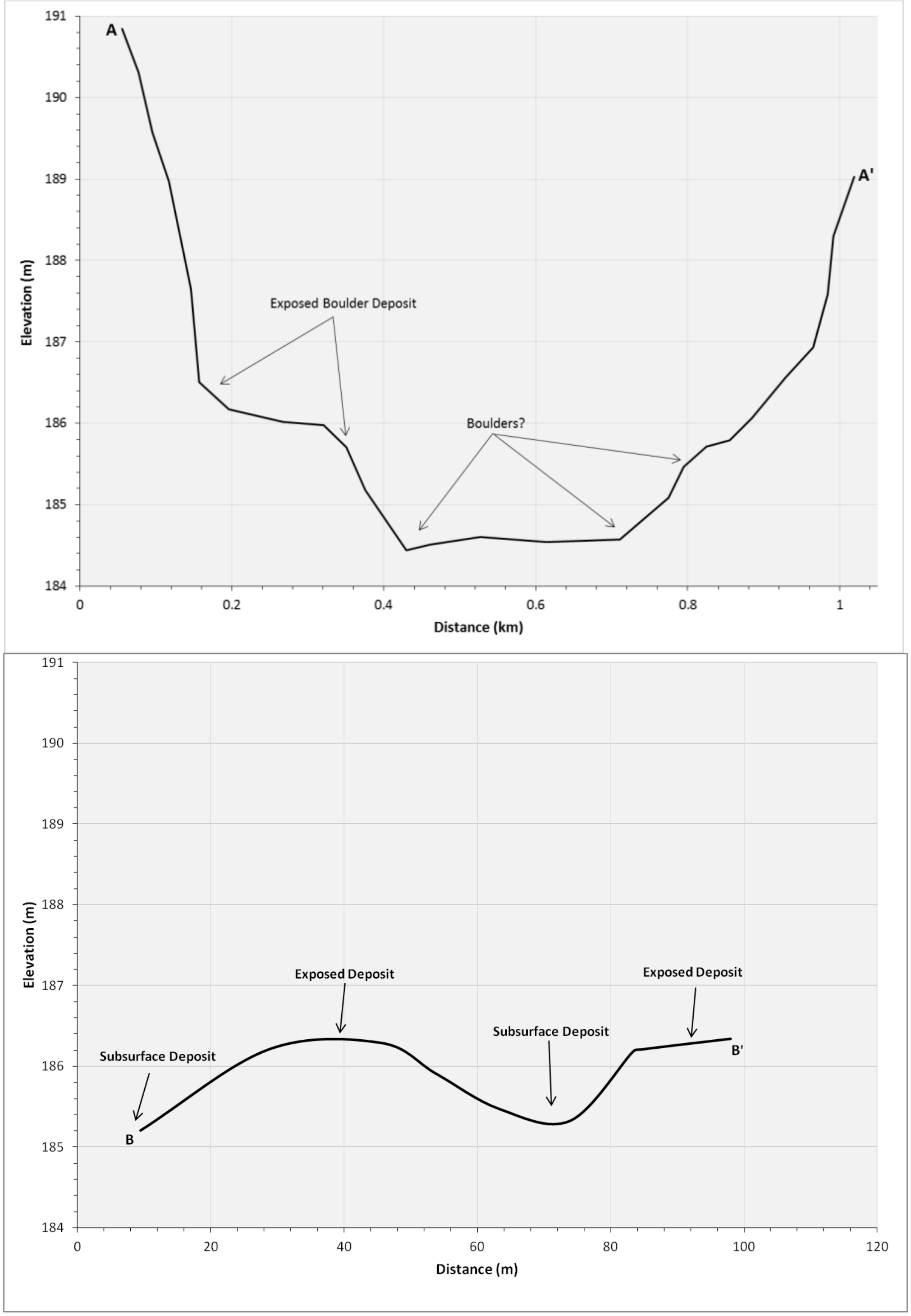

Fig. 10. Cross-section A-A’ (top) and B-B’ (bottom) (see Fig. 8 for locations) taken across the boulder exposure.

4.3.1 Wolman Pebble Count

Analysis of the 240 clasts measured using the Wolman Pebble Count indicate that the surface of the alluvium rich boulder deposit is composed of very poorly sorted, very coarse gravel (Folk and Ward, 1957; Wentworth, 1922). The grain-size distribution of the surface sediment is polymodal; however two modes are most prominent (Fig. 11). The maximum grain size recorded (D_{max}) was 1,448 mm. The median grain size recorded (D_{50}) was 87.6 mm (Table 4). 90% of the sample was finer than 1,302 mm (D_{90}) and 10% was finer than 12.2 mm (D_{10}).

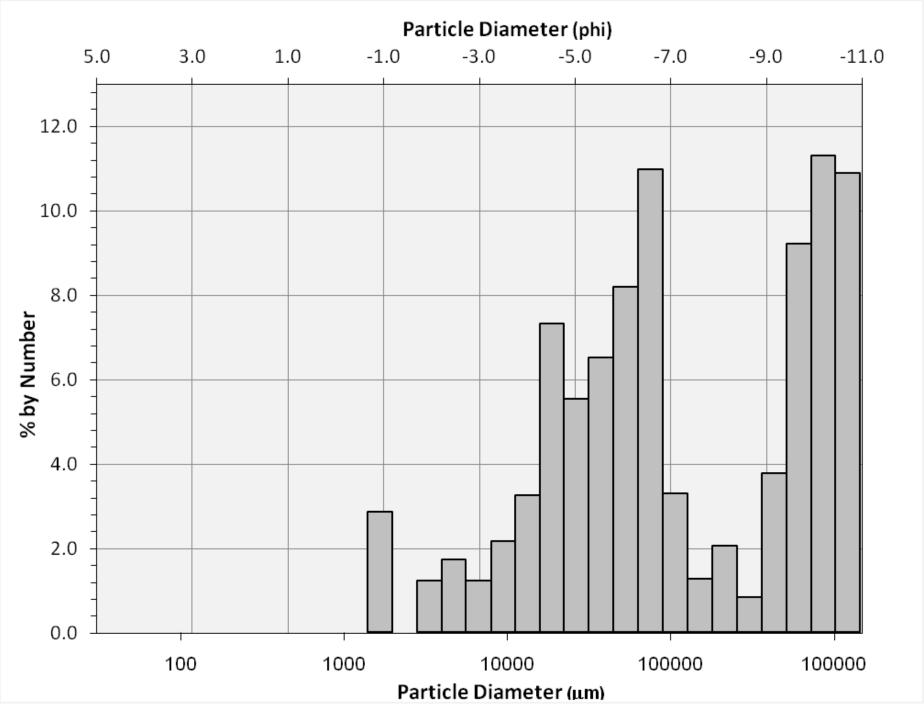

Fig.11. Grain-size distribution of the surface sediment analyzed from the Wolman Pebble Count.

4.3.2 Bulk Sediment Sample

The sieved subsurface bulk-sample was finer-grained than the surface sediment analyzed through the Wolman Pebble Count. This sediment was very poorly sorted medium gravel (Folk and Ward, 1957; Wentworth 1922). This sample had a slightly polymodal grain size distribution, but overall each size fraction measured was equally represented (Fig.12). The median grain size recorded was 14.8 mm (D_{50}) (Table 4). For the entire bulk sample, 90% of the sample was finer than 95.5 mm (D_{90}) and 10% was finer than 7.3 mm (D_{10}).

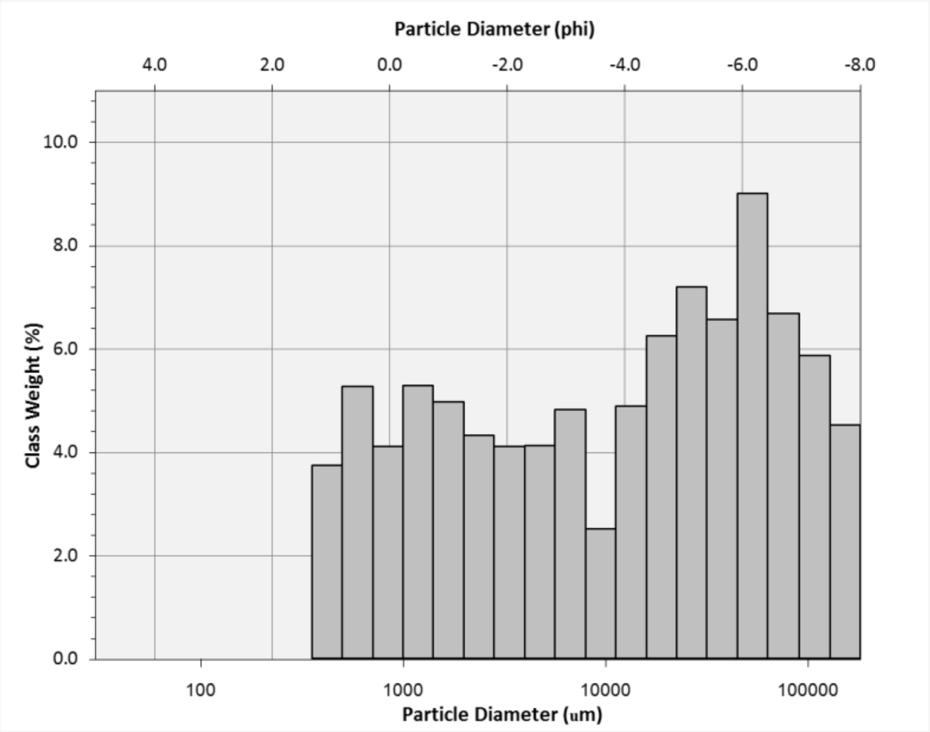

Fig.12. Grain size distribution graph of the bulk subsurface sample.

Table 4. Grain size distribution for different samples of the exposed boulder-rich alluvium.

Sample	D_{50}	D_{90}	D_{10}	D_{max}
Wolman Count	87.6	1302	12.2	1448
(+) 6.35mm subsurface sample	43.4	121.5	13.8	128.0
(-) 6.35mm subsurface sample	1.7	6.0	0.5	6.35
Entire subsurface sample	14.8	95.5	7.3	128.0

The total loss of sediment as a result of sieving was 2.3% including the pan weight (sediment below .250 mm was not included in this analysis). Disregarding pan weight, this error is reduced to 0.5%. Another possible source of error, which may have slightly skewed the grain size statistics, is contamination from overlying sediment. The sediment overlying the excavated hole from which our subsurface sample was collected composed of finer-grained silts and clays. Precautions were taken to minimize this contamination. However, there is a slight chance that undetected contamination did occur.

4.4 Well Log Analysis

4.4.1 Bedrock Topography

The DEM produced from water well data to represent bedrock topography (Fig.13) had a RMS between measured points of 13.5 meters. Elevation ranged from a maximum of 255 meters to a minimum of 120 meters, with an average bedrock elevation of ~173 meters. Bedrock elevations are significantly higher in Kent County compared to Ottawa County, where an abrupt truncation in bedrock topography occurs near the Kent county line. The bedrock elevations along the Grand River in Kent and Ottawa average 167 meters and 149 meters, respectively. The DEM suggests 3 regions of bedrock elevations which are close to present land surface elevations. The first occurs approximately 2.5 km west of the confluence of the Thornapple and Grand Rivers and is contained within our study area. This elevated region extends west for roughly 5.5 km and has an average elevation of 172 meters (Fig. 14). The second bedrock high, located approximately 4.0 km west of Ada, Michigan, has an average elevation of 172 meters and extends for roughly 2 km. The third and largest bedrock high along the Grand occurs near the city of Grand Rapids, Michigan and coincides with the location of the previously described bedrock exposure in the river. This region possesses a rough average elevation of 179 meters and occurs along the river for ~9 km.

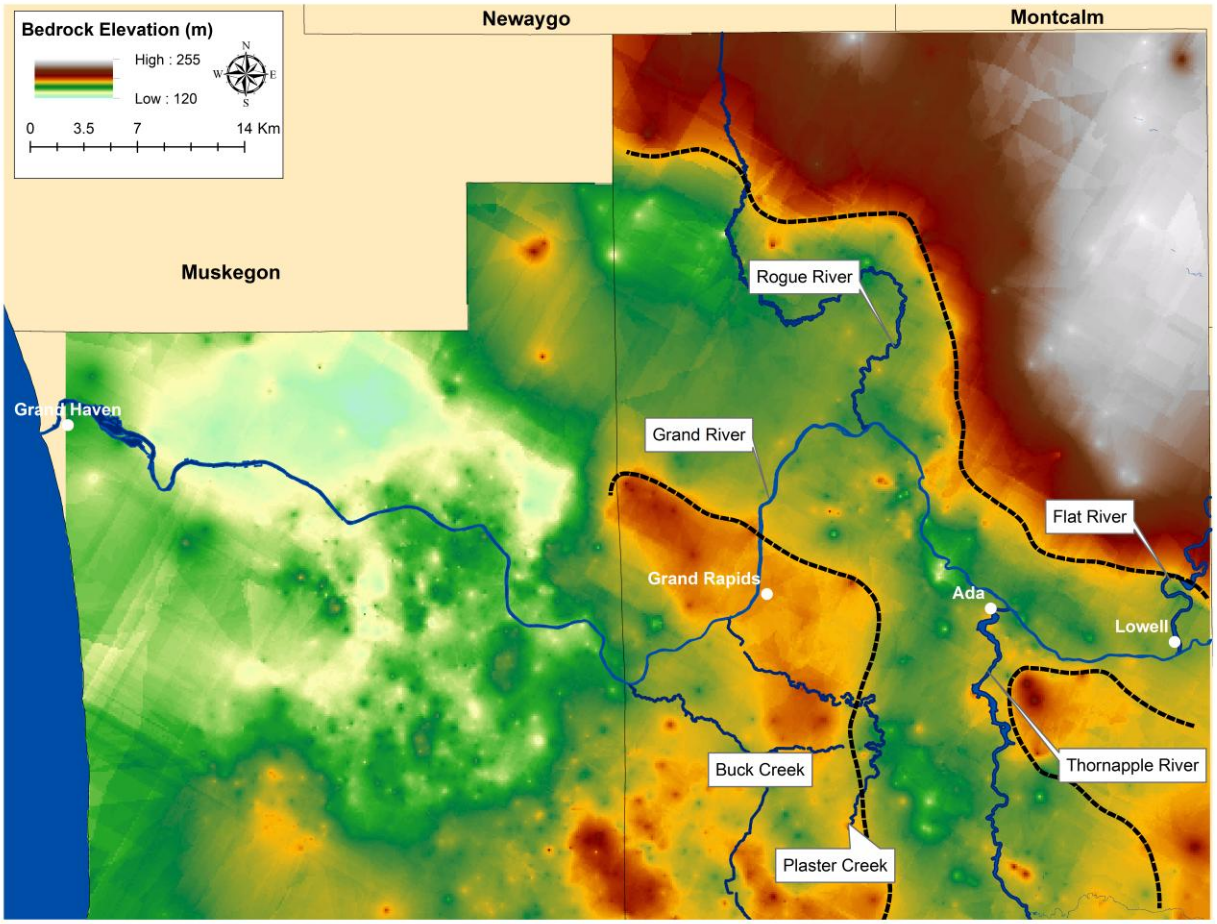

Fig. 13. Bedrock topography map of Kent and Ottawa counties. The dashed line represents the bedrock valley.

The bedrock topography map also suggests the existence of a subsurface bedrock valley in Kent and Ottawa counties. Overall, the valley strikes roughly NW-SE and lies directly below portions of the Grand, Thornapple, and Rogue rivers. However, the portion that underlies the Thornapple River appears N-S trending. Valley width averages ~15 kilometers. The mean elevation along the bottom of the valley is roughly 160m, 26.2 meters lower than the average bedrock elevation of Kent County (186.2 meters). This finding supports the hypothesis of a pre-existing valley along the Grand River (Bretz, 1952; Kehew, 1993), and adds to the previous work of others (Rieck and Winters, 1979, 1980; Winters and Rieck, 1982) who have also interpreted its occurrence.

4.4.2 Sediment Thickness

The sediment thickness map illustrates the thickness of sediment deposits over the bedrock subsurface (Fig. 14). This map lends qualitative support to accuracy of the bedrock topography map from which it was derived (see section 4.4.1), as it accurately predicts the location of the known bedrock exposure through the city of Grand Rapids, Michigan (sediment thickness of 0 meters). The map also predicts two locations of shallow or nearly exposed bedrock along the Grand River in Kent County. The first occurs approximately 8 km west of the confluence of the Thornapple and Grand Rivers (Fig. 14; Box 1). The second occurs just west (~1km upstream) of Lowell, MI and is contained within our study area (Fig. 14; Box 2). The map does not predict any bedrock exposures in Ottawa County. Overburden (sediment) thicknesses range from 0-160 meters.

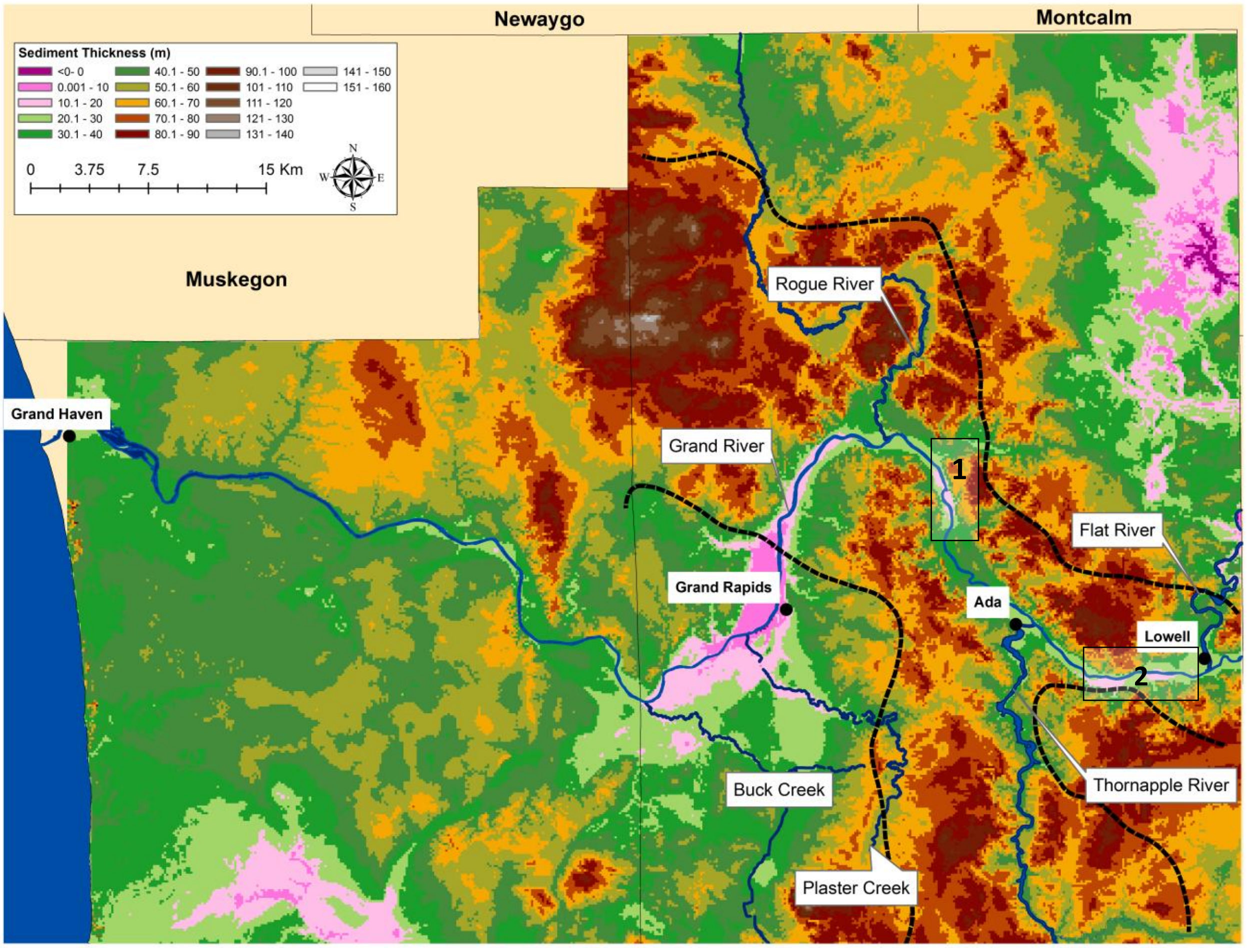

Fig. 14. Sediment thickness through Ottawa and Kent counties. Shades of pink indicate shallow or exposed bedrock (< 20 m overburden thickness). Numbered boxes indicate undescribed bedrock exposures / shallow bedrock in the river valley (see text). Dashed line represents the outline of the bedrock valley identified in Fig. 13.

4.4.3 Alluvial Thickness and Boulder Distribution

Interpolation of alluvial thickness (Fig. 15) for Kent and Ottawa counties resulted in a 7.19 meter RMS. Overall, alluvial thickness ranged from a maximum of 198.5 meters to a minimum of 6.0 meters. The average alluvial thickness is 38 meters across both counties. Both alluvial sediment thickness and extent of boulder deposits seem to be much less in Ottawa County; the alluvial thickness averages 28 meters and the county contains 59 boulder occurrences. This is compared to a mean alluvium thickness of 45 meters and 174 recorded boulder deposits in Kent County. Cross-cutting Kent County, there appears to be a roughly NW-SE trending deposit of thick (~50 meter average), boulder-rich alluvial sediment. The strike of this deposit coincides with the strike of the bedrock valley identified on the bedrock topography map (section 4.3.1). From the east, this deposit roughly follows the course of the Grand River until it's confluence with the Rogue, where it extends along the Rogue River into northern Kent County.

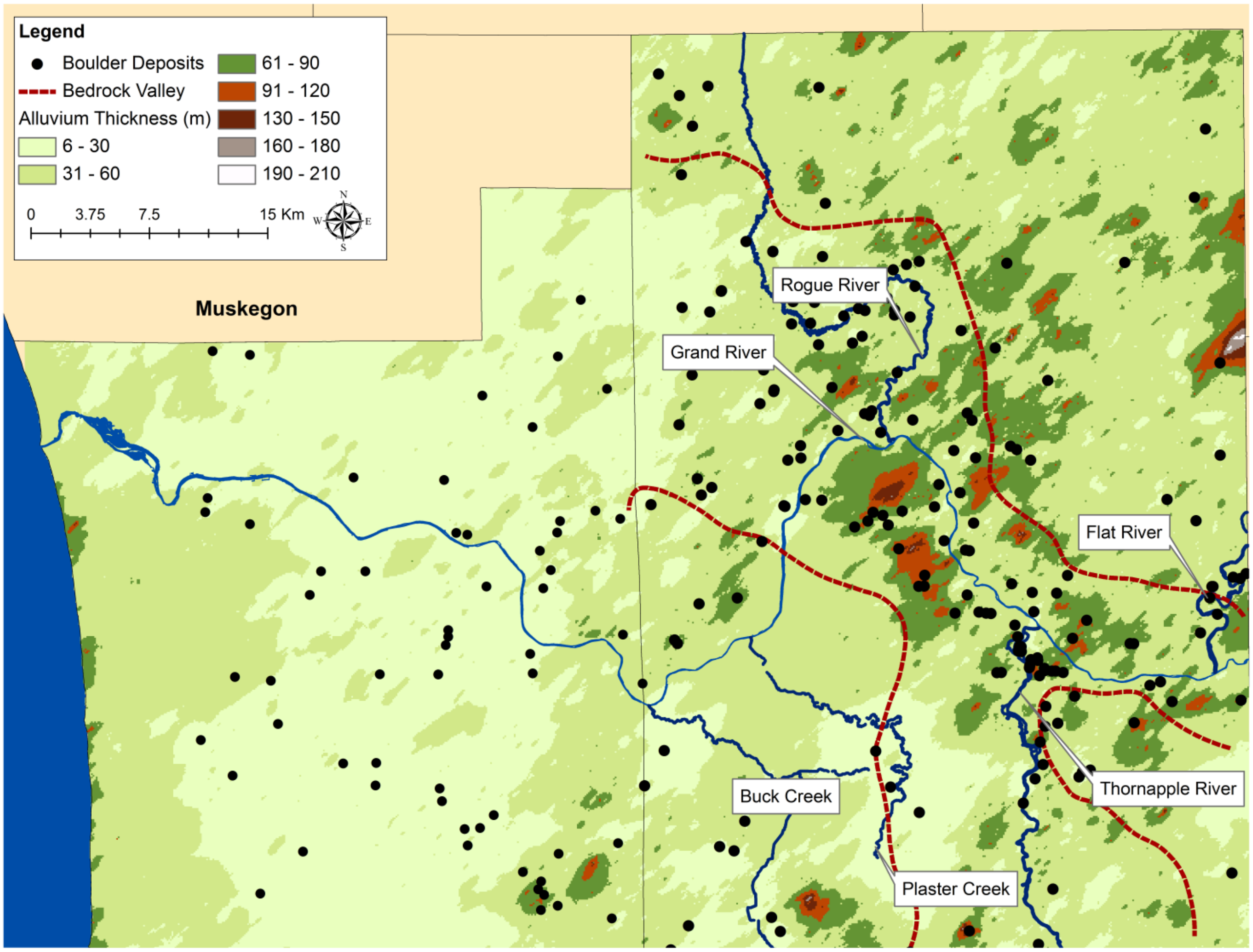

Fig. 15. Alluvial thickness map of Kent and Ottawa counties. Boulder deposits are represented by black dots on the map. Dashed line represents the outline of the bedrock valley identified in Fig. 13.

5. Analysis and Discussion

We interpret the bedrock valley identified on the bedrock topography map to represent a drainage system that pre-dates the Last Glacial Maximum (LGM). DEM analysis suggests that this feature also influenced meltwater drainage during the early stages of the Wisconsinan glaciation. This influence can be observed today through several geomorphic features present along contemporary GR and GRV. We also believe that the bedrock valley influences the location and extent of natural hydraulic controls currently active in the modern GR east of Grand Rapids, MI.

5.1 Geomorphic History

The existence of a pre-glacial valley underlying the GRV has been theorized by previous workers (Bretz, 1952; Kehew, 1993). Our findings support this theory as well as add to similar findings by previous workers who have reported the bedrock valleys extension south and west (Rieck and Winters, 1979; Winters and Rieck, 1982). We interpret this valley to represent a drainage system that pre-dates the LGM. We also believe that this valley played a large, previously undescribed role, in meltwater allocation and drainage during the Wisconsinan stage, Woodfordian substage of the Pleistocene. In addition to the bedrock topography map, evidence supporting these interpretations include: 1) the N-S trending, thick, boulder-rich alluvium deposit in Kent County (Fig. 16) that overlies the bedrock valley (Fig. 15); 2) field observations and grain size analysis supporting the existence of the deposit described in (1); and 3) documented findings of pre-LGM organic material in, and near the mouth of, the bedrock valley. The following outline represents our interpretation of the geomorphic history of the GR and GRV pre-LGM through the Woodfordian substage of the Wisconsinan glaciation. This interpretation is based upon literature review (Eschman and Farrand, 1970; Kehew and Kozlowski, 2007; Kozlowski et al., 2005; Rieck and Winters, 1979, 1980, 1982; Winters and Rieck, 1982) and the above numbered (1-3) evidence:

- Pre- LGM? (≥ 65 ka): We propose the existence of a large bedrock river (hereby referred to as the Ancient Grand River (AGR)), occupying the floor of a bedrock valley roughly 20 kilometers wide and 19-26 meters deep at its maximum (~160 meters in elevation). This river's outlet was north of the modern GR and likely drained into an ancient Lake Michigan roughly 17 meters lower in elevation than the modern lake.
- Nebraska – Wisconsinan glacial cycle (≤ 65 ka): Glaciers advanced over the region and began to infill the bedrock valley with glaciofluvial and glacial deposits of both local and exotic origin. During glacial retreat, fines were winnowed from these deposits. Boulders, from various glacial episodes, began to accumulate near bedrock highs (sills) in the valley, armoring the AGR. During interglacials, one or more stable paleo-surfaces developed in the region at an elevation similar to that of the boulder armor (Rieck and Winters, 1980, 1982).
- Early Wisconsinan (~15 ka): During the LGM, the bedrock valley was nearly filled with alluvium. As the Laurentide ice sheet retreated, it began to take on a lobate form. Meltwater entered the valley (now an ill-defined depression) from two different sources: 1) as ice-marginal stream discharge from the LML; and 2) as sub-glacial tunnel channel discharge from the Saginaw Lobe to the east (Fisher et al., 2005; Kehew and Kozlowski, 2007; Kozlowski et al., 2005). This meltwater ponded into the nearly alluvium-filled valley to an elevation of approximately 240m amsl, at which point it discharged southwest, through the Thornapple River Valley (TRV) (Kehew et al., 2013). A confluence of sub-glacial, tunnel channel, meltwater discharge from the Saginaw lobe likely joined the discharge from the GRV at the top of the drainage divide in the TRV.
- Late Wisconsinan (~13 ka): Upon retreat of the LML east to the outer Valparaiso position (Fig. 3), the only structure holding the southern draining Glacial Grand River to its course was a moraine dam (inner Valparaiso). The Valparaiso dam was somehow breached. Dam failure resulted in discharge, possibly catastrophic, into the Ross channel. This event also caused a flow reversal of

the N-S draining Thornapple River and marked the formation of the "big bend" visible in the modern Grand River. With retreat of the LML to the Ravenna Moraine, a lower outlet opened to the west (the Zeeland channel). This occurrence marks the period in time where our interpretation of the subsequent history of the western portion of the Glacial GR largely agrees with previous accounts.

- Late Wisconsinan- Present: The formation of the eastern portion of the GRV is largely the product of sub-glacial tunnel channel discharge from the Saginaw lobe, not "step-wise erosion" through recessional moraines as previously suggested. Subsequent proglacial lake discharge eroded incised the valley to an elevation controlled by the bedrock exposure in Grand Rapids, MI and the pre-LGM boulder-armor deposits.

5.2 Pre-LGM alluvium deposits

5.2.1 Mapped boulder-rich alluvium deposits

Of the 233 total documented boulder occurrences using water well data, 176 (75%) occur within the mapped extent of the bedrock valley (Fig. 12), and 78% of those (138/176) correlate with the mapped, N-S striking, thick alluvium deposit across Kent County which filled the bedrock valley (Fig. 15). Boulder deposits in the bedrock valley average 186 meters in elevation. This correlates favorably to the boulder deposit characterized by this study (~184-186 meters amsl). In Ottawa County, no observable trend in boulder deposits was identified, suggesting they may be the result of glacial erratic deposition. In only two locations do boulder occurrences recorded in the well-logs appear to be related to moraine deposits; 9 boulder deposits occur across the Ravenna moraine in Ottawa County and 10 lie parallel to the Valparaiso moraine in Kent County.

Along the mapped portion of the GRV, it appears that most of the valley floor east of Grand Rapids, MI is composed of thick deposits of pre and post-LGM boulder-rich alluvial sediment. We interpret these deposits to be similar in origin to that of the characterized boulder-rich alluvial deposit (Fig. 8). Boulder-rich alluvium exposed along the modern valley floor is supported by field observations recorded by this study, as well as observations documented in previous studies (Bretz, 1952; Eschman and Farrand, 1970; Kehew, 1993). However, contrasting previous interpretations, we do not interpret these deposits to represent “channel bottom remnants” of the previously described E-W draining Glacial Grand River (Bretz, 1951a; Bretz, 1951b; Bretz, 1952, 1964; Kehew, 1993; Leverett and Taylor, 1910). We believe these deposits represent a pre-LGM bed armor which was exposed following river incision during glacial lake discharge through the GRV. Incision ceased at the GR’s current elevation due to the natural armoring provided by these deposits as well as the limestone sill exposed in Grand Rapids, Michigan.

West of Grand Rapids, GRV sediment deposits appear to contain significantly less amounts of boulder-rich alluvium. This statement is supported by the alluvial thickness map (Fig. 15), the sediment thickness map (Fig. 14), and field observations by this study and of previous studies (Eschman and Farrand, 1970; Larson et al., 1994). Only one sediment class from the lithologic classification system used in this study (Table 1), Clay Alluvium, was not mapped. Based upon this, and through inference of the sediment thickness map (Fig. 13), one can logically conclude that Ottawa County contains significantly greater amounts of clay and clay alluvium deposits compared to alluvium deposits. We interpret the presence of clay to represent some form of glacial till, or possibly offshore deltaic deposits.

5.2.2 Field-characterized boulder-rich alluvium deposit

The following salient observations and data were accumulated for the exposed, boulder-rich alluvium deposit examined in the field:

- The boulders are too large to be transported under the range of flows recorded for the modern Grand River (Fig. 16a)

- None of the clasts examined (at any size fraction) showed evidence of glacial striations
- Stratification is visible in the subsurface exposure of the deposit
- A "pit and groove" morphology was displayed by many clasts (Fig. 16b)
- Extremely variable weathering between clasts, including clasts of the same lithology
- Highly variable degrees of roundness between clasts
- A bimodal distribution of lithology was observed; both exotic (Ultra-mafic, granitic, etc.) rocks and locally derived (Bayport Limestone and Michigan Formation) clasts were present.
- The deposit is poorly sorted
- The surface of the deposit varies by up to 1 meter in elevation over very short distances (<20 meters), and is exposed at the current WSE of the GR
- The deposit is permeable enough to allow groundwater to flow through it
- A roughly ~1cm thick layer of sand overlays the deposit in the subsurface where it is not exposed

Fig. 16. Photo**s** of boulder-rich alluvial sediment: A) largest exposed boulder; B) example of the odd "pit and groove" morphology on face of many clasts examined**.**

These observations and data lead to several possible interpretations regarding the origin of the deposit:

1. The deposit was formed by the modern GR
2. This deposit is a glacial till
3. Outburst floods deposited the sediment
4. The deposit is an accumulation of glaciofluvial sediment from various glacial episodes

The modern GR possess insufficient of stream power, even at its largest flows, to transport this material. Although the polymodal grain size distribution of the deposit is indicative of a ground-laid till deposit, evidence of glacial transport was not visible on any of the clasts examined. Based on past interpretation of lake level elevations and discharge chronology through the GRV (Bretz, 1966; Eschman, 1980; Eschman and Farrand, 1970; Eschman and Karrow, 1985; Robards, 1980), the elevation of this deposit is too low to have been deposited by the outburst floods proposed by previous workers (Eschman and Karrow, 1985; Kehew, 1993). The presence of fines in the deposit also argues against an outburst origin for the deposit. The interpretation which we believe is most consistent with the observations and data is that this deposit represents an accumulation of glaciofluvial sediment from several glacial episodes. The observations that support this conclusion are: 1) the varying degrees of weathering between rocks of all sizes; 2) the odd “pit and groove” surface morphology exhibited by many of the clasts, which we interpret to be the result of exposure to high discharge, erosive flow, which could have transported these boulders; 3) the elevation of the outcrop below LGM sediment; and 4) the distribution of boulder occurrences roughly coincident with the ancient GR valley.

5.3 Bedrock and Boulder Controls on River Gradient

Based on field observations and DEM analysis, it appears that bedrock surfaces and boulder-rich alluvium accumulations are the primary natural hydraulic controls that exist along the modern Grand

River through Kent and Ottawa County. However, bedrock topography may have an underlying influence on the location and extent of boulder-rich alluvium accumulations.

Cross-sectional analysis of bedrock and land surface DEM data suggests bedrock influence on land surface and river morphology in Kent and Ottawa counties. The terrain of the bedrock subsurface appears to influence both topographic relief characteristics exhibited by the modern land surface and the distribution of natural hydraulic controls along the Grand River through the mapped portion of its course. Significant changes in relief (i.e. highs and lows) exhibited by the bedrock subsurface are somewhat mirrored by the modern land surface (Fig. 17). Bedrock terrain appears to be a function of lithology. Locations exhibiting high bedrock relief seem to correlate with harder, more weather-resistant strata such as limestone (e.g. Bayport Limestone) and dolomite (e.g. Michigan Formation), whereas topographic lows appear to correspond with softer, less resistant lithologies (e.g. Marshall Sandstone). This hypothesis is not unique to this study. Previous workers who have mapped bedrock in the region suggest a correlation between bedrock subsurface relief and strata composition (Winters, 1982).

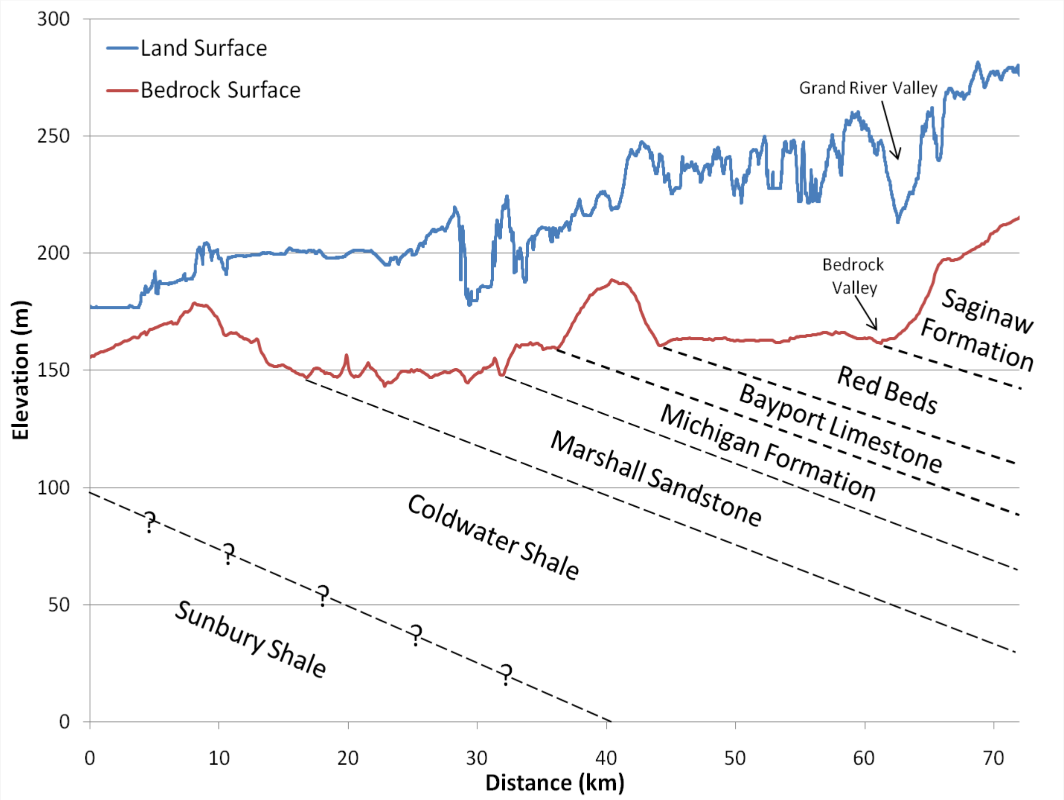

Fig. 17. Elevation profile of bedrock and land surfaces (A-A', Figure 13). Topographic highs/lows in the land surface correlate to topographic highs/lows in the bedrock surface (with the exception of valley-fill). Approximate geologic contacts are plotted as dashed lines in the graph.

A similar trend is apparent when comparing cross-sectional profiles of the bedrock subsurface to the water surface elevation of the GR through Kent and Ottawa counties (Fig.18). The generalized slope (i.e. total rise/total run) of both surfaces is markedly similar. The gradient of the Grand River through this reach (0.00011; 0.59 feet/mile) nearly matches that of the underlying bedrock surface (0.00012; 0.62 feet/mile). Previously identified knickpoints along this reach (in Grand Rapids and Ada; Fig. 4) as well as smaller-scale breaks in river gradient, appear to correlate with changes in the relief of the underlying bedrock surface.

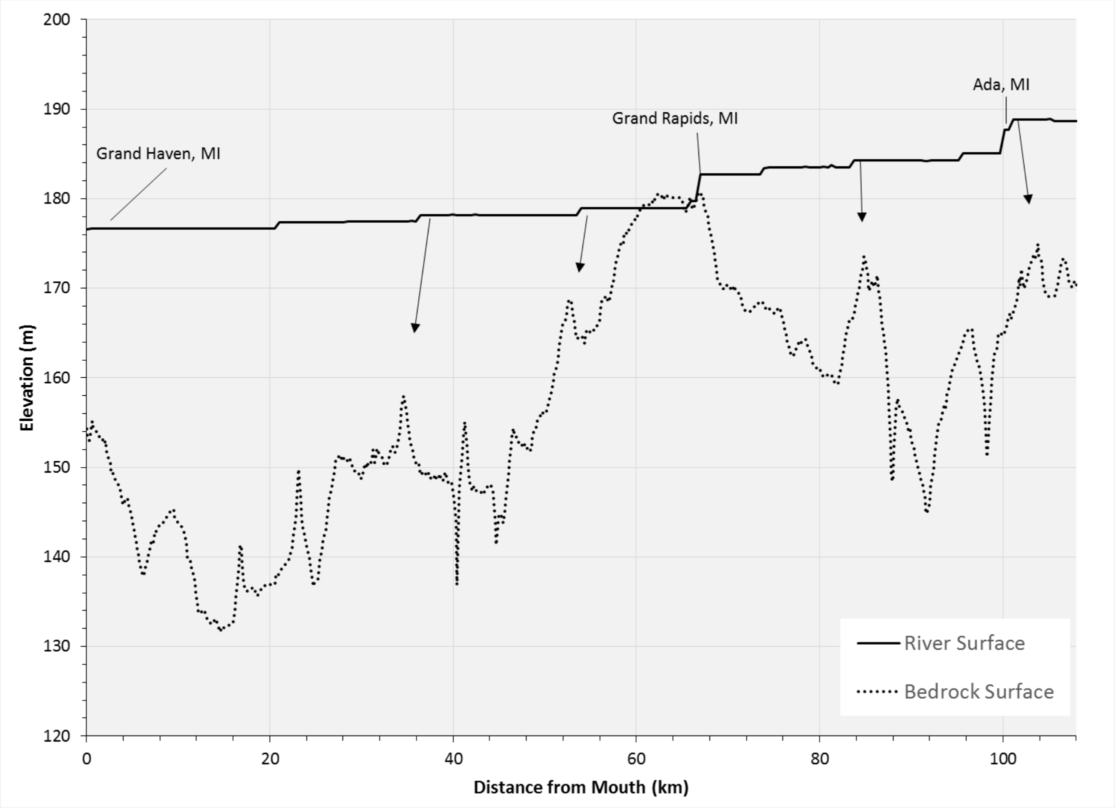

Fig. 18. Longitudinal profile of the WSE and bedrock topography along the GR through Kent and Ottawa County.

Based on this observation, we propose that the bedrock influence on the location of active natural hydraulic controls in the modern GR is twofold: 1) through bedrock exposures in the river bed, as is the case in Grand Rapids, MI; and 2) secondarily by controlling the location of boulder-rich alluvium deposition. As previously described in the geomorphic history section above (section 5.1), it is hypothesized that boulder rich alluvium accumulation (during previous glacial episodes) likely occurred behind exposed bedrock sills along the AGR (which flowed north and emptied into an ancestral Lake Michigan). These sills are lower in elevation than the current active sill in Grand Rapids, MI (the bedrock sill active in Grand Rapids today was not controlling the gradient). This boulder-rich alluvium pavement was covered in drift during the Wisconsinan glacial period. It is believed that re-exhumation of the GRV exposed these boulder-rich alluvial deposits as the river eroded down to its current elevation. These exposures are currently active as natural hydraulic controls, such as the knickpoint near Ada, MI (Fig. 17).

7. Summary and conclusions

Bedrock exposures and boulder-rich alluvial deposits provide the GR through Kent and Ottawa County with its largest natural hydraulic control. Based on bedrock topography data, there appears to be only one occurrence of exposed bedrock through the mapped extent. This exposure occurs at Grand Rapids, MI in the Grand River as a limestone sill. Field reconnaissance and observation suggests that exposed boulder-rich alluvial sediment is present along the GR. The exposure of boulder-rich alluvial sediment is roughly coincidental with bedrock highs in the subsurface (shallow bedrock).

The gradient of the river east of Grand Rapids, MI, is largely the product of channel degradation of glaciofluvial fill over a pre-historic subsurface bedrock valley. Within these glaciofluvial deposits, hard points in the form of boulder-rich alluvial deposits occur. These deposits prevent the river from reaching equilibrium, and knickpoints are established along its grade. West of Grand Rapids, the gradient of the Grand River is largely controlled by lake phases of Lake Michigan. This portion of the river represents a relatively young fluvial environment (compared to the river east of Grand Rapids, MI) whose dominate sediment is till-related clay and silt.

Removal of the dams in Grand Rapids, MI may result in a lowering of the WSE upstream. The extent to which the WSE upstream is lowered will be controlled by the natural bedrock sill in Grand Rapids, MI. If WSEs are lowered upstream, it may result in increased exposure of boulder-rich alluvium occurrences. These exposures provide unique habitat to Grand River. Ecosystem benefits provided by these exposures include: 1) cool groundwater infiltration and/or hyporheic exchange; 2) substrate suitable for spawning, macro-invertebrates, and mussels; and 3) micro-habitat for fish. Given these benefits, this exposure may provide an analogue for the restoration efforts in Grand Rapids, MI.

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