

Model for Lava Dam Removal Using a Sediment Flux Dependent Stream Power Model

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Abstract

A single basaltic lava flow entered the Little Colorado River channel in the late Pleistocene, making it an ideal candidate for studying a river's response to a lava flow blockage. Approximately ~125 km from where the Little Colorado River enters the Grand Canyon, remnants of the lava flow are seen along the western canyon wall of the Little Colorado River downstream of Grand Falls. Grand Falls features a knickpoint in the process of creating an epigenetic gorge adjacent to the basalt filled paleochannel. Modeling of the removal of this basalt flow from the Little Colorado River channel shows strong dependence on erodibility with lithological changes when using a sediment flux dependent stream power model.

1.1 Introduction

The steady-state profile of a river was first described by geomorphologist G.K. Gilbert (1877) as a concave upward curve due to the idea that as water volume in a river decreases, its grade becomes steeper. A river itself may be removed from its steady concave curve by forms of transient responses due to but not limited to uplift of a region, change in lithology, reorganization of river systems, or river damming. In the case of river damming, the dam itself creates a new base level for the upstream end of the river while below the river's base level stays at its original pre-dam level. In many cases, the upstream reaches of the channel will aggrade until it reaches the height of the dam, causing shallow streambed slopes to develop close to the dam. But what happens when sediment and water on the upstream end of the dam over tops it? A river will begin to remove the dam through the process of incision. The start of incision on the downstream end of the dam will initially create a propagation of a steep channel slope upstream until the entire dam is removed. As

more of the dam is removed, sediment influx from upstream of the dam may change to increase or inhibit erosion of the dam. When a dam is emplaced the question is how will the river remove the dam, how will the river equilibrate itself, and will we be able to infer previous damming of a river based off of its current profile?

One process in which damming can occur is when a lava flow comes in contact with a stream channel. This phenomenon is observed countless times on many rivers across the western US. As the lava initially comes to a river valley it spills over until it comes in contact with the bottom of the channel and it will gradually fill upwards. At the initial point of inflow the lava flow has its crest. A large portion of the flow will continue in the downstream direction of the channel as well as a small but significant flow upstream. This type of damming is seen all over the western interior of the US due to widespread volcanism within this area since the late Eocene. In the Grand Canyon, lava flows have repeatedly dammed the Colorado River and were first analyzed by Hamblin (1994). Using $^{40}\text{Ar}/^{39}\text{Ar}$ dating and rare earth element analysis Crow et al. (2015) was able to compare the remnants in the Grand Canyon to find that there have been 17 lava flows within the last 2 million years. In conjunction with the multiple lava flows, movement on the Toroweap or Hurricane Faults is not well constrained so modeling of incision history of the lava dams here would be difficult. Some of these lava flows in the Grand Canyon show catastrophic failure due to emplacement onto unstable slopes, hydrothermally weakened basalt flows, or weakness in the fractured basalt (Hamblin, 1994). In southeast Oregon, the Owyhee River had been dammed on six separate occasions in the late Cenozoic and none show catastrophic failure (Ely et al., 2012). The Owyhee River either was diverted around the lava flow or poured over the crest of the lava flow (Ely et al., 2012). Here we have limited constraints for modeling. The Little Colorado River has been dammed by a single lava flow just northeast of Flagstaff, Arizona around 20 ka and is to this day continuing to remove the obstruction (Duffield et al., 2006). Because the Little Colorado River is currently within the process of removing a single lava dam and its age and its dimensions are well constrained, it is the perfect scenario to test our understanding of the parameters controlling river incision and dam removal.

1.2 Geologic Setting

The area of interest, Grand Falls, is within the Colorado Plateau in central Arizona, and its geographic location can be seen in Figure 1. Here the bedrock consists of Paleozoic and Mesozoic strata tilted slightly towards the northeast. Specifically near the canyon of the Little Colorado River the bedrock walls are composed mostly of the Kaibab Formation, a fossiliferous sandy limestone (Billingsley et al., 2014). The surrounding area towards the southwest has seen multiple volcanic events dating back to the Miocene, much of which is sourced from the San Francisco Volcanic Field (Moore and Wolfe, 1976).

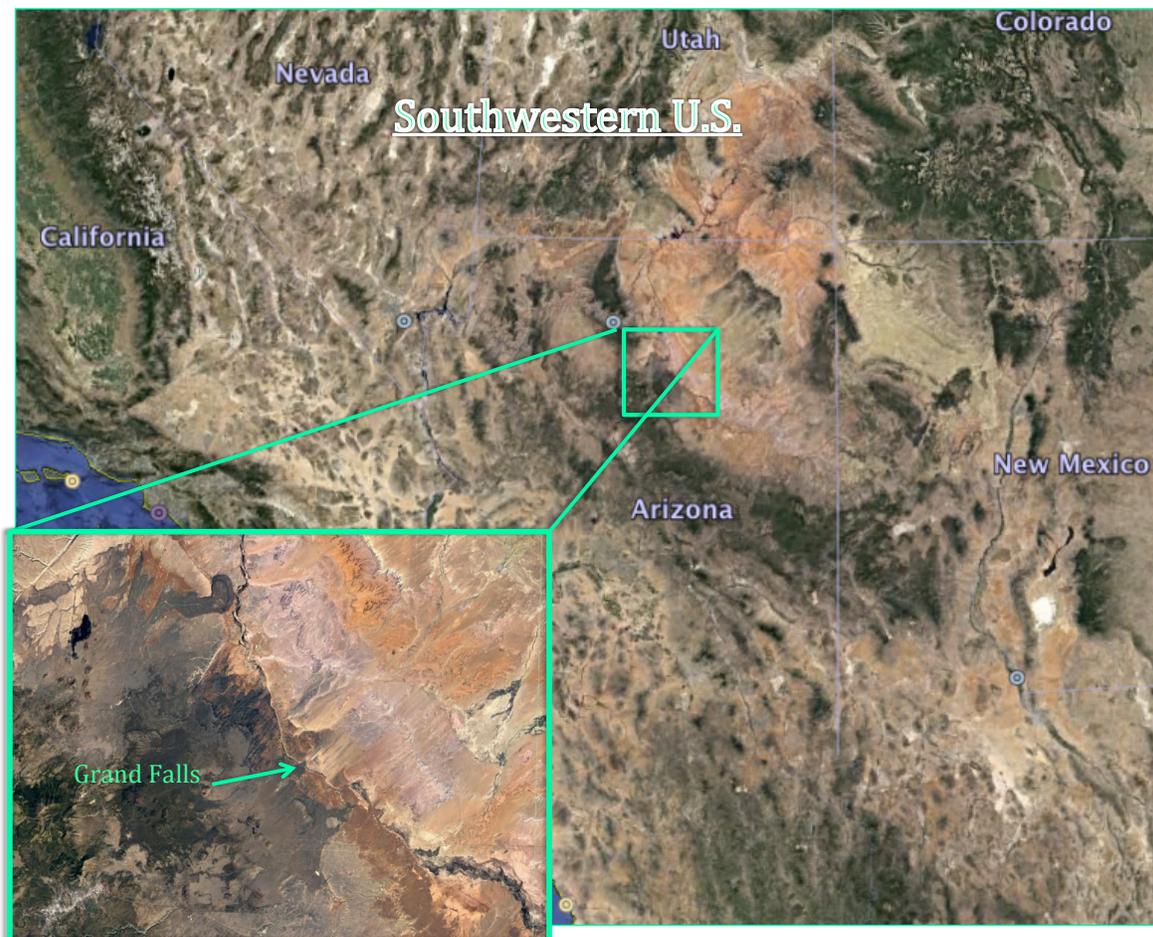


Figure 1: Geographic location of Grand Falls using Google Earth

The Little Colorado River canyon was dammed by dark-grey alkali olivine basalt and is sourced 13 km to the southwest to Sproul crater, west of the larger Merriam Crater (Billingsley et al., 2014). The basalt is non-vesicular and contains phenocrysts of olivine (Duffield et al., 2006). A study done by Duffield et al. (2006) dates the lava flow back to 20 ka by compiling four different methods including $^{40}\text{Ar}/^{39}\text{Ar}$ ages, infrared stimulated luminescence dating of baked mudstone, cosmogenic ^3He from non-eroded to slightly eroded lava tops, and correlation using paleomagnetism. It is suspected that two or more flows created the basalt dam at Grand Falls due to the layering of flows seen in cross-section of the paleochannel fill (Billingsley et al., 2014). The exposed lava fill at Grand Falls is a unit of thick columnar jointed basalt, with four thin slightly dipping flows of basalt, 1-2 m thick above it (Duffield et al., 2006). The lava flow at Grand Falls consist of five or more cooling units, though most of what is exposed is said to be of one event due to similarities in flow and composition (Duffield et al., 2006). In this study this basalt flow will be categorized as one unit of flow and cooling. The lack of hyaloclastite suggests that there was no interaction between water and lava during the emplacement of the dam (Duffield et al., 2006).

Once this basalt flow reached the Little Colorado River on the western rim, it filled up the canyon to a height of 65 m or more, traveled 33.5 km downstream, and 16 km upstream (Hanson et al., 2008). The flow also managed to reach the opposite rim of the canyon at the crest location creating a lobe-like cap towards the northeast extending ~1 km across the eastern rim (Duffield et al., 2006). Due to this damming, fluvial sediments filled up the drainage upstream allowing the river to flow around the crest of the basalt, including the lobe, and flow over the eastern canyon rim into the paleochannel reach filled with basalt (Billingsley et al., 2014). The channel filling basalt downstream of the lobe was removed much faster than the sedimentary bedrock under the river's diverted path. This resulted in a steep point in the river profile where the current river enters its previous gorge at the downstream end of the basalt lobe. This steep reach is referred to as Grand Falls because of the seasonal waterfall it produces over this ~60 m drop. A view looking towards Grand Falls and the buried paleochannel from downstream can be seen in Figure 2.



Figure 2: Grand Falls refers to the waterfall over the steep reach in the Kaibab Limestone on the left. The buried paleochannel filled with basalt is seen on the right. The bottom of the image shows the columnar basalt to be part of the bedrock. (Image from Google)

There is no evidence that a lake filled up behind the lava dam so it is speculated that intermittent floods brought water and sediment to the empty space upstream of the dam, allowing water to evaporate in the desert climate while sediment aggraded. The Little Colorado River is no longer incising or removing the basalt flow but instead is incising into the sedimentary bedrock to the east of the flow. Because of this process, the “new” canyon that will be cut into the Kaibab Limestone to the east of the lava flow is called an epigenetic gorge. An epigenetic gorge is defined as a new river gorge carved by a channel being laterally displaced from its original paleovalley that has been filled in or blocked (Ouimet et al., 2008). Therefore Grand Falls is in the process of creating an epigenetic gorge within the Kaibab Limestone. Where the river goes around the lobe, the Little Colorado River has cut down approximately 7m into the Kaibab Limestone (Duffield et al., 2006). Remnants of the basalt flow still exist on mostly the western side of the canyon and

form a part of the bed of the river 25 km downstream (Duffield et al., 2006). The Little Colorado River also cut about 2m below its assumed paleochannel depth approximately 10 km downstream of Grand Falls (Duffield et al., 2006), but overall the downstream channel of the Little Colorado River can be said to follow its paleochannel elevation. The Grand Falls geology can be seen in the USGS Geologic Map of The Easter Quarter of the Flagstaff Quadrangle, Coconino County, Northern Arizona. A cropped image of this map is shown in Figure 3, where the basalt flow (Qbm1) is shown with its outer lobe and its downstream remnants as well as the Quaternary age fill of sediments behind the lava flow (Billingsley et al., 2014)

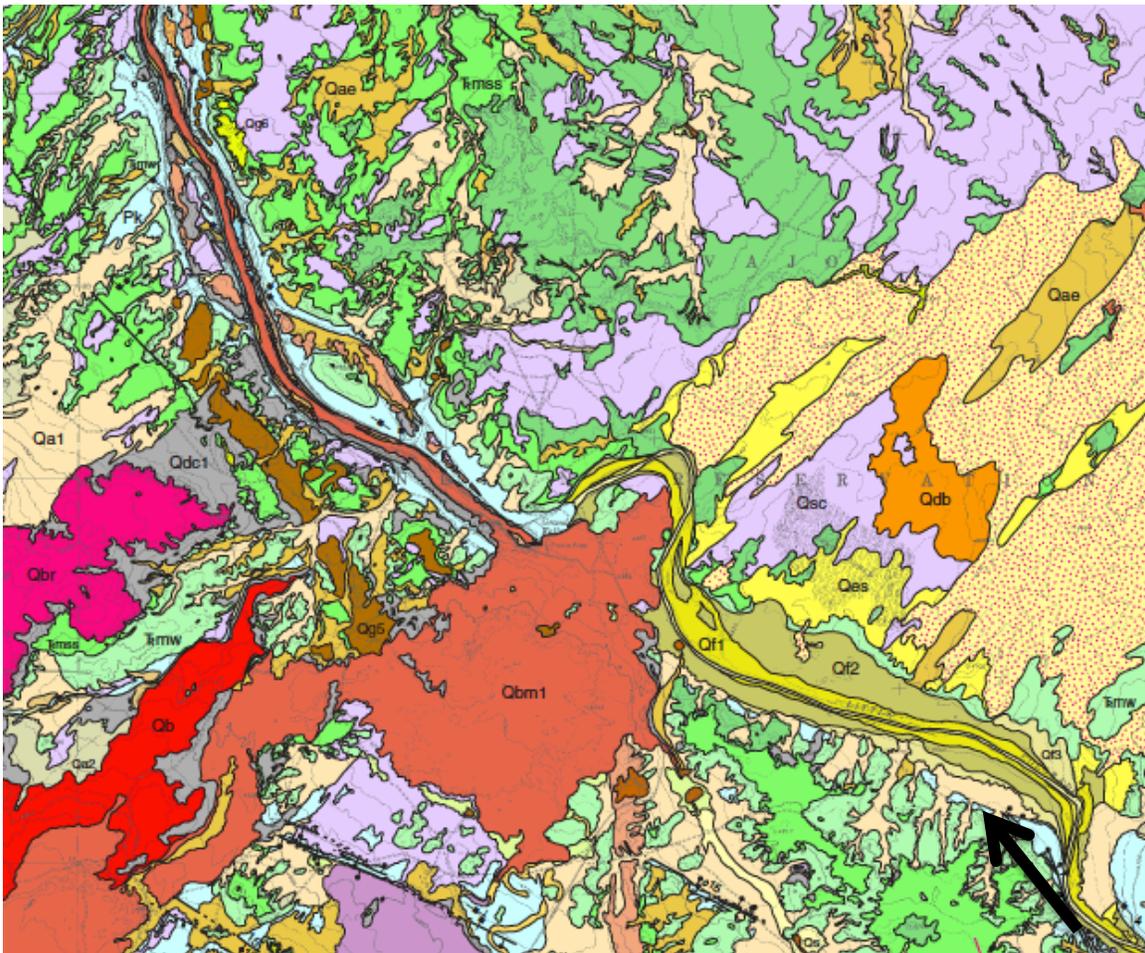


Figure 3: Clipped version of the USGS Geologic Map of Grand Falls. The orange-red Qbm1 is the basaltic flow, the green-yellow Qf1 and Qf2 are flood-plain deposits, and the light blue Pk is the Kaibab Limestone (Billingsley, 2014). Arrow in southeast corner shows flow direction.

Little Colorado River Watershed of Grand Falls Area

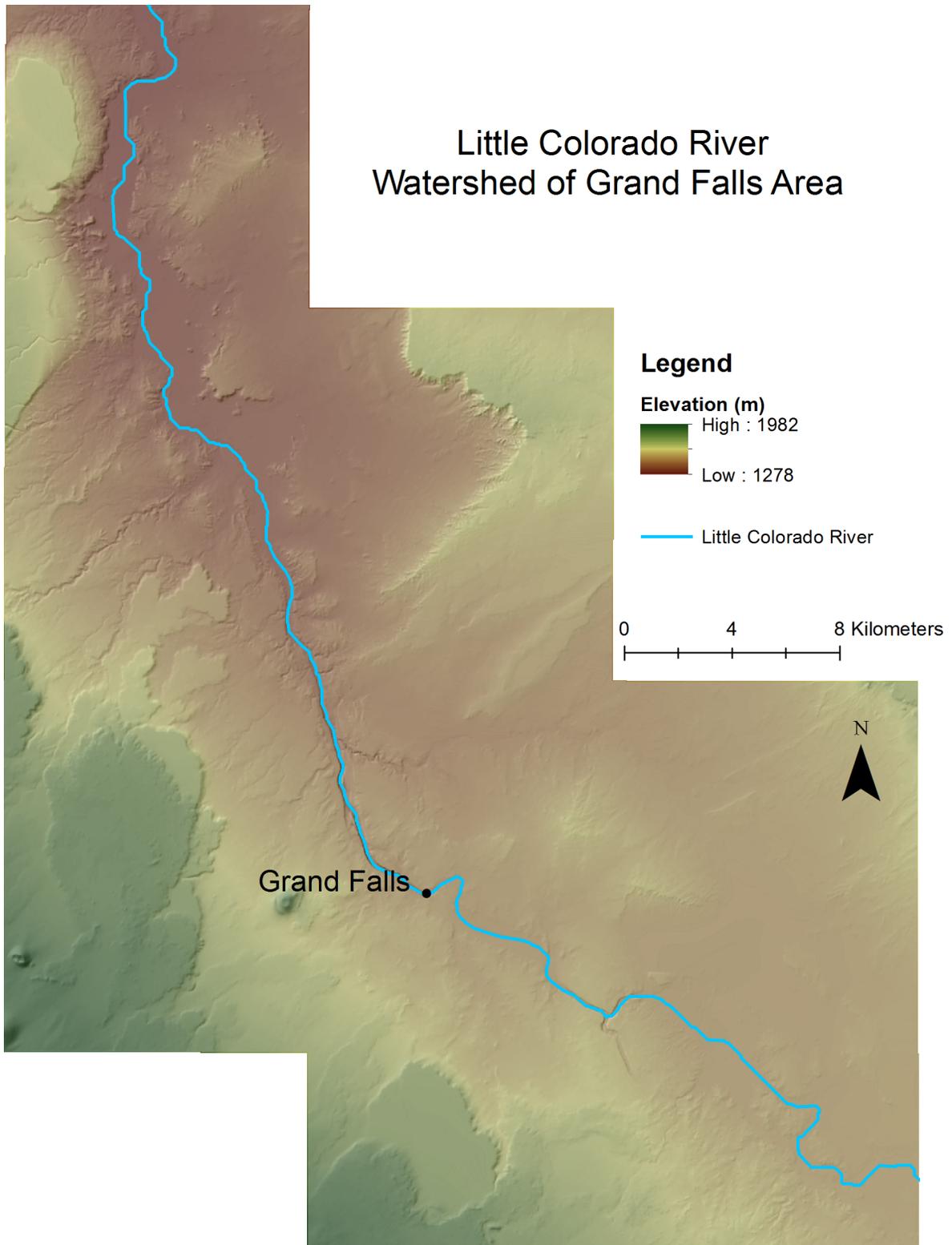


Figure 4: Digital Elevation Model of 30m resolutions of Grand Falls and the adjacent areas, displaying the Little Colorado River and the location of Grand Falls.

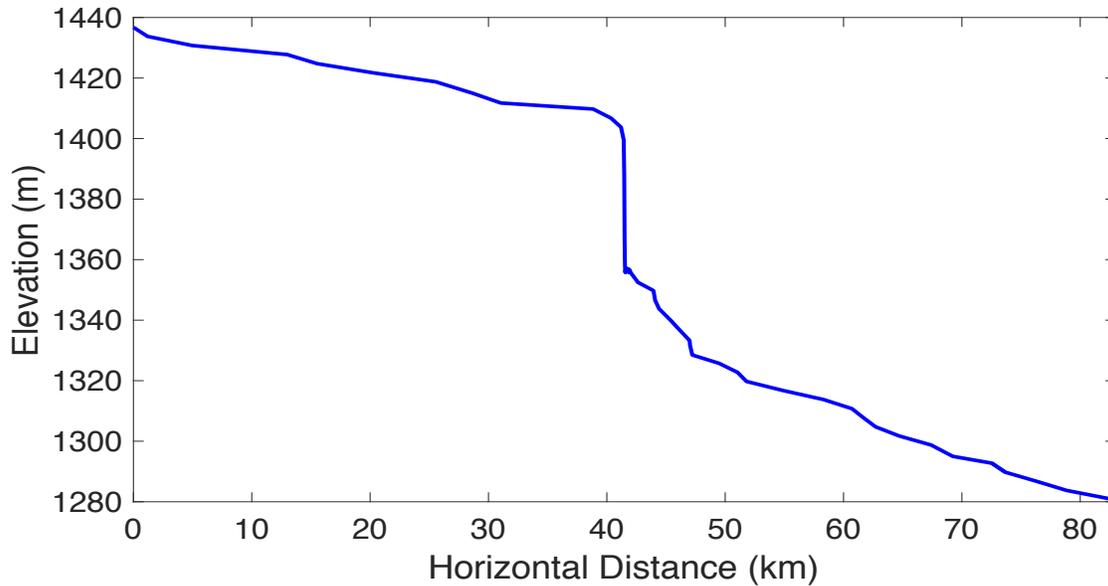


Figure 5: Little Colorado River longitudinal profile, showing large knickpoint at today's Grand Falls. Longitudinal Profile is smoothed out from DEM whose resolution is 30m.

2. METHODS

2.1 Modeling Approach

Dynamic models of river incision encompass and compress geologic timescales in order to better visually understand the lengthy and complex behaviors of rivers. By simplifying a rivers process into a 1D numerical model, we can begin to interpret what the river sees in its longitudinal profile as it erodes into bedrock over time. We recreated the incision history at Grand Falls using a computational program written in MATLAB. The Little Colorado River's longitudinal profile was extracted from a topographic digital elevation model (DEM) of the surrounding area using the geographic information system ArcGIS (Figure 4). About 83 km of the Little Colorado River was extracted to fully encapsulate the upstream and downstream end of the basalt flow at Grand Falls (Figure 5).

Although other lava dams have existed just south of Grand Falls on the Little Colorado River, they have since been removed before the emplacement of the lava at Grand Falls and therefore they are negligible in terms of understanding the

erosional history of removal at Grand Falls. The lava dam of this study led to fluvial sediment aggradation upstream of the lobe at Grand Falls; therefore the initial conditions of this model have the downstream end of the lava emplaced in the channel and its upstream profile following the gradient of the aggraded sediment upstream (Figure 7). To accurately correlate my model with the timing of incision, the time it would take to fully aggrade the canyon behind the lobe needs to be calculated. The rate at which the space was filled behind the lava dam was approximated using the average yearly influx of suspended sediment along the Little Colorado River at Cameron, AZ, ~55 km downstream of Grand Falls. Using an average width of the channel upstream of Grand Falls and the pre-dam slope of the Little Colorado, a rough estimate of sediment infill volume was calculated to be $(2.8 \pm 0.9) \times 10^8 \text{ m}^3$. Using this volume and the rate of sediment influx $9,500 \pm 100 \text{ m}^3/\text{day}$, the aggradation period was calculated to only last decades, 82 ± 27 years. Here, we assume that today's climate and sediment flux was similar to that of the Little Colorado River 20 ka. Error takes into account larger and smaller widths of the upstream channel as well as lower and higher ends of sediment flux data from Cameron, AZ. These estimates are conservative since we don't include bedload. In this case we assume this amount of time is negligible when dealing with the time scale of dam emplacement and removal. If the aggradation of fluvial sediments upstream of Grand Falls had taken on orders of centuries, its incorporation into the model might be deemed necessary.

The paleoslope of the Little Colorado River before the emplacement of the flow is estimated by measuring the slope at the downstream end of its current longitudinal profile. This is a reasonable attempt in recreating paleochannel slope because the buried channel seen at Grand Falls lies at a similar elevation to that of the Little Colorado River today and little to no downcutting has occurred past this paleochannel downstream of Grand Falls (Duffield et al., 2006).

The alluviated channel upstream of Grand Falls has a lower gradient than that of the channel below the falls, which reflects aggradation upstream of Grand Falls (Figure 5). Little incision has occurred through this upstream end, only ~7 m of incision through the Kaibab Limestone around the lobe created by the crest of the

lava flow (Duffield et al., 2006). Upstream beyond the lobe aggradation and incision are in equilibrium, creating a graded reach. This allows for an assumption that sediment transport capacity is equal to sediment flux in this upstream section, since a graded stream is where slope is adjusted to carry the total sediment load supplied from upstream, with the available discharge and channel characteristics (Mackin, 1948). This assumption allows us to interpret and put a constraint on the value of the Little Colorado River's transport capacity using drainage area and slope.

My model is set to begin when aggradation fills up the upstream end of the lava crest, allowing the shape and influences of the upstream end of the lava flow below the aggraded sediment to be ignored. Only the shape of the lava flow downstream of its crest is recreated. Using an image Duffield et al. (2006) provides of their interpretation of the original shape of the lava dam from observed remnants (Figure 6) a half-Gaussian curve shape is used to represent the thickness of the lava flow where it intersects the channel (Figure 7). Although the nature of basalt flows is not perfectly smooth like in our model, it is a close representation of the lavas original flow shape. According to Duffield et al.'s (2006) interpretation of the incision history downstream of the dam, the channel has incised up to ~2 m net incision into the bedrock downstream of the lava flow.

At the start of our model, we include a steady low gradient above the crest, representing the graded reach. The lava flows interpreted shape is then followed, with its crest intercepting the end of the graded fluvial sediments. The lava flow crest is interpreted to be 72 m in height in order to converge with the top of the graded reach and to have the lava flow rest on the pre-dam slope. The lava flow top and Kaibab Limestone are at the same elevation at their boundaries in this model. The low gradient graded upstream reach is assumed to be the Kaibab Limestone for its portion near the lava flow. The vertical line between the lava flow and Kaibab Limestone in the model is also the location of Grand Falls on the longitudinal profile of the Little Colorado River. The lava flow is set on top of the pre-dam gradient and this gradient extends past the end of the lava flows profile. This initial shape is where the model is initiated to remove the lava dam (Figure 7).

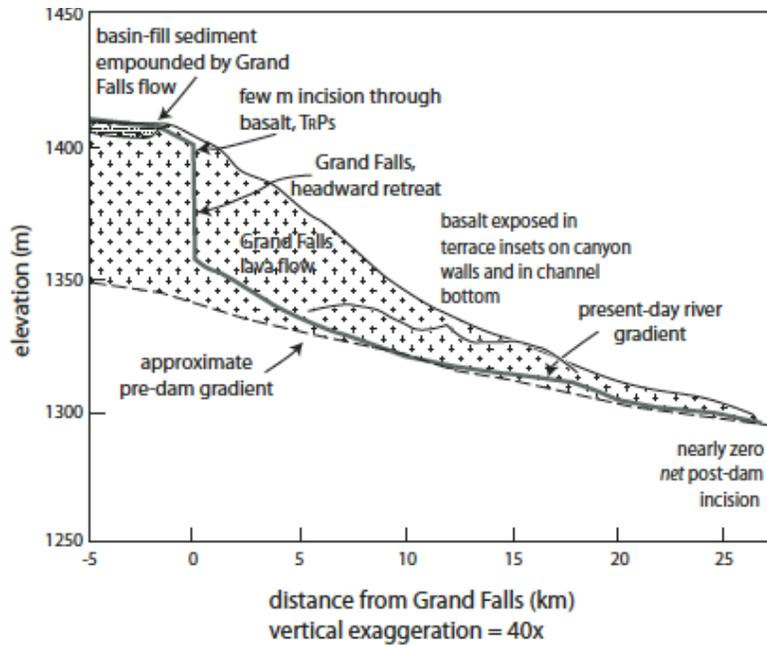


Figure 6: Sketch from Duffield et al. (2006) showing the inferred paleochannel, modern stream channel, and Grand Falls basalt flow.

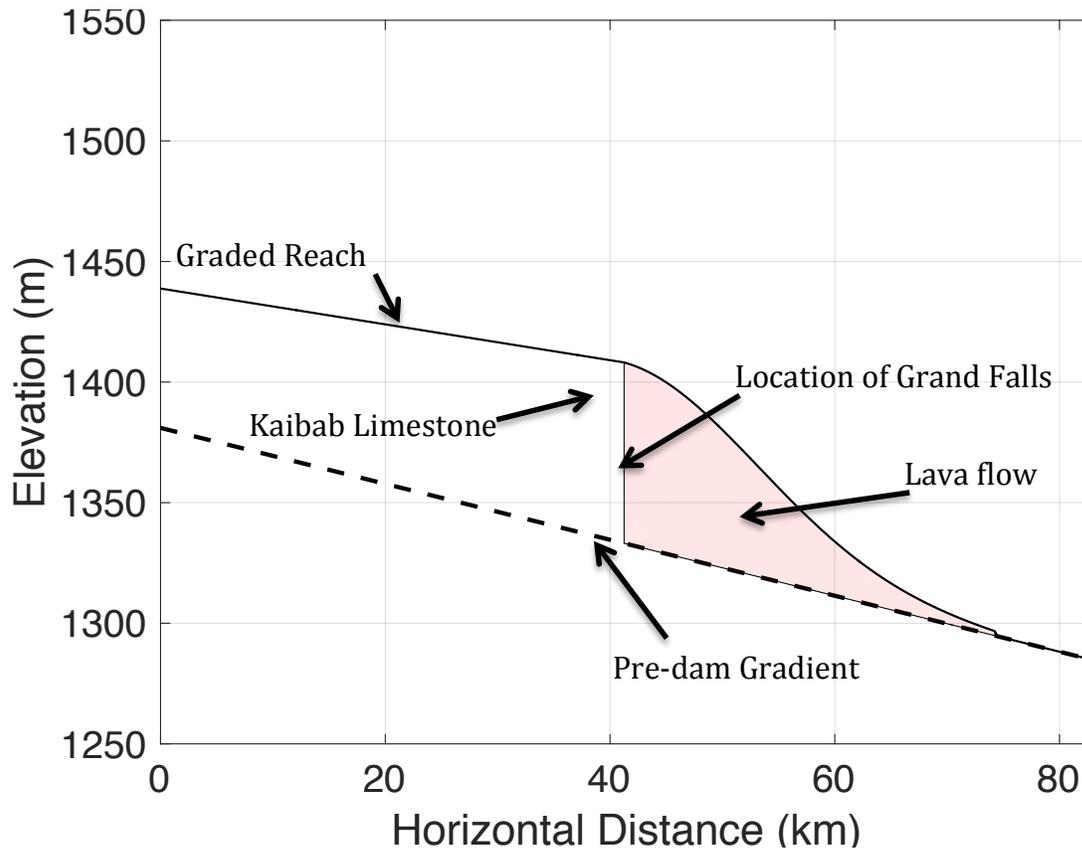


Figure 7: Initial shape of river profile with upstream alluvium at a low slope, dashed line shows paleoslope, and lava dam in a Gaussian shape in faint red.

2.2 Incision Model

This study will compare two different incision models, simple stream power and a sediment flux dependent stream power to see which will recreate the modern morphology seen at Grand Falls. Our interpretation of sediment flux giving the channel the ability to promote incision is based only on the process of abrasion. This study does not analyze how other processes of erosion due to plucking or weathering affect the removal of the lava dam.

2.2.1 Unit Stream Power

Lava dam removal can be analyzed by looking at the unit stream power law that governs the rate of downcutting (dz/dt) within geologic media,

$$\frac{dz}{dt} = K A^m S^n$$

where z is channel bed elevation, t is time, K is an erodibility constraint that is based off lithology, climate, and channel properties, A is drainage area, S is channel slope, and m and n are positive exponents whose values have been discussed and can be derived from physical properties of a channel (Whipple and Tucker, 1999, 2002). Exponent m varies with hypsometry of a river basin and represents a discharge-drainage area relationship (Stock and Montgomery, 1999). Although drainage area should vary with downstream distance of a channel, that is ignored in this case study because of its minute change throughout the reach of the area of interest. Exponents' m and n can be expressed as the intrinsic concavity (θ) of a channel as follows,

$$\theta = m/n$$

The drainage basin shape can express the concavity of a stream if the channel is under a steady and uniform erosion (Whipple and Tucker, 2002). The exponent n depends on the dominant erosion process of the catchment, varying (in theory) from $2/3$ to $5/3$ (Whipple et al, 2000). A commonly observed value of channel

concavity is 0.5 (Tucker and Whipple, 2002) and for bedrock rivers it can vary between 0.3 and 1.2 (Whipple, 2004). This study will compare debated values of m and n for bedrock channels to develop a working model for lava flow removal.

2.2.2 A Threshold Term

Erosion by a river occurs when boundary shear stress exceeds a critical threshold, usually occurring during flood events (Snyder et al., 2003). Using cosmogenic ^3He surface dating of exposed fluvial surfaces, Baynes et al. (2015) tied removal of basaltic lava flows in Northeast Iceland to large flooding events occurring in the Holocene. Although a threshold would better represent the large flood events causing most of the erosion, a fixed-magnitude event with an intermittency factor can be acceptable for modeling the influence of climate on erosion over larger time scales (Phillips and Jerolmack, 2016). Therefore, due to the simplicity of our model, a fixed-magnitude flood event is characterized in our drainage area, and the intermittency factor is incorporated into the parameter K .

2.2.3 Sediment flux

In Taiwan the Da'an River shows importance of a sediment flux term in river incision. Here a knickpoint generated by the 1999 Chichi earthquake remained stationary for a period of five years during which time bedload did not exist due to gravel extraction upstream behind an anticline (Cook et al., 2012). Erosion and propagation of the knickpoint only occurred when the excavation ceased and large typhoons swept the area (Cook et al., 2012), showing the importance of a sediment flux dependent incision model as well as a threshold. Because of this idea, a dependency of sediment flux was added to my model. In the case of the Da'an River no incision occurred without bedload, and then once bedload became available the knickpoint moved a total distance of 430 m within just two years (Cook et al., 2012). In the case of damming if abrasion is the dominating erosion process, until water and sediment accumulates upstream no significant amount of erosion is possible downstream of the crest. When water or sediment does eventually pass over the crest, it will be able to do work on the basalt and the bed. The river loses its abrasive

tools until the sediment back fills the dam and then travels downstream to begin to remove the dam. Sediment flux can be included to the unit stream power law following Whipple and Tucker (2002),

$$\frac{dz}{dt} = f(Q_s) K A^m S^n$$

Where $f(Q_s)$ is a function of sediment flux. In simple stream power, $f(Q_s)$ is deemed as being equal to 1, meaning sediment has no effect on erosion rate. The $f(Q_s)$ function embodies the ability of sediment load to erode the bed, where Q_s is the volumetric rate of sediment flux. In principle, sediment can enhance the stream's ability to erode the bed by providing tools for abrasion, but it can also cover the bed and thereby protect the bed from incision (Sklar and Dietrich, 1998; Whipple and Tucker, 2002).

Upstream of Grand Falls the sediment will aggrade and protect the bed from erosion. Sediment flux can inhibit or promote erosion depending on the transport capacity within the stretch of the river. The dual influence of sediment can be modeled in a simple way by using a parabolic form for $f(Q_s)$, with a maximum when the sediment flux is half of the transport capacity of the channel (Whipple and Tucker, 2002) (Figure 8). The basic idea behind this is that bedrock erosion rate will be the greatest when volumetric sediment flux is equal to half of the transport capacity of the stream. As volumetric sediment flux begins to increase and come close to the transport capacity erosion will diminish as sediment covers the bed and protects it. This idea of a dual influence of sediment flux is directly shown in this parabolic model by heightening or preventing erosion. Initially on the parabolic curve when sediment flux is very small relative to transport capacity, any increase in sediment flux promotes erosion due to more particles being available to abrade bedrock. When sediment flux is greater than half the transport capacity, any further increase in flux represses the rate of erosion. Following Whipple and Tucker (2002) we use the parabolic form of sediment flux,

$$f(Q_s) = 1 - 4 \left(\frac{Q_s}{Q_c} - \frac{1}{2} \right)^2$$

Where Q_s is sediment flux and Q_c is transport capacity. Due to the generic form of a parabolic curve, if there is no sediment flux there is no erosion. The issue with allowing Q_s/Q_c to change with time allows for the ratio to drop in a runaway feedback (Whipple and Tucker, 2002). If steepening occurs, the transport capacity becomes larger while sediment flux remains the same, dropping the Q_s/Q_c ratio. This would create steeper slopes because of insufficient tools that would then create a runaway feedback.

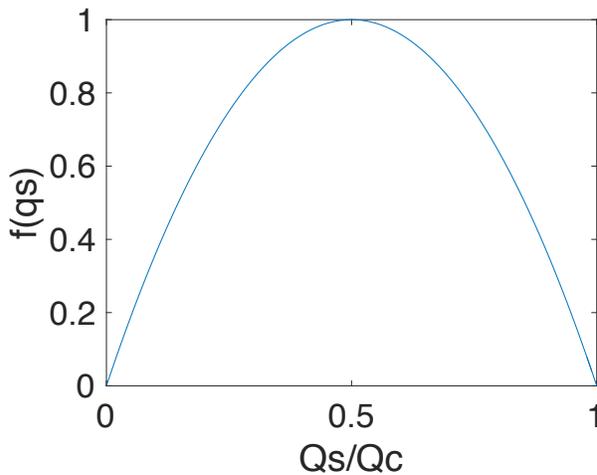


Figure 8: Diagram of sediment flux function showing dual dependencies on erosion based off ratio of sediment flux to sediment transport capacity.

2.3 Model Conditions

2.3.1 Constraints

At the Grand Falls gaging station the drainage area is reported as 5.4×10^{10} m². A sediment flux of 0.11 m³/s was taken from the USGS site at Cameron, Arizona just 55 km downstream of Grand Falls. The sediment flux data is for suspended sediment, and it would be preferred to have data on bedload, but since bedload is a fraction of suspended sediment, we will account for this difference in the erodibility parameter K .

Due to the well-defined parameters on the lava flows shape done by Duffield et al. (2006) reconstruction of the lava flow was relatively simple. A crest height of

larger than 65 m and a length of flow of 33.5 km (Hanson et al., 2008) were manipulated to form a Gaussian Curve shape downstream of the crest of the lava dam.

2.3.2 Upstream Area

Following Gasparini (2006) sediment transport capacity can be generalized by the notion that it depends on the streams discharge and slope at a location multiplied by constant (K_2),

$$Q_c = K_2 A^{m_t} S^{n_t}$$

where K_2 is another erodibility parameter, m_t and n_t are scaling parameters and in this model $m_t=n_t=1$ for simplicity. K_2 has the same sensitivity as parameter K as well as dependence on sediment properties. Here a threshold is ignored for sediment entrainment in the simple power law equation. With an increase in slope or discharge sediment transport capacity will also increase, and therefore in my model sediment transport capacity changes due to large differences in slope along the longitudinal profile. At Grand Falls, the upstream section has experienced little to no erosion due to sediment flux since damming. In this case, the sediment transport capacity must equal the sediment flux due to the lack of erosion and lack of more aggradation. This allows for a computation of the coefficient K_2 using the slope of the alluvium, the drainage area, and the sediment flux, knowing $Q_s = Q_c$ here,

$$K_2 = \frac{Q_s}{A S_{alluvium}}$$

where $S_{alluvium}$ is the slope of the alluvium behind the crest of the dam calculated from the DEM longitudinal profile. This assumption states that at any point along the Little Colorado River where the slope is equal to the slope of the alluvium there will be no incision. Sediment flux is a function of erosion rates upstream on the bed as well as on hill slopes causing sediment flux to converge and increase with downstream distance. Although the sediment flux in this model remains constant.

Table 1: Summary of Constraints

Drainage Area	Height of Lava	Length of lava	Alluvium slope	Sediment Flux	Paleoslope	Start of Model
$5.4 \times 10^{10} \text{ m}^2$	~70m	33.5 km	~0.0007	0.11 m ³ /s	~0.0012	20 ka

3. Results

3.1 Removal Shape

The current profile of the Little Colorado River is steep at the point between the basalt and the Kaibab formation with a knickpoint present within the Kaibab formation. This modern morphology allows for the greatest amount of incision to be within the basalt. Just 5 km below the modern falls, the Little Colorado River first meets its paleo streambed. Here, the river has incised through ~60 m of basalt. Yet the knickpoint lies ~5 km upstream of this point. This occurrence of significant incision through the basalt but relatively limited knickpoint propagation into the Kaibab could also indicate that the limestone unit is actually more resistant to erosion than the basalt or a question of timing. The question of timing refers to the fact that the Grand Falls we see today potentially may just be showing us the beginning of erosion into the Kaibab Limestone.

3.2 Erodibility Parameter

We use the unit stream power model as well as its conjunction with sediment flux to test their application in removing the lava dam. Each test run begins with a different value for m and n , and then the erodibility parameter (K) is calibrated to create a profile similar to that of the modern Little Colorado River at Grand Falls. Table 2 shows the values chosen for m and n and their corresponding K values for the Kaibab Limestone and the ratio of the K value for basalt with respect to the Kaibab Limestone. The following figures show how different exponents on slope and drainage area affect the final shape of the rivers profile, with their corresponding erodibility parameters. The erodibility parameter is constrained to closely mimic today's longitudinal profile seen in Figure 5. Each of the following seven figures

describes the parameters set in Table 2. Each black line in the figure represents 2,500 years, and the last line closest to the modern longitudinal profile represents the model's modern profile output. The light blue line represents the modern longitudinal profile of the Little Colorado River.

Table 2: Comparison of Model Parameters

	m	n	m/n	K (Kaibab)	K(Basalt/ Kaibab)	Figure
Simple Stream	0.5	1	0.5	9.5×10^{-12}	1	9
Power	0.5	1	0.5	2.7×10^{-6}	5	10
Sediment Flux	1	1	1	4.3×10^{-12}	5	11
Dependent	0.5	1	0.5	9.5×10^{-07}	5	12
Stream Power	5/6	5/3	0.5	9.5×10^{-9}	5	13
	1	2	0.5	9.5×10^{-10}	5	14
	5/6	5/3	0.5	1.8×10^{-8}	5	15

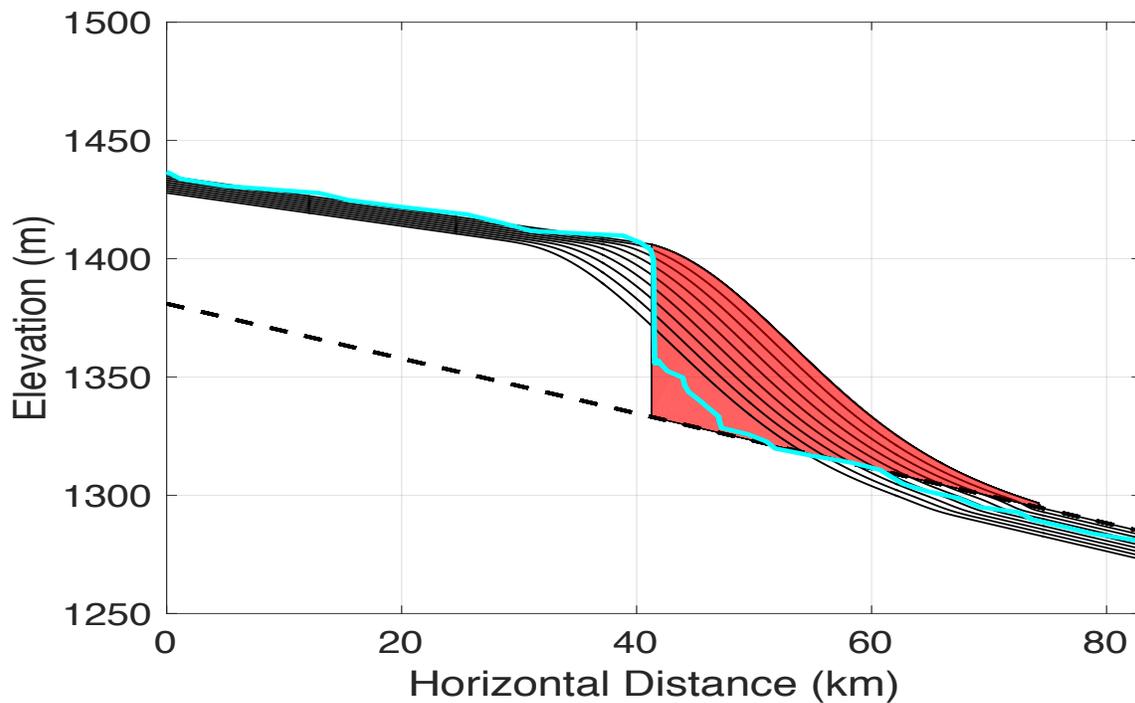


Figure 9: Using simple stream power with erodibility of lava equal to erodibility of underlying and adjacent strata.

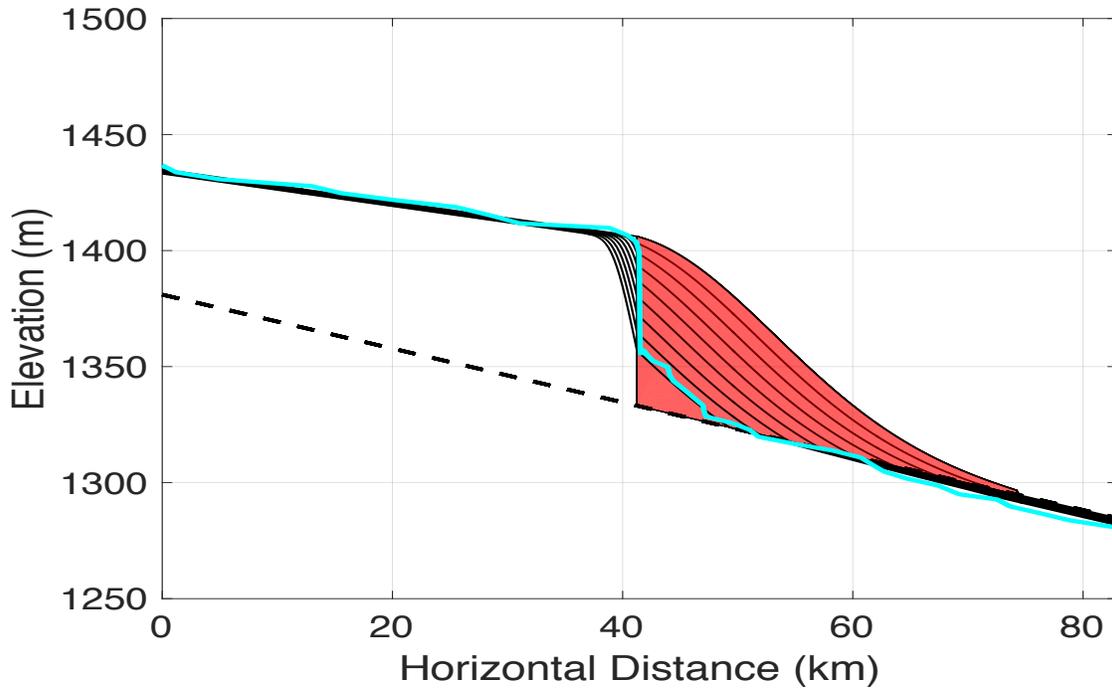


Figure 10: Using simple stream power with erodibility of lava to be five times greater than erodibility of strata. Downstream profile is similar to today's profile, but erosion through what is assumed to be the graded portion is not.

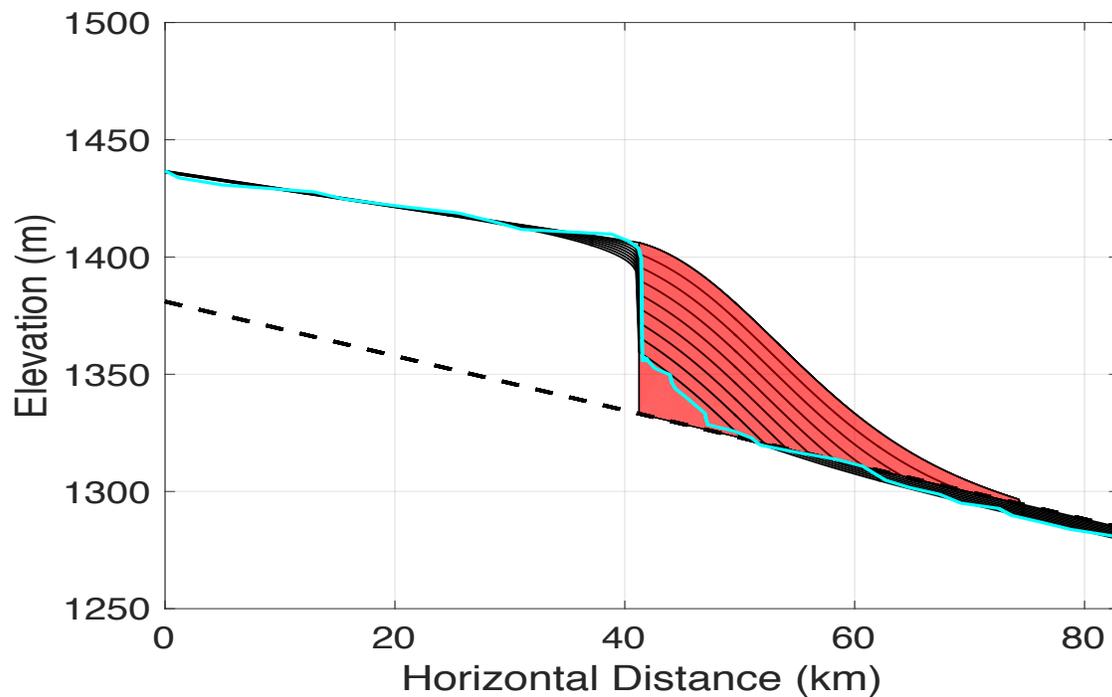


Figure 11: Sediment flux dependent linear stream power with erodibility of basalt five times greater than surrounding strata. Steep knickpoint here might be a function of "tool" starved, due to ratio of sediment flux to sediment transport capacity decreasing.

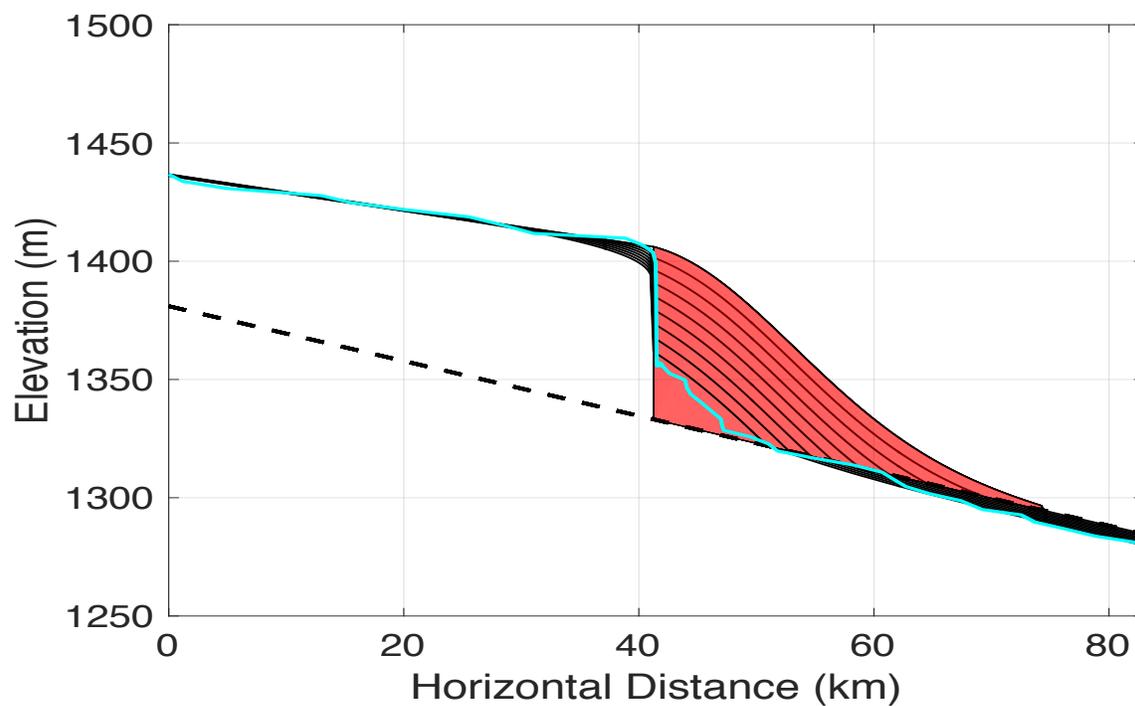


Figure 12: Sediment flux dependent stream power with $m = 0.5$, $m/n = 0.5$ and erodibility of basalt is five times greater than surrounding strata.

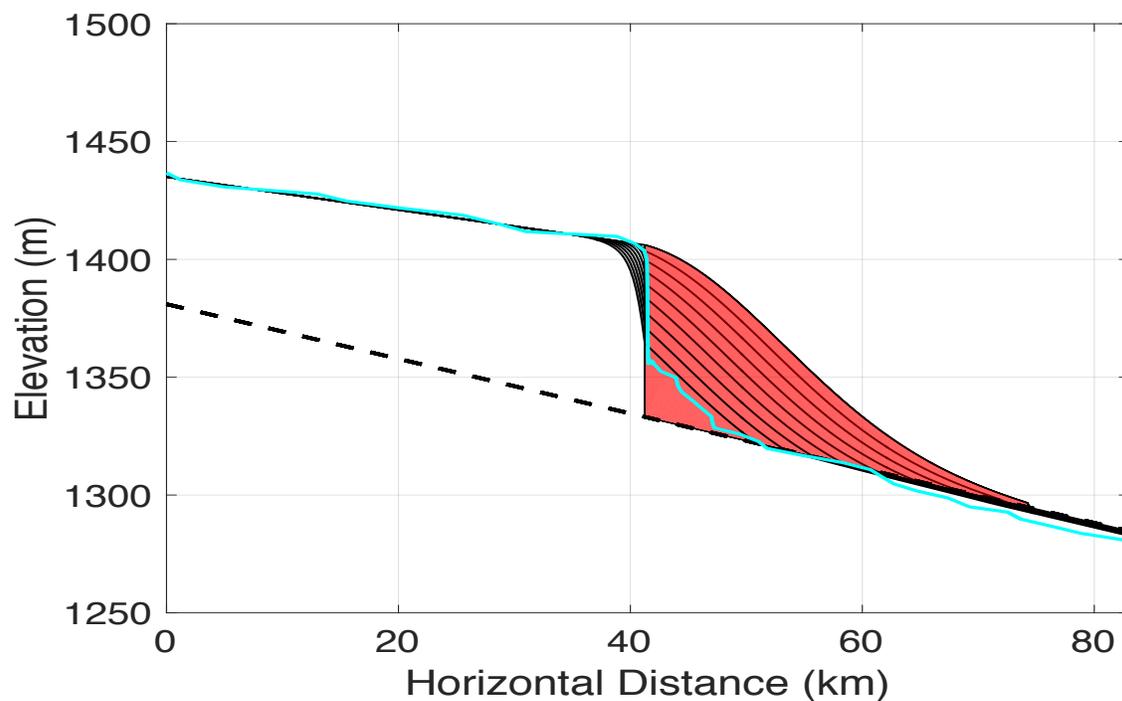


Figure 13: Sediment flux dependent stream power with $m = 5/6$, $m/n = 0.5$ and erodibility of basalt is five times greater than surrounding strata.

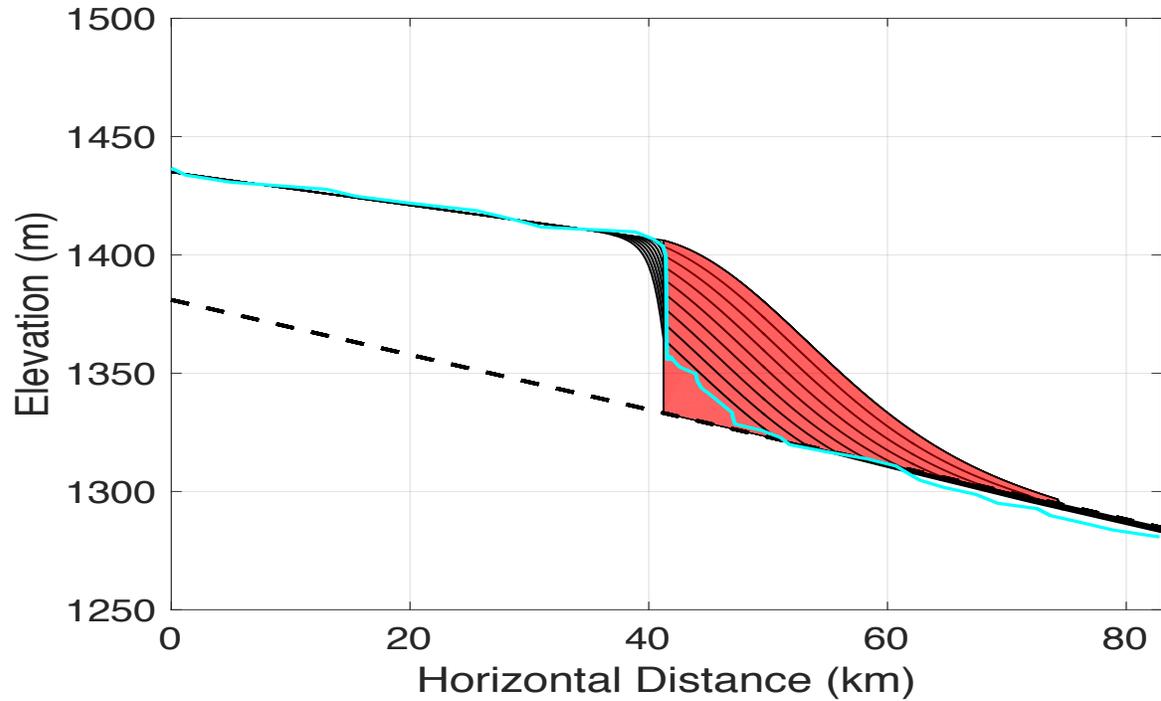


Figure 14: Sediment flux dependent stream power with $m=1$, $m/n = 0.5$ and erodibility of basalt is five times greater than surrounding strata.

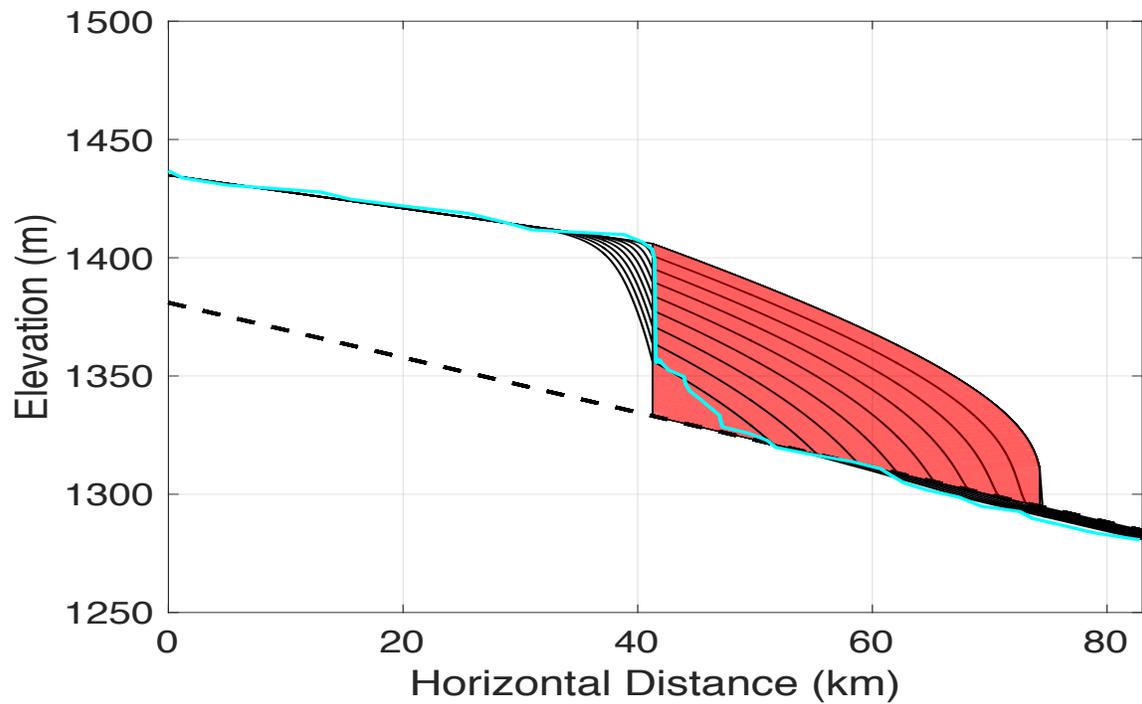


Figure 15: Same parameters as Figure 13, but with a change in lava flow initial shape.

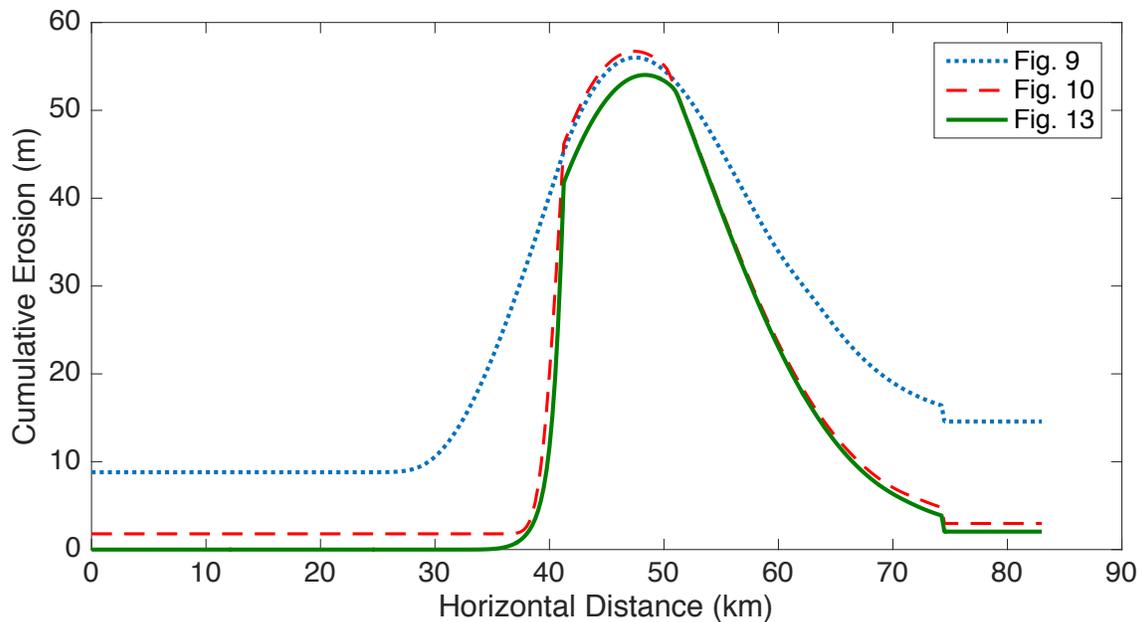


Figure 16: Plots of cumulative erosion for incision models in Figures 9, 10, and 13.

4. 1 Discussion

For a stream power model to show the near vertical knickpoint in the Kaibab, with the channel having incised ~ 2 m below the basalt 25 km from the flow's crest, the erodibility parameter of basalt must be 5 times larger than the Kaibab Limestone. The unit stream power model without incorporation of a sediment flux did not fully create the modern morphology seen at Grand Falls, since erosion in this model was steady upstream of the crest (Figure 16). When the erodibility of basalt is equal to the erodibility of the surrounding strata the profile retains its gradient and shape inherited from the flow itself but gets displaced and the finished profile does not show the near vertical morphology of the knickpoint seen at Grand Falls. Cumulative erosion in the downstream strata and upper reaches is larger than expected when erodibility is the same throughout the model (Figure 16). The model of Figure 9 shows the importance of the erodibility parameter of the basalt flow versus the Kaibab Limestone in order to achieve today's morphology at Grand Falls. Although scaling of channel slope on incision helped initial propagation of erosion through the steep section of the dam, no erosion to give today's profile was achieved without giving the basalt a higher erodibility.

The final profile without any scaling of discharge and slope with a sediment flux dependence, resulted in no change in the upper reaches, steeping between the boundary of the Kaibab Limestone and the basalt flow, close to complete removal of the lava flow, and little downcutting past the paleoslope in the bottom reaches of this segment. Because of the nature of the Figure 13's final profile ($m = 5/6, n = 5/3$) matching best to the current profile of the Little Colorado River, I will discuss next the nature of erosion of the lava dam on the basis of this figure.

Initial incision occurs across the entire reach below the crest of the lava dam. Within the lava flow itself the largest amount of incision is seen on its steepest neck, to the left of its center (Figure 16). Less incision is done on the top of the lava flow due to shallower slopes. At the end of the lava flow the slope is the shallowest, which allows for little incision at first. However as time progresses the bottom end of the lava flow becomes steeper and increases incision within the original center of the lava flow.

Within the sedimentary layers themselves, there is a relatively small amount of incision within the Kaibab at the boundary and even less heading upstream. Incision here within the Kaibab is due to increased slope, as the crest of the lava flow gets shorter in height, creating a large slope change at the boundary, which will cause an upstream propagation of this steepening. Because the erodibility of the limestone is smaller than the basalt this steep knickpoint created here is hung up against the Kaibab Limestone. Downstream of the lava flow, little incision is seen within the Kaibab Limestone, which is in part due to the low slope in comparison to the steepness of the lava flow, but also due to the erodibility being less than the basalt. The model shows up to 2 m of incision within this lower reach (Figure 16), which is on par with Duffield et al.'s (2006) field data.

The model here predicts $\sim 3\text{mm/yr}$ of incision within the center of the basalt where incision is the greatest and $\sim 0.1\text{mm/yr}$ of incision in the lower reaches of the Kaibab limestone.

4.2 Erodibility, the answer

Subtle differences are seen when comparing the four different tests on scaling of slope on a sediment flux dependent incision model. This leaves the difference in erodibility between the basalt and strata to be the major player in creating the morphology seen at Grand Falls.

A recent study on incision of lava flows in Iceland showed that the removal of basalt dams is a quick process in regards to geologic time. These Icelandic lava flows appear to have been eroded during periods of intense canyon cutting by catastrophic floods, during which basaltic columns appear to have collapsed creating a clear vertical knickpoint (Baynes et al., 2015). Although this study's model is unable to produce such an effect, Baynes et al. (2015) study suggest that basalt erosion can be relatively rapid if you have a catastrophic flood. This relatively rapid incision is supported by the idea that individual basalt flow units fail by toppling of jointed columns, representing a natural weakness in this particular type of lithology. Although this model shows the steepening at the boundary to be a function of change in lithologies, a bigger idea might also be conducive, in that the basalt is removed more rapidly because of toppling of its columns creating a steep knickpoint, that would then be hung up at the lithologic boundary.

Another field example that illustrates the role of column toppling in erosion of basalt flows is the Box Canyon of Idaho. Here nearly vertical headwalls and canyon walls characterize the canyon's morphology. This geometry suggests that the vertical joints of the basalt promote toppling of columns and initiate propagation of a knickpoint upstream (Lamb et al, 2008). Using samples of boulders within the canyon, Lamb et al. (2008) were able to calculate the discharge needed to move these boulders as well as their ages to find that erosion of this canyon probably happened due to a megaflood (Lamb et al, 2008). Persistence of waterfalls and knickpoint morphology can result from toppling of individual blocks in bedrock units that are interwoven with near vertical joints, as in this case of columnar basalt (Lamb and Dietrich, 2009). This type of bedrock fracturing and knickpoint morphology and retreat may be the reasoning for the steep headwall here at Grand

Falls and may also have contributed to relatively quick removal of the basalt relative to erosion of the surrounding bedrock.

The best-fitting model is sediment flux dependent, which inherently depends on bedload hitting and eroding the bed, but another process might be at play here. Plucking of the basaltic columns is a process that is not fundamentally shown in this model.

4.3 What happens next?

The Little Colorado River now needs to remove the Kaibab limestone around the lobe of the basalt flow to completely remove the dam. The removal of these strata can result in long-term or short-term effects on the longitudinal profile of the river. In the case of short term, the river would just remove the dam and have no effect on the longitudinal profile as shown by Crow et al. (2015). Ely et al. (2015) found that the lava dams in the Owyhee River show relatively rapid incision through the basalt with no lasting impact on the river profile for time scales $>10^6$, but that the redirecting of the river due to the damming creates distinct valley morphology and impacts local bed load beyond the life of the dam itself. In the case of long-term, the steepening into the sedimentary layers may result in headward erosion of the knickpoint, which would propagate upstream and erode past the paleochannel depth. In this case, knickpoint propagation morphology must not be delineated as a tectonic response or lithology changes but as a result of damming. Whether the river cuts through the entire lava dam or flows around it to form an epigenetic gorge may complicate the effects on the final profile of the river. This would further the complicate the retrieval of tectonics from topography.

4.4 Limitations with the Model

The model assumes the location between the Kaibab Limestone and the basalt and that the boundary is completely vertical. The vertical boundary is an oversimplification but for the purposes of this model it shows how with a more vertical transition erosion will decrease at Kaibab limestone, creating a knickpoint at the boundary. Our assumption that transport capacity is equal to sediment flux is

another simplification since we assume that the upstream reach is in equilibrium since the meandering Little Colorado River in the fluvial sediments upstream cuts and deposits nearly simultaneously. The use of a simple Gaussian curve to represent the shape of the lava flow can be criticized but on the other hand using a different shape (Figure 15) has little effect on the model's basic behavior.

Although the linear stream power model and the sediment flux dependent stream power model both have the ability to recreate today's profile, neither is an accurate representation of how the lava dam is eroded through. In order to recreate a profile similar to today's using stream power model, the basalt must be 5 times as erodible as the underlying and adjacent strata. This is a less intuitive result, since it is common to believe that basalt would be stronger when compared to a sedimentary rock. This high erodibility may reflect more efficient erosion of basalt through the detachment and toppling of basalt columns due to drag and shear of over flowing water, pore fluid pressure, and possible buoyancy from plunge pools at the base of the waterfall created by the knickpoint (Lamb and Dietrich, 2009). This toppling can explain the greater cumulative erosion into the basalt in the stream power model, although the bedrock fracture geometry does not play a role in this model's knickpoint morphology and upstream propagation.

4.5 Future Studies

Although this study only refers to the initial erosional structure of lava dam removal, it is important to look towards what happens after the crest is breached. One case might cause steepening of the Kaibab Limestone to increase to the point where knickpoint propagation is inevitable through the entire upstream reach of the Little Colorado River.

Even though the stream power model is able to predict some elements of the current profile we see at Grand Falls, it may not be the right answer. Further studies can be done here with analysis and focus on the process of basalt column toppling.

5. Conclusion

This study looked to simple stream power and sediment flux dependent stream power to recreate the incision history of the Little Colorado River focused at the basalt lava dam at Grand Falls. To this day the lava flow is being removed and limited constraints of the lava flow and the channel helped recreate its incision history. When using a stream power model, regardless of whether it is sediment flux dependent or not, to return today's morphology at Grand Falls with a knickpoint at the boundary between the basalt dam and the adjacent strata, the basalt must have an erodibility parameter that is five times greater than its adjacent strata.

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