River Adjustment and Flood Hazards on the Colorado Front Range

Joel Sholtes, PhD, EIT
Department of Civil and Environmental Engineering
Colorado State University

Brian Bledsoe, PhD, PE
College of Engineering,
University of Georgia

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COLORADO STATE UNIVERSITY

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Abstract

Stream power, a hydraulic metric representing the potential erosive energy of a flood, is relatively easy to estimate using remotely sensed data and can perform well in predicting channel response to floods. Using a dense network of peak discharge estimates from the 2013 Front Range floods and LiDAR-derived digital elevation models, we estimated stream power and related metrics at the reach scale along 16 stream and river segments in the Front Range of Colorado. Channel response to the floods was qualitatively categorized, and channel width and net erosion and deposition were measured at the reach scale. With these observations and measurements, we evaluated the relationship between stream power and geomorphic metrics and channel response to floods by applying statistical models and evaluating downstream trends in channel response. As a proof of concept, we applied the best performing empirical model to predict channel response to a range of flood frequencies. Finally, we participated in developing a framework for mapping the "fluvial hazard zone" within the State of Colorado, which will be further refined and piloted in 2017.

Keywords

Floodplain management, flood hazards, geomorphology, stream power, floodplain mapping, statistical modeling

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Introduction

Nearly 25% of flood insurance claims in the U.S. come from areas outside of the 1% annual exceedance probability (AEP, i.e., 100-year) floodplain (Michael Gease, FEMA natural hazards specialist, quoted in Walker, 2014). Flood-related impacts outside of the 1% AEP floodplain were observed throughout the Colorado Front Range after the September 2013 floods, despite peak discharge estimates having magnitudes less than or equal to the 1% AEP flood (Houck, 2014). Observations of river adjustment and the extent of flooding along the St. Vrain River near Lyons and Longmont, for example, demonstrate that dynamic river processes (channel adjustment) played an important role in exacerbating flood damages. Channel avulsion (channel acquiring a new route), erosion, and deposition processes during a flood all change the boundaries of the river and the floodplain leading to unexpected and unmitigated flood impacts. As recognized by Congress and FEMA in the 1994 National Flood Insurance Reform Act, ignoring river change during floods may in some cases underestimate hazards in the floodplain. Existing methods for determining risk of river channel adjustment are generally labor intensive and rely on historical aerial photograph coverage (State of Washington, 2014), largely lacking in Colorado, or are based on gross simplifications of geomorphic processes (Kline and Dolan, 2008).

We develop new methods to characterize and predict river change within a river and floodplain corridor using information on flood hydraulics coupled with observations and measurements of channel change. Using pre- and post-flood data in a GIS environment, this study identifies zones within a watershed that are more susceptible to change, and ultimately leads to planning tools and guidance tailored to the floodplain planning and management needs of state and local governments. This work compliments the “Fluvial Hazard Zone” mapping framework developed by J. Sholtes while working under this grant in conjunction with K. Jagt and M. Blazewicz (Jagt et al., 2015) for the Colorado Water Conservation Board’s Floodplain Management Program, which is presented herein.

Objectives

This report is organized around four main objectives, which build upon one another:

1. Quantify and map the extent and severity of river change within the Front Range as a result of the 2013 floods and characterize the downstream patterns of channel change from the foothills to the plains.
2. Develop a predictive model linking remotely sensed hydraulic and geomorphic predictor variables with channel adjustment severity during floods.
3. Apply the predictive models in a magnitude and frequency-based framework to map predicted channel response to floods and analyze geographic patterns of channel sensitivity in relation to flood frequency.
4. Develop a process-based framework for delineating fluvial hazard zones.

Data and Methods

Stream Power – Channel Adjustment Modeling

We begin by considering the relationship between stream power and channel response to floods in a predictive statistical modelling framework applied at the geomorphic reach scale (100 to 500 m). Specifically, we developed a cumulative logit model that predicts an ordinal response (i.e., low, medium, high) based on continuous or categorical predictor variables. This model was fit to a dataset developed in cooperation with the U.S. Forest Service National Stream and Aquatic Ecology Center. This dataset utilized a dense network of peak discharge estimates for the 2013 Front Range Floods made from various sources along with LiDAR-derived digital elevation models (DEMs, accessed at geodata.co.gov, November 2015 to May 2016) to estimate the parameters needed calculate total and unit stream power, defined below. Peak discharge values of the 2013 floods for dozens of locations across the Front Range were estimated using a variety of indirect techniques discussed in Moody (2015). Other predictor variables were considered such as the ratio of valley width to channel width (confinement ratio), as well as the change in stream power from an upstream to downstream reach expressed as a gradient ($\Delta\omega/\Delta x$) and a difference ($\Delta\omega$), where ω is unit stream power (defined below), Δ represents a finite difference, and x is a streamwise length. Predictor variables were related to an ordinal response variable based on five categories of response:

1. No detected geomorphic change
2. Infrequent eroded streambanks (<25% of overall streambank length)
3. Numerous eroded streambanks (>25% of overall streambank length) and/or sporadic floodplain scour
4. Substantially widened channel over the majority of the reach length
5. Major geomorphic change, with avulsions, braiding, or roadway embankments and high terraces eliminated or substantially eroded

Geomorphic response categories were determined using a combination of high resolution pre- and post-flood aerial imagery, field visits, and LiDAR-derived DEMs-of-difference. Note that reaches lacking a visible floodplain and bound by bedrock valley walls were excluded from this investigation due to their limited ability to adjust to floods. All of these parameters were evaluated at the geomorphic reach scale on 16 rivers and streams including the Cache la Poudre River at the northernmost extent to Coal Creek at the southernmost extent and includes 531 individual reaches. This dataset and statistical modelling approach are discussed in more detail in a forthcoming publication (Yochum et al., In Review). A summary of the attributes of the streams included in this study along with the floods they experience is provided in Table 1.

Table 1 Physical characteristics of streams included in cumulative logit model. The flood recurrence intervals, where available, were extracted from Yochum (2015).

Stream	Overall Length (km)	Number of Reaches	Contributing Area (km^2)	Stream Slope (percent)	Flood Return Interval (years)	Unit Stream Power (W/m^2)	Geomorphic Change Classes
Cache la Poudre	19.4	41	2700 to 2900	0.2 to 1.0	25 to 50	80 to 700	1 to 3
Fish	2.5	6	34 to 41	1.1 to 2.2	>200	310 to 730	5
Big Thompson	44.0	93	430 to 1500	0.2 to 6.3	100	28 to 4900	2 to 6
N.F. Big Thompson	6.9	14	190 to 220	1.4 to 3.6	>100	180 to 2900	5
Buckhorn	18.7	46	130 to 370	0.7 to 5.0	25 to 50	300 to 4700	3 to 6
Little Thompson	19.6	45	24 to 130	1.3 to 10.5	----	210 to 7000	2 to 6
N. Saint Vrain	15.0	39	260 to 320	0.5 to 6.4	----	310 to 7000	4 to 6
Middle Saint Vrain	7.1	21	70 to 83	2.0 to 8.9	----	180 to 3700	2 to 5
S. Saint Vrain	15.2	31	170 to 240	1.0 to 7.0	----	360 to 3800	4 to 5
Saint Vrain	4.4	11	560 to 570	0.8 to 1.0	>200	85 to 600	3 to 5
Left Hand	31.8	84	46 to 180	0.3 to 6.4	>200	60 to 4700	2 to 5
James	6.6	18	23 to 48	2.8 to 5.8	----	690 to 2900	3 to 5
Little James	2.2	7	4.3 to 7.9	5.0 to 8.0	----	1000 to 2400	3 to 6
Fourmile Canyon	3.4	8	12 to 19	2.6 to 5.1	----	120 to 3100	5
S. Boulder	8.2	17	290 to 330	0.8 to 2.0	50	130 to 640	2 to 3
Coal	21.1	50	23 to 69	1.0 to 6.1	100 to 200	440 to 4700	2 to 5

Quantitative geomorphic response variables were also calculated as part of this effort. These include percent change in top of bank channel width as a result of the flood. Channel width was estimated along each reach using 0.75 x 0.75 meter LiDAR-derived hillshade rasters of pre- and post-flood conditions. Sediment flux as a result of the flood was calculated for each reach by sampling DEMs-of-difference (DoDs) within the river corridor along each reach. This includes reach-scale deposition, erosion, and net erosion or aggradation in units of volume. Each DoD was sampled in flat areas where no pre- and post-flood topographic change was expected. The standard deviation of the absolute values of elevation change within these DoDs was then used as a sample of DoD error. We masked (removed) each DoD image of cells whose values fell within ± two standard deviations, which approximates a 95% confidence interval for significantly different DoD values under assumptions of normality.

These quantitative response variables were evaluated longitudinally to study the patterns of channel response and the relationship between unit stream power and channel response moving from the canyons of the foothills to the plains. They were not included in the effort to predict channel response using statistical models. Rather, they are used to understand the longitudinal variation in channel response to floods, especially within slope and valley confinement transition zones where complex responses were observed.

Total stream power, Ω, is a hydraulic metric that quantifies the potential energy dissipation rate per unit channel length available to conduct work on the channel margins. It is defined as follows:

$$\Omega = \gamma Q S$$

where, γ is the specific weight of water, Q is discharge (peak flood discharge), and S is the slope of the energy gradeline, approximated as the channel bed slope over an individual reach. Total stream power, Ω, has units of Watts (W) per meter of channel length (W/m). Unit stream power, ω, is equal to total stream power normalized by the width of the flow and has units of W/m^2. Here, we estimated the flow width as the post-flood channel width in confined reaches, and as the peak flow top width in unconfined reaches as modeled in a one-dimensional hydraulic model (HEC-RAS v. 4.1). Unit stream power incorporates information regarding the width of the flow resulting in larger values of ω for more narrow channels relative to wider channels, all other variables being equal.

Total stream power and unit stream power are popular metrics for evaluating channel response to floods at a reach scale as well as longitudinally (Magiligan 1992; Costa and O'Connor 1995). Unit stream power is also used as the driving variable in some sediment transport models (Bagnold, 1977; Eaton and Church, 2011). Total stream power is a convenient driving variable to consider as it only requires estimation of a slope and a discharge value and can be mapped relatively easily using remotely sensed data in a GIS environment (Vocal-Ferencevic and Ashmore, 2012). Topographic slope from a digital elevation model can be combined with either on the ground estimates of flood discharge or estimates based on regional flood peak regression equations to estimate total stream power over large geographic areas (Parker et al., 2015).

Total stream power, unit stream power, downstream change in (unit) stream power, (unit) stream power gradient, as well as channel confinement were used as predictor variables (Table 2) in various cumulative logit models to explore the predictive capabilities of these variables on the ordinal response variables. Cumulative logit models were fit using the `clm()` function in the `ordinal` package (Christensen, 2015) in `R` (version 3.2.2; R Core Team, 2015). Predictor variable significance was tested using a likelihood ratio test with the `anova()` function in `R`. A leave-one-out analysis was conducted to evaluate model accuracy, whereby the model was fitted to data from $n - 1$ reaches and then used to predict the left out observation over all observations. This type of model performance analysis provides accuracy estimates computed for observations that are independent of the model.

Table 2. Cumulative logit model predictor variables.

Variable	Definition
usp / sp	unit / total stream power
grad.usp / grad.sp	unit / total stream power gradient
dUSP / dSP	delta unit / total stream power
slope	reach slope
conf	channel confinement ratio
conf.cat	channel confinement category

Model accuracy was compared among many models with differing predictor variables. Subsets of the dataset were also used to fit these models. For example, reaches with slopes > 3% are hypothesized to have a different geomorphic response to floods given the potential for step-pool formation and concomitant energy dissipation (David et al. 2010, Yochum et al., In Review). Therefore, a subset of the data containing reaches with slopes < 3% was used to evaluate whether model performance improved without these observations.

Additionally, we assessed the influence of lumping response categories on model accuracy. The ability to accurately predict channel response to floods based on a 5-category scale is valuable, but, at a minimum, floodplain managers and occupants are likely only interested when and where "major geomorphic change" is predicted. As such, we assessed the accuracy of various models fit to a two-category response variable by lumping response categories 2 and 3 (low to moderate channel response) and categories 4 and 5 (extensive channel widening to major geomorphic change). Note that only four out of 531 observations were classified as 1 (no geomorphic change detected). Therefore, these observations were removed, leaving four response categories.

Channel Adjustment Mapping

To evaluate the spatial patterns of the magnitude and frequency of channel adjustment to floods within the Front Range, we applied one of the cumulative logit models resulting from the statistical analysis discussed in the previous section in a mapping application. As a proof of concept, we used the most basic and best-performing model based solely on total stream power as a predictor variable and a two-category response variable (minor or major geomorphic response).

We estimated total stream power ($\Omega = \gamma QS$) at the reach scale (500 to 4,500 m) for floods with annual exceedance probabilities ranging from 10% to 0.2% (10 to 500 year recurrence intervals). A minimum drainage area of 26 km^2 (~ 10 mi^2) was chosen to match the size of the majority of the streams used to generate the cumulative logit model (Table 1). A hydrologically-corrected database of stream lines and drainage areas, NHDPlusV2, was used to generate the stream network used in this study (U.S. EPA and U.S.G.S., 2012). A peak flood discharge value for each recurrence interval evaluated was calculated for the midpoint of each reach using the Colorado application of StreamStats (StreamStats Version 3, http://water.usgs.gov/osw/streamstats/, accessed May, 2016), which uses a set of empirical equations to estimate peak discharge as a function of various physical and climatological properties of the watersheds (Capesious and Steven 2009). Average reach slope was calculated for each reach based on a 10 meter DEM (National Elevation Dataset, http://nationalmap.gov/elevation.html, Accessed March 2016).

Average reach slope and peak discharge for each recurrence interval flood were used to estimate total stream power as described above. This value was then used as input for the two response category cumulative logit model (minor and major geomorphic response categories) to predict channel response along each reach for each flood magnitude. The result of this work, then, is a map of predicted channel response over a range of flood magnitudes and frequencies.

Fluvial Hazard Zone Mapping Protocol

As a result of the 2013 Front Range floods, the State of Colorado passed a bill authorizing funding for natural hazard mapping including "erosion zone mapping" (SB 15-245). Following the passage of this act, the CWCB convened a technical group to develop a framework for mapping this zone in Colorado. We collaborated with K. Jagt and M. Blazewicz to develop such a framework and guidelines for mapping what we term "fluvial hazard zones" (FHZ, defined below) in Colorado. This effort relied on reviewing existing methodologies for mapping the region within the riparian corridor susceptible to fluvial geomorphic hazards associated with the erosion or deposition of sediment, channel avulsion, and hillslope erosion by the channel during flood events. This fluvial hazard zone has many definitions and names ranging from the "erodible corridor" (Piegay et al., 2005), to the "channel migration zone" (Olson et al., 2014), to the "erosion hazard zone" (City of Austin, 2013). Here, we defined it as "*the area a stream has occupied in recent history, could occupy, or could physically influence as it stores and transports sediment and debris during flood events. The objective of a mapped* ***fluvial hazard zone*** *is to identify lands most vulnerable to fluvial hazards in the near term."* (p. 2, Jagt et al., 2015). By mapping FHZs, the State hopes to create an informational tool that suports local floodplain management programs in communicating flood hazards to those living and working within active river corridors.

As discussed above, FEMA does not currently regulate this zone on a widespread basis and has not adopted an approach for doing so. A primary reason for this may be that unlike floodplain inundation modelling (which contains its own uncertainty), no readily defensible and generally applicable physically-based approaches exist to model the FHZ. A multitude have been proposed and most are region-specific (c.f., FEMA 1999, Piegay et al. 2005, Jagt et al., 2015 and ASFPM 2016 for reviews). This is due to myriad relationships between channel sensitivity to floods and the resisting (e.g., bed and bank sediment, vegetation, and geology) and driving forces (e.g., flow hydrology, channel slope) that result in geomorphic change. This highly complex, stochastic, and even chaotic phenomenon of channel response to floods makes generally-applicable modelling insurmountable.

To develop guidelines for mapping the FHZ in Colorado we first reviewed existing protocols, approaches, and regulations regarding geomorphic hazards associated with riverine flooding. We also conducted interviews with state and local officials involved in developing and implementing FHZ mapping programs. These interviews focused on the context of geomorphic hazards that lead to a particular state or locality's FHZ program as well as the technical aspects of its development. Summaries of local programs are detailed in Jagt et al. (2015) and ASFPM (2016). Many of these approaches are tailored to the climate and flood morphology of the state or region in which they were developed. Some methods are focused on incised urban streams (City of

Austin), some are focused on channels that tend to incrementally translate meanders downstream (State of Vermont), and others take a more holistic view of potential channel responses to floods in more geomorphically-dynamic rivers (State of Washington).

In Colorado, there are a wide variety of river types based on physiographic province, geomorphic context (e.g., position within the watershed and confinement by the valley walls), and hydroclimatology. These include alpine streams which tend to only receive snowmelt runoff, foothills streams which are steeper and also receive sporadic heavy rainfall from convective precipitation, to arid streams in the western desert and eastern plains which may be ephemeral yet subject to violent flash flooding on occasion. No one method for delineating the FHZ can apply to all of these types of rivers. Based on the technical group's knowledge of flood response to flooding in Colorado, as well as insight garnered from recent FHZ mapping efforts in Colorado using existing methodologies from other states, we developed a framework for delineating the FHZ that borrows from many existing methodologies. This framework is described below in the Results and Discussion.

Results and Discussion

Stream Power – Channel Adjustment Modeling

In general, the cumulative logit modeling used to predict the ordinal response of geomorphic change categories (Minor Response to Major Response, 2-5) tended to over predict the number of category 4 and 5 responses and under predict responses for categories 2 and 3 (Table 3). Observed geomorphic response categories were skewed towards categories 4 and 5 due to the extreme nature of these floods in much of the study area. This resulted in models whose fitted parameters are weighted to these greater response categories. Cumulative logit models perform best with a more balanced number of observations in each response category. A selection of fitted models and results are presented (Table 4).

Models with single predictor variables, namely unit stream power and total stream power performed fairly well with 68% and 71% of observed channel response categories predicted correctly, respectively in the dataset with <3% slopes and categories 4 and 5 lumped. Adding other predictor variables such as channel confinement and unit stream power gradient (*grad.usp*, *grad.sp*) or difference (*dUSP*, *dSP*), improved model skill but only marginally. For example, by adding total stream power gradient and channel confinement category to the total stream power predictor, percent predicted correctly increased from 71% to 74%. These gains in predictive performance were made in geomorphic response categories 2 and 3. These additional variables were significant in the model as evaluated by likelihood ratio tests between models with and without parameters of interest (Table 4). When only considering two response categories (lumped categories 2 and 3, and 4 and 5), additional predictor variables did not increase the accuracy of models.

Total stream power tends to result in greater prediction accuracy than unit stream power in these models. Channel confinement ratio as a continuous variable tends to perform about as well as a simple two-category variable where confined is defined as a confinement ratio ≤ 7 and unconfined as > 7. Models that included slope, a more readily evaluated predictor, in place of total stream power or unit stream power performed poorly tending to only predict category 4 or 5 responses over nearly all reaches.

The best performing models include total stream power or unit stream power, delta or the gradient of (unit) stream power, and one of the confinement variables as predictors (Tables 3 and 4). To interpret the model parameters, we consider the unit stream power-based model 6 fitted to the dataset with reaches whose slopes are < 3% and with response categories 4 and 5 lumped. Based on the coefficients of this model, for a 100 W/m^2 *increase* in unit stream power, the ratio of the odds of moving *up* in geomorphic response category is 1.6 ($e^{4.43E-3*100}$) or a 1.6 to 1 greater chance of being in the next highest response category holding the other variables constant. This translates to a probability of 0.6 for moving up in response category. The probability of moving up a category for a 300 W/m^2 increase in unit stream power is 0.8. Unit stream power ranged from approximately 30 to 4,350 W/m^2 in the dataset used to fit this model. For a 100 unit *decrease* in unit stream power from upstream to downstream reaches (*dUSP*), the probability of moving *up* a response category is 0.55. Delta unit stream power ranged from approximately -3200 to 2100 W/m^2. This means that negative unit stream power gradients (high unit stream power to low) tend to result in more geomorphic change. Here sediment deposition responses in reaches with negative unit stream power gradient may be playing a role in channel change. Finally, going from confined to unconfined categories results in a 0.7 probability of moving up in response category indicating that unconfined reaches are more susceptible to channel change (Figure 1).

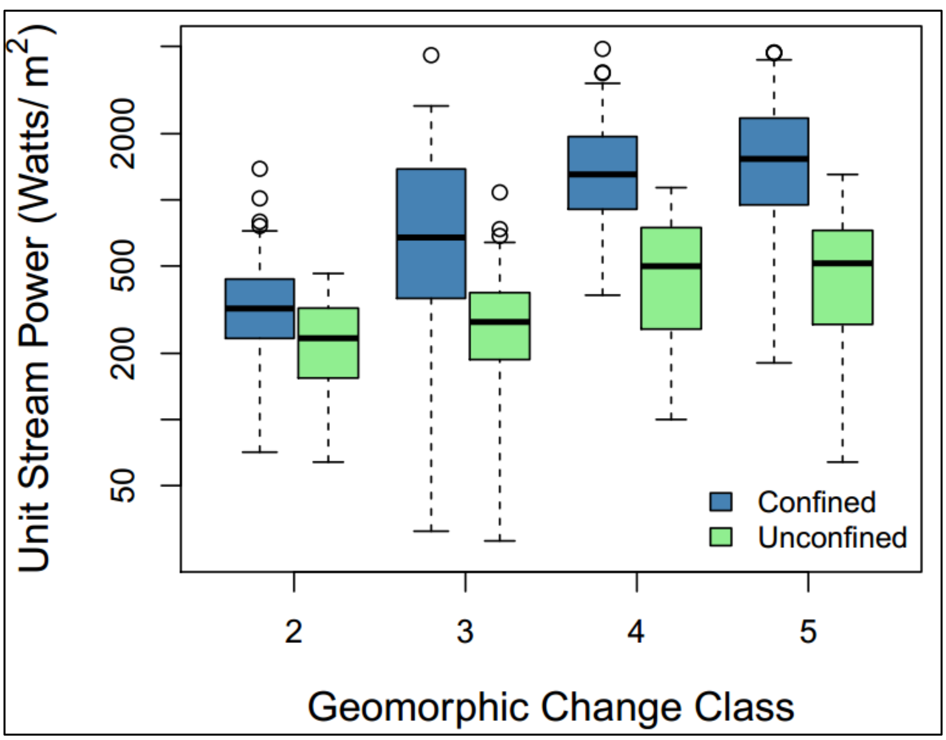

Figure 1 Boxplots of unit stream power values by geomorphic change class and channel confinement category.

Table 3. Leave-one-out cumulative logit model accuracy results.

Model	**Predictor Variables[1]**	**Dataset[2]**	**Model Sensitivity by Geomorphic Change Category (%)[3]**				**Model Accuracy (%)[4]**
			2	**3**	**4**	**5**	
1	usp + usp:conf	1	4	19	10	85	44
2	sp + sp:conf.cat	1	0	29	33	78	49
3	usp + 'usp:conf.cat	2	0	50	9	75	43
4	sp + sp:conf.cat	2	2	58	32	75	52
5	sp + sp:conf + dSP	3	33	35	92		74
6	usp + conf.cat + dUSP	3	18	26	92		70
7	sp	3	15	32	93		71
8	usp	3	7	21	93		68
9	sp + sp:conf + grad.sp	4	71		86		81
10	usp + conf.cat + dUSP	4	63		84		77
11	sp	4	67		89		82
12	usp	4	63		85		78
13	sp + sp:conf	5	60		90		81
14	usp*conf + dUSP	5	47		91		78
15	sp	5	60		92		83
16	usp	5	37		91		75
17	slope + conf	5	12		97		72

(1) See Table 1 for predictor variable definitions. The operator "*" denotes both an additive and an interaction affect betw een the tw o variables. The operator ":" denotes an interaction effect betw een tw o variables.

(2) Dataset 1 is the complete dataset; dataset 2 only contains reaches w ith slopes < 3%; dataset 3 is the same as 2 but w ith geomorphic change categories 4 & 5 lumped into one response category; dataset 4 is the same as 2 but w ith categories 2 & 3 lumped and categories 4 & 5 lumped (tw o response categories); and dataset 5 is the complete dataset w ith the same tw o response categories as in dataset 4.

(3) Model sensitivity is defined as the percent of correctly-predicted geomorphic response w ithin each response category based on a leave-one-out analysis.

Table 4. Select cumulative logit model parameter values

Model	Model Accuracy (%)	Threshold Coefficients[1]		Predictor Variable Coefficient Values						POA
		$\theta 2\|3$	$\theta 3\|4$	β_1[2]	P-Value[3]	β_2	P-Value	β_3	P-Value	P-Value[4]
5	74	0.97	2.84	1.66E-04	<2.2e-16	-8.33E-05	1.68E-06	-1.77E-06	3.40E-07	0.02
6	70	0.61	2.24	4.43E-03	<2.2e-16	8.69E-01	1.12E-03	-1.69E-03	8.34E-04	0.09
13	81		1.92	1.20E-04	<2.2e-16	-1.42E-06	6.43E-05			n/a
15	83		1.86	1.03E-04	<2.2e-16					n/a
16	75		0.42	1.57E-03	<2.2e-16					n/a

(1) Cumulative logit model threshold coefficient values demarking cumulative logit threshold(s) betw een categories.

(2) Model parameter coefficient logit values reported in same order as "Predictor Variable" column in Table 3.

(3) Probability of coefficient being zero based on likelihood ratio test.

(4) Proportional odds assumption: probability associated w ith likelihood ratio betw een fixed and unfixed threshold intercept values. Larger probability values indicate that proportional odds assumption of cumulative logit models holds. Low est p-value associated w ith the parameter that results in largest divergence from proportional odds assumption. Models w ith tw o response categories are not applicable to this type of analysis.

Longitudinal Variation in Channel Adjustment to Floods

Here we compare the results of post-flood channel adjustment measurements and classifications with downstream longitudinal variation in unit stream power. In general, we observed that unconfined reaches downstream of confined reaches tended to exhibit dramatic geomorphic responses in spite of relatively lower unit stream power within these unconfined reaches. This phenomenon can be seen in the relatively lower unit stream power values associated with a given geomorphic change category (Figure 1). Major geomorphic responses to the Front Range floods were observed along the transition from the foothills to the plains where unit stream power dramatically reduced and valley bottoms became less confined. A DEM of difference showing relatively little change along a confined and armored reach of the North Fork of St. Vrain Creek and then subsequent channel avulsion and deposition is a visual demonstration of this type of response (Figure 2).

Longitudinal plots of geomorphic response classification, channel widening, and net erosion and deposition of sediment show a distinct lag affect whereby greater values of response category, percent widening, and net deposition tend to follow local maxima of unit stream power (Figures 3-5). At the transition from the foothills to the plains, this lag effect continues for several kilometers downstream.

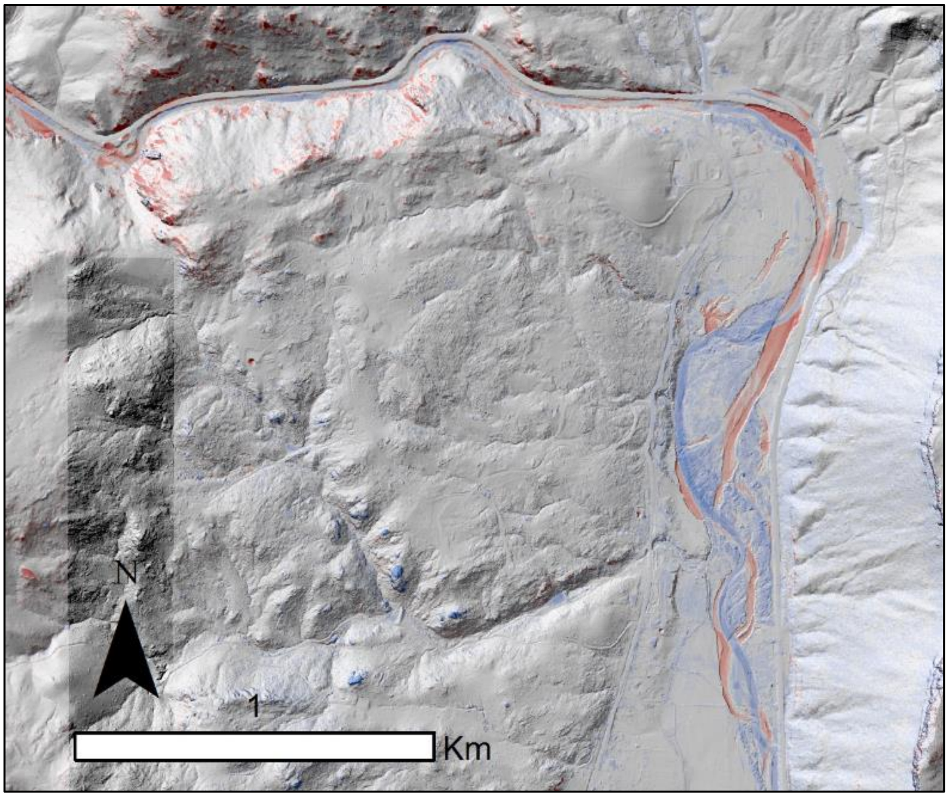

Figure 2 Example of a DEM of Difference showing transition from confined and degradational to unconfined and aggradational on the North Fork of the St. Vrain River. Blue shades indicate deposition and red shades indicate erosion.

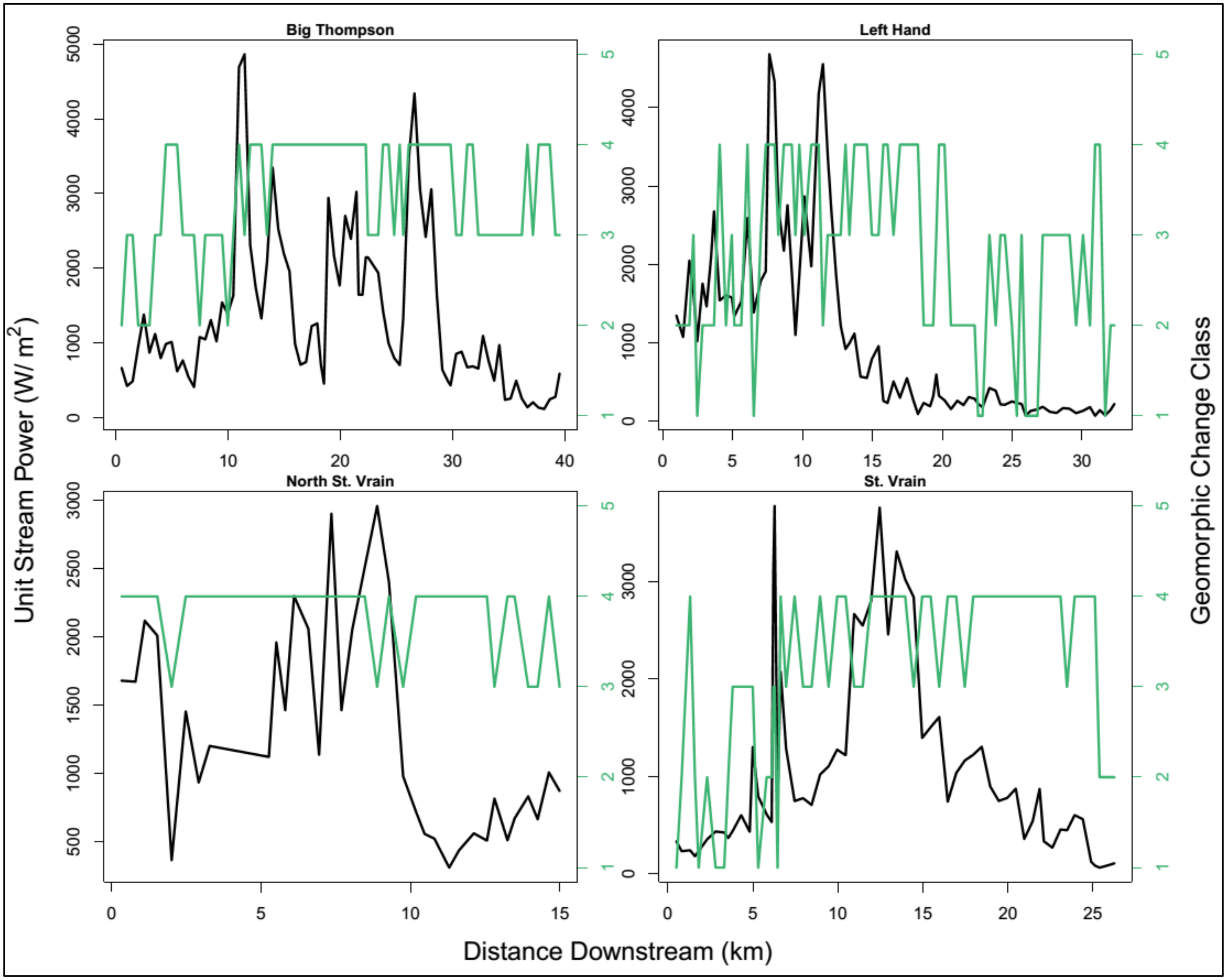

Figure 3 Longitudinal variation in unit stream power (black) and geomorphic change classification (green) for selected streams.

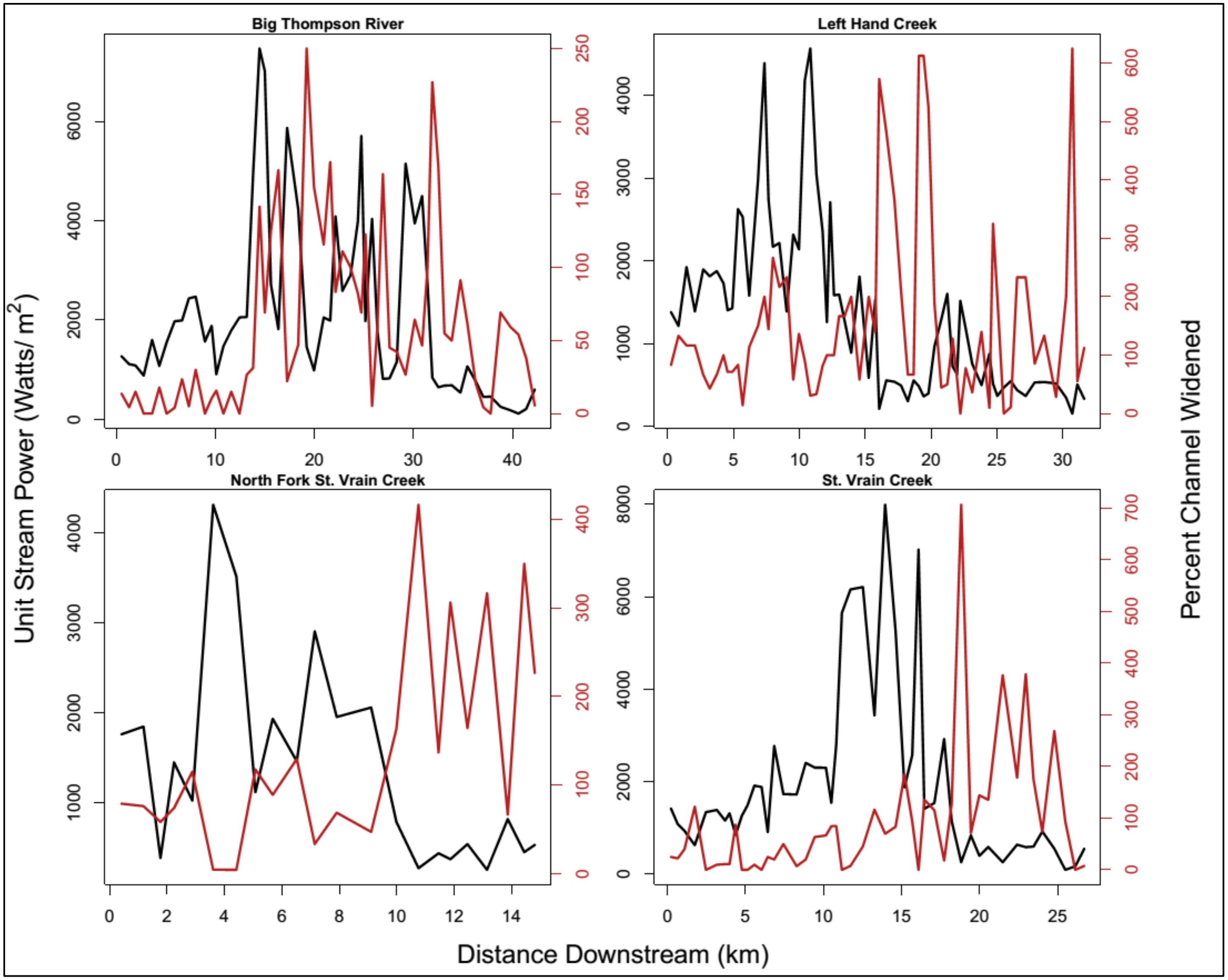

Figure 4 Longitudinal variation in unit stream power (black) and channel widening (red) for selected streams.

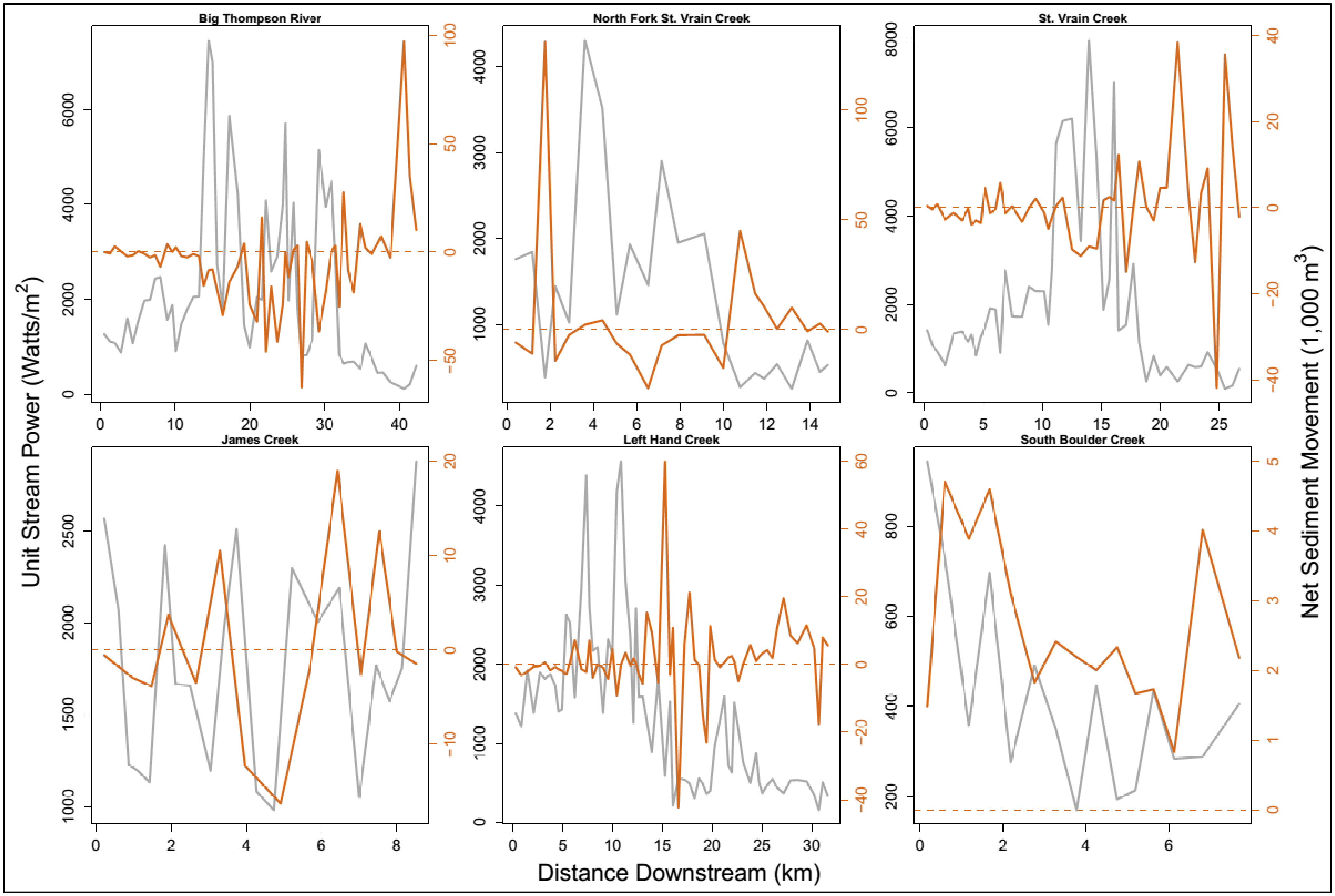

Figure 5 Longitudinal variation in sediment erosion (-) and deposition (+) (orange) compared with unit stream power (grey).

Tracking the reach-scale geomorphic response class longitudinally (Figure 34) shows an initially low value of geomorphic response in most of the headwaters followed by a dramatic increase in geomorphic response within the foothills where the epicenter of rainfall occurred and where the peaks in unit stream power occurred. However, as unit stream power tapers off in the transition from foothills to plains, geomorphic response remains elevated for substantial distances downstream. A dramatic lag effect. Spikes in percent channel widening tended to lag behind spikes in unit stream power, with some of the largest spiked occurring in the immediate area of the transition from steep and confined reaches within the canyons of the foothills to the unconfined reaches on the plains (Figure 4). Here, large channel avulsions where observed.

In all cases where we estimated net sediment movement in the transition from the steep, confined foothills to the mild-sloped and less confined plains (Big Thompson, St. Vrain, North St. Vrain, Left Hand) a sharp spike in net aggradation occurs at some lag downstream of the transition (Figure 5). Note that the reach-scale sediment balance oscillates between net aggradation and degradation along the plains. Following zones of net aggradation, new scour and channel avulsion were observed resulting in zones of net degradation.

To quantify this lag effect, we conducted cross-correlation analysis to understand the lag-distance of unit-stream power that best correlates to downstream channel. The lag distances of unit stream power best correlated with channel widening range from five reaches lengths on the Big Thompson to nine reach lengths for the North and South Forks of the St. Vrain Creek. Maximum cross-correlation values ranged from 0.3 to 0.5. Based on an average reach length of 575 meters, this translates to elevated values of unit stream power at three to five kilometers upstream having a correlation with downstream widening.

These analyses indicate a strong longitudinal connection between upstream hydraulic forcing and downstream response. Nevertheless, a relationship does exist between local unit stream power and channel response to floods. In a separate, companion manuscript, Yochum et al. (In Review) found that a direct and more monotonic relationship between local (unit) stream power and ordinal geomorphic response category was most evident along reaches where longitudinal variation in channel slope and confinement was minimal, and where channel slopes were < 3%. Previous research has found that step-pool bedforms begin to develop in reaches with slopes > 3% resulting in increased turbulence and greater loss of hydraulic energy (Montgomery and Buffington, 1997). This may confound the relationship between stream power and channel response.

Channel Adjustment Mapping

Using the total stream power-channel response model (model 15, Tables 3 and 4) with two response categories, minor (categories 2-3) and major (categories 4-5), we mapped predicted channel response to floods of varying frequencies (10% to 0.2% AEP) using USGS regional flood regression equations (Figures 6-9). This mapping application results in predictions of major geomorphic change largely on mainstem rivers in the plains. The 10% AEP flood (10-year recurrence interval flood) is predicted to result in major geomorphic change on limited portions of the mainstems of the Cache la Poudre River, Saint Vrain Creek, and the South Platte River (Figure 6). Major geomorphic change predictions extend upward on these mainstems towards the edge of the foothills for the 1% AEP flood (100-year) and include all major Front Range rivers (Figure 8). An exception to this trend is the South Platte River for which major geomorphic change is predicted well into the foothills. Mapped predictions of major change from the 0.2% AEP flood (500-year) extend upward into the foothills, but by no means cover all reaches included in this study (Figure 9). These results appear to under-predict the observed geomorphic change within foothills streams caused by 2013 floods with annual probabilities ranging from 2% to 0.2% (Table 1).

The maps of geomorphic change provided in Figures 6-9 rely on estimates of peak discharge based on regional regressions of stream gage data as well as statistical hydrology methods (fitting probability distribution functions) to extrapolate gage records and estimate extreme events such as floods with annual occurrence probabilities of ≤ 1% (Capesius and Stephens 2009). Many of the streams in the Front Range foothills fall under the "Mountain" hydrologic region and are lumped together with all high elevation gages, whereas the mainstems beyond the foothills are included in the "Plains" region, which contains much flashier hydrology and relatively larger flood peaks for a given annual exceedance probability. This may result in under-predicting peak discharge values of rare floods within the foothills of the Front Range due to lumping flood frequency statistics of these streams with higher elevation streams across the entire Colorado Rocky Mountain region, which means lumping snowmelt and convective precipitation floods together.

Jarrett and Costa (1988) document that the majority of very extreme flood events on the Colorado Front range are the result of convective precipitation events rather than snowmelt runoff events. Using regional flood frequency methods, they demonstrate that convective precipitation flood magnitude-frequency relationships follow a different probability distribution than snowmelt events. In fact, lumping these two flood sources together for a flood frequency analysis results in under-predicting the magnitude and frequency of extreme flood events. Therefore, the peak discharge values generated from StreamStats and used in our estimation of total stream power likely underestimates stream power for a given flood event in the foothills region, thereby underestimating probable the extent of major geomorphic change there.

In addition to the above discussion on flood hydrology, the single predictor variable model (total stream power) used in this mapping application is most limited and least accurate at large transitions of channel slope (and stream power) and reaches influenced by floodplain encroachment (especially on the plains and through urbanized areas). As discussed above, reaches within the transition zone from foothills to plains experienced dramatic geomorphic responses despite having relatively low values of local stream power. This is due in large part to a reduction in sediment transport capacity whereby sediment in transport through the foothills is deposited in the channel and floodplain in this transition zone (c.f., Gartner et al. 2015). This leads to major geomorphic changes such as channel avulsion, widening, and downstream meander migration. These effects were observed for approximately 2-10 km downstream of this transition (Figures 3-5). Regardless of model predictions, reaches within these transitions were identified as fluvial hazard zones based on observations of channel widening and aggradation, as well as the geomorphic change classification and statistical modeling portions of this study.

Many of the reaches included in the dataset used to calibrate the model were influenced by floodplain encroachments as well as bank revetment such as reaches bordered by roadways and rip-rapped embankments within the foothills. However, we excluded reaches bordered by gravel ponds on the plains. Many of the levees separating rivers and gravel ponds on the Front Range failed during the 2013 floods causing channel avulsion. This particular response was not accounted for in the statistical model, but does pose a major fluvial geomorphic hazard. Therefore, reaches bordered by gravel ponds and areas in the river corridor downstream of these should be considered high fluvial hazard zones in general.

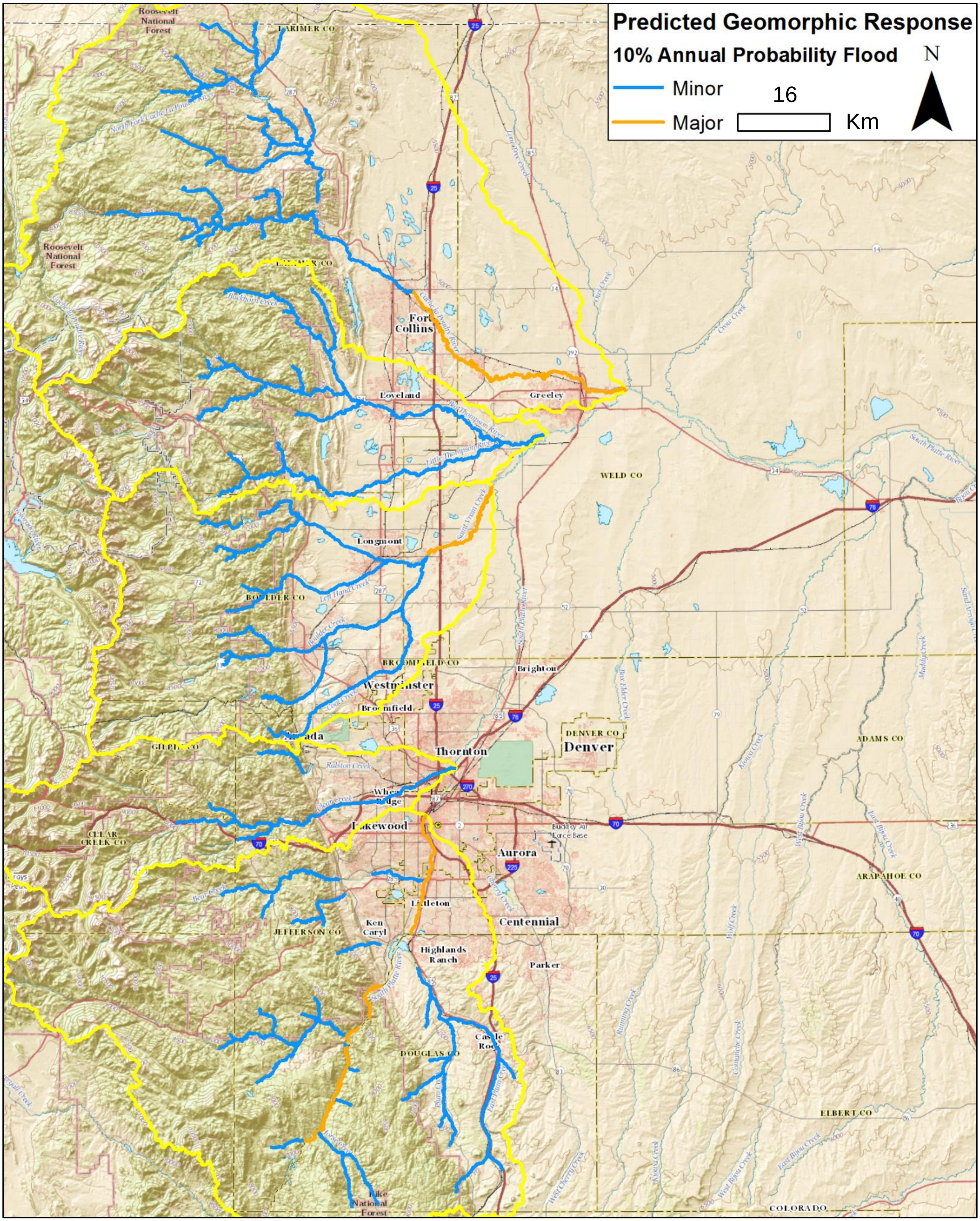

Figure 6 Predicted degree of geomorphic response to the 10% annual probability flood event. Yellow borders defines HUC-8 watershed boundaries.

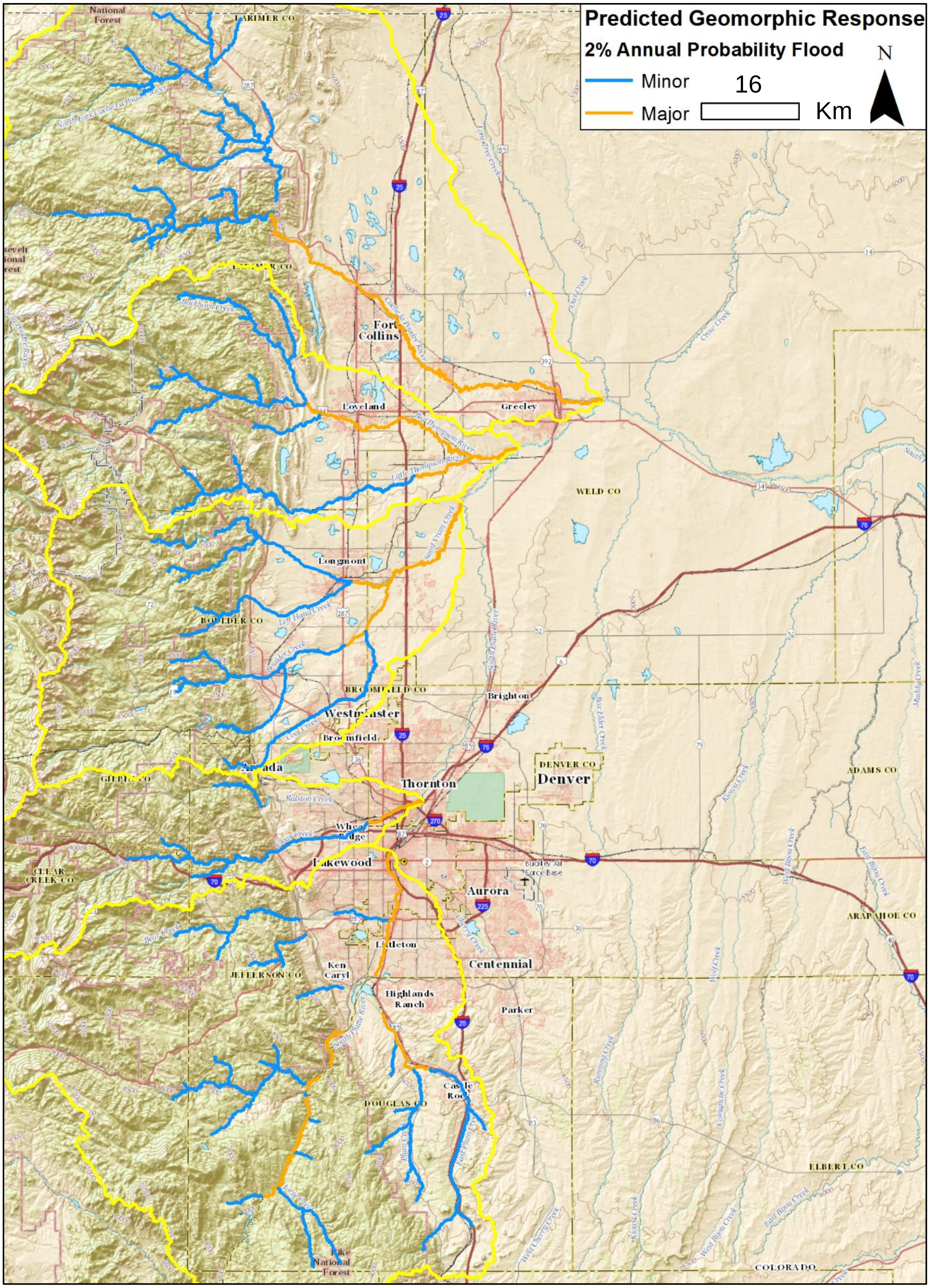

Figure 7 Predicted degree of geomorphic response to the 2% annual probability flood event. Yellow borders defines HUC-8 watershed boundaries.

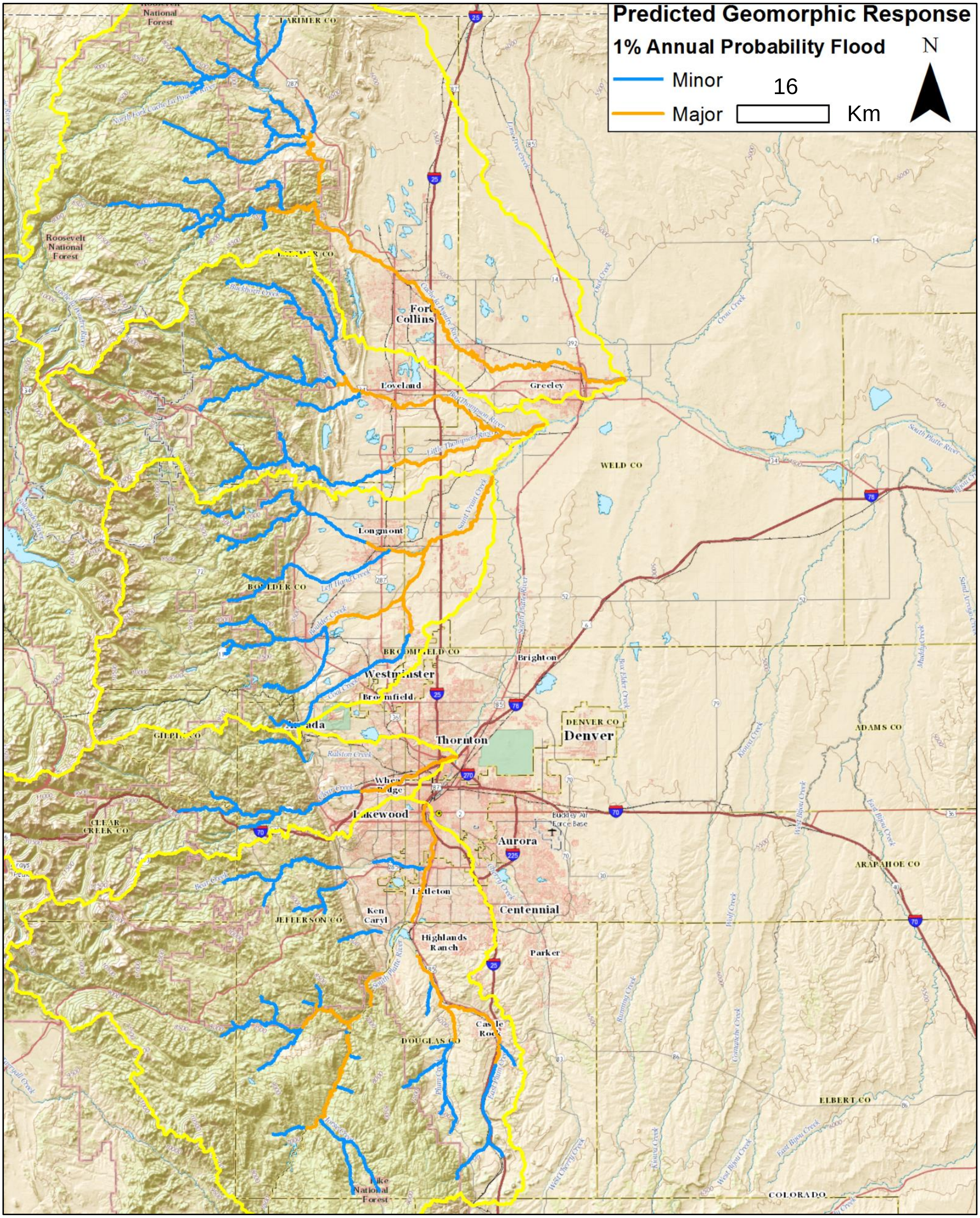

Figure 8 Predicted degree of geomorphic response to the 1% annual probability flood event. Yellow borders defines HUC-8 watershed boundaries.

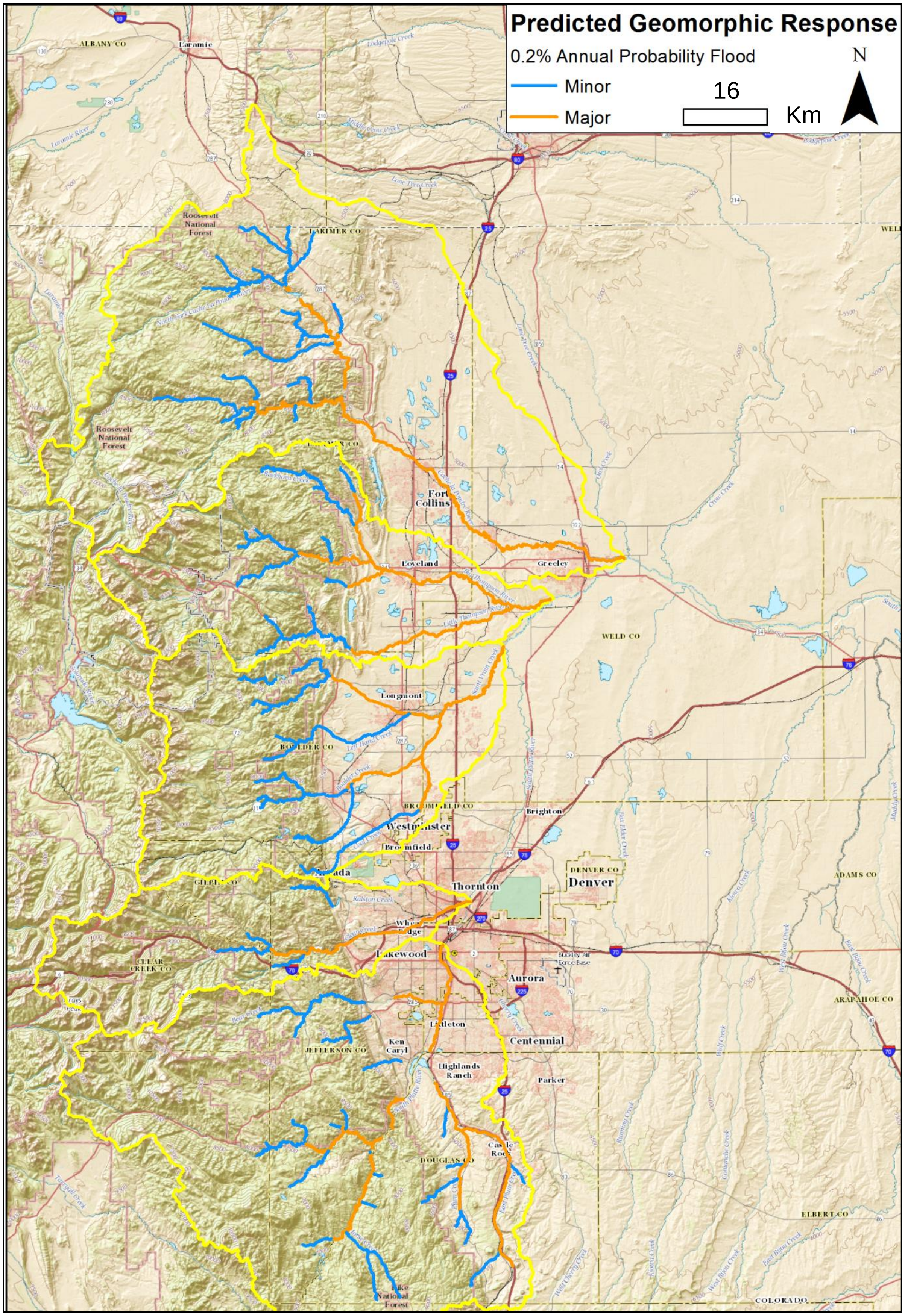

Figure 9 Predicted degree of geomorphic response to the 0.2% annual probability flood event. Yellow borders defines HUC-8 watershed boundaries.

Fluvial Hazard Zone Mapping Protocol

As a result of our interviews of state and local FHZ officials and reviews of their respective FHZ mapping methods, we developed a framework for mapping the FHZ in Colorado (Jagt et al., 2016). Considered a "planning level" mapping protocol, this framework relies on remotely-sensed data (e.g., aerial photographs and LiDAR-based digital elevation models) and is designed to be applied over a relatively large scale (i.e., watershed scale) with minimal field effort outside of limited field validation. This is called a "Level 1" FHZ assessment and the framework is depicted as a flow chart in Figure 10. Level 2 assessments requiring more extensive field efforts and perhaps hydraulic and/or sediment transport modelling are called for where Level 1 FHZ maps are deemed too coarse and where other compounding factors listed in Figure 10 might lead to the need for a Level 2 effort.

Different approaches for Level 1 mapping of the FHZ are based on relative values of channel slope and confinement, drainage area, and level of urbanization. Note that this is currently a framework for mapping the FHZ and not a prescriptive methodology. Values of slope, channel confinement, as well as appropriate buffer distances to assign to the FHZ along a channel have not been thoroughly studied and may vary from region to region. The State is in the process of issuing a request for proposals to further develop and refine this framework and implement pilot mapping effort.

In its current state, the FHZ framework offers varying approaches based on certain properties of a reach of interest. The first step in this process is delineating geomorphically-distinct reaches expected to respond in a similar manner to a flood. These reaches represent the fundamental unit of analysis and FHZ mapping products are based on this scale of analysis. All reaches with drainage areas less than 2 mile^2 are considered headwater channels and a simple buffer is applied out from the channel centerline. This buffer width may need to vary depending on the geomorphic setting. For reaches in urbanized areas, a maximum potential depth of channel incision is estimated and a setback from the edge of each bank is applied to the channel based on conservative estimates of hillslope failure angles. A maintenance buffer might also be applied.

Reaches with high to medium slopes (slope categories not yet quantified), a comprehensive delineation of the "active river valley" where the channel may occupy under the prevailing flow and sediment regime is made. Within the active river valley, components of the FHZ may include avulsion hazard zones, erosion hazard zones, and alluvial fan zones. Avulsion hazard zones are identified as topographically-low areas within the river corridor that may "capture" the mainstem of a river during a flood event. Erosion hazard zones are elevated areas such as hillslopes and terraces adjacent to the floodplain that are erodible and have the potential of being undermined by flood flows. Finally, alluvial fans are geomorphic features that are particularly hazardous due to the unstable nature of stream channels flowing down fans (French 1987). Use of LiDAR-derived digital elevation models with a resolution on the order of 1 meter is necessary to perform this approach to the FHZ. For mild-sloped reaches that are unconfined, a buffer from the meander centerline line represents FHZ with the addition of any avulsion hazard zones that may be identified.

Next steps in the development of the FHZ include studying river response to floods among a variety of physiographic regions to quantify ranges of channel slope and confinement for which the various components of the FHZ may apply. In addition, appropriate buffer widths to be attributed to the various FHZ component must be identified. For example, what multiple of channel top width should be used to define the width of the meander-beltline buffer for mild-sloped channels? Studies of previous river response to floods on these rivers is necessary to answer this question.

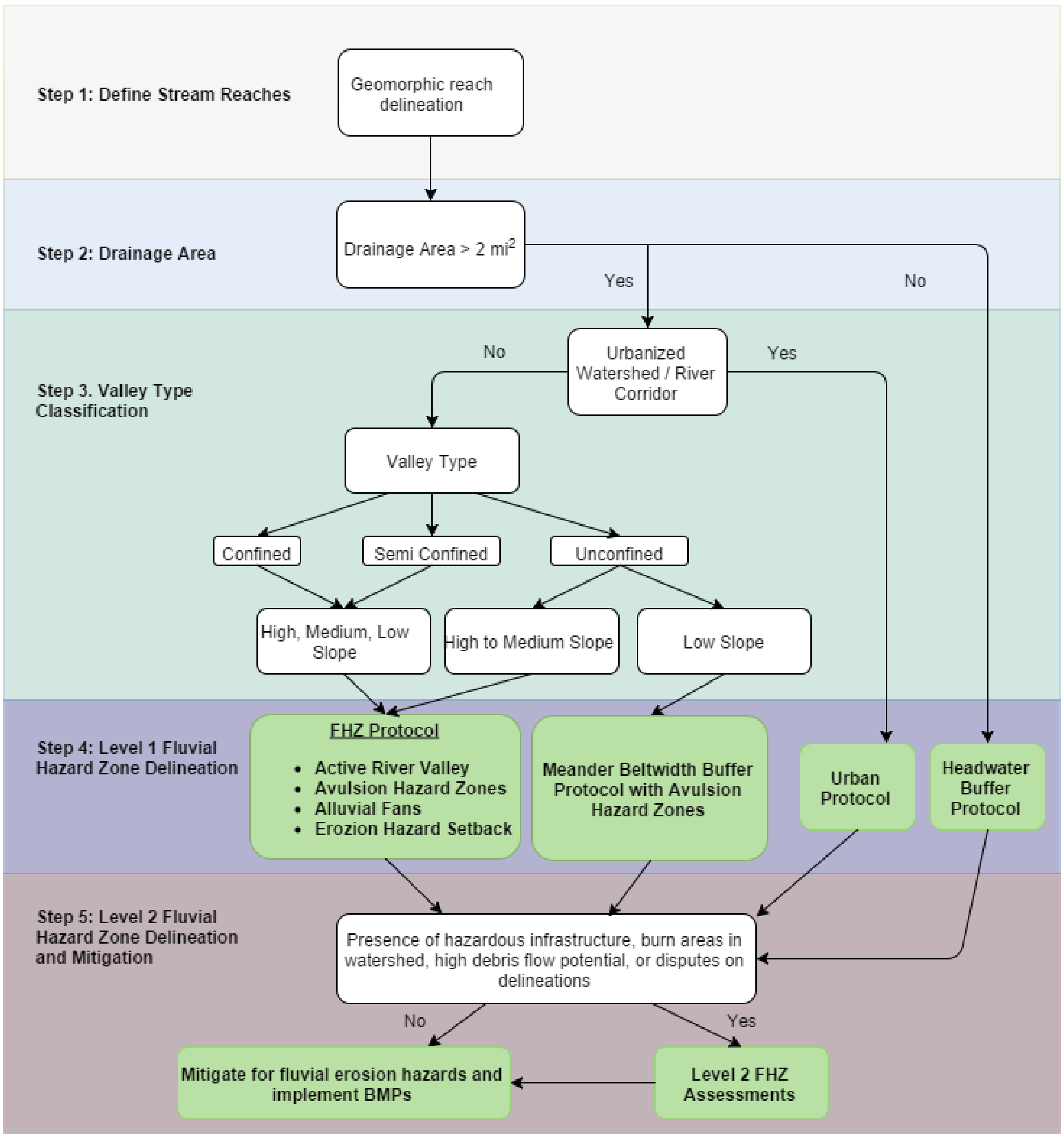

Figure 10 Fluvial hazard zone mapping flowchart (from Jagt et al., 2016).

Conclusions and Recommendations

We partnered with the U.S. Forest Service to develop a geospatial database of predictor variables and categorical geomorphic response variables documenting river adjustment as a result of the 2013 Front Range floods. We also quantified channel adjustment using estimates of pre- and post-flood channel widths as well as sediment erosion and deposition. These data were then used to characterize longitudinal trends and patterns in channel adjustment as well as create a statistical model used to predict channel response as a function of readily mapped and remotely-sensed data. As a proof of concept, one of these models was applied to predict channel response at the reach scale across the Front Range (Cache la Poudre to South Platte Rivers) at various flood frequencies.

Total stream power and unit stream power are both strong predictors of ordinal geomorphic response categories. In datasets with more than two geomorphic response categories, including additional predictor variables such as channel confinement category as well as changes in stream power in adjacent upstream reaches increased model accuracy. However, if geomorphic response categories are collapsed into just two (minor and major response), then a single variable model based on total stream power performs the best (Tables 3 and 4).

Longitudinal trends in channel response to the floods indicates that channels within unconfined reaches downstream of confined reaches within the foothills as well as those within the transition zone from the foothills to the plains are more geomorphically sensitive to floods. Greater geomorphic response was observed for relatively smaller values of unit stream power in unconfined reaches (Figure 2), and this elevated response extended several kilometers downstream of the foothills within the plains after unit stream power values had reduced (Figure 3). Channel widening tended to occur downstream of peaks in unit stream power (Figure 4), and substantial aggradation was observed immediately downstream of confined foothills reaches (Figure 5). All of these observations indicate that the transition zone from the foothills to the plains is highly geomorphically responsive to floods.

Application of the cumulative logit model that predicts “minor” and “major” geomorphic response categories to reaches within the Front Range demonstrated some limitations of available tools (Figures 6-9). Regional flood peak regression equations may underestimate peak discharge values for extreme flood events within the foothills region, thereby under-predicting the magnitude and extent of channel response to floods within this region. This modelling approach assigns discrete geomorphic response categories to a particular reach based on underlying probabilities. Assigning one response category obscures the continuum of probable response that may occur in rivers as a function of stream power metrics and other geomorphic variables. Future mapping applications based on these methods may be developed to communicate the likelihood of major geomorphic response as a continuous hazard index along the entire drainage network.

Finally, we participated in developing a framework for mapping the "fluvial hazard zone" as part of the State of Colorado's flood hazard mapping program (Figure 10). This framework will be piloted by the State and its partners in a subsequent effort over the coming years. It is our hope that the results presented herein and in subsequent peer-reviewed journal articles can inform this effort.

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