We thank Dr. Lague for his comments on our manuscript. We respond below, in the context of Dr. Lague’s detailed comments. In addition to edits that directly address Dr. Lague’s comments, we have made several additional edits to the manuscript to improve the writing and to add citations to recent literature.

**Associate Editor D. Lague, review and recommendation of “Coarse bedload routing and dispersion through tributary confluences” by K. I. Imhoff and A.C. Wilcox**

The authors have benefited from two in-depth reviews and they have answered many of the reviewers detailed comments. The reviewers agreed that this work is original and tackles an interesting question with new (and hard to get) data. Looking at grain transport in confluences is a very interesting idea and goes beyond the traditional bias of focusing on “simpler” trunk channels. I concur that this work should be ultimately published in Esurf. While the revised MS is now in better shape, there are unfortunately a number of important issues remaining that prevent publication at this stage. I highlight them below.

One of the main issue is that the authors have failed to answer the reviewer’s general comments in particular those of reviewer #2 which I find where spot on the main weakness of the paper: the statistical treatment of the data, and the fact that the MS’ conclusions does not seem fully supported by the data. Let me expand on this:

While both reviewers have emphasized the novelty of the dataset and the scientific interest that studying grain transport in confluences represents, they both have, and in particular reviewer #2, strong reservations on how this dataset is exploited. Given the limited number of confluences and control site studied, the limited number of particles (believe me I understand that these are data really hard to get), and the short duration of the study (~1 flood), it is extremely difficult to draw robust inference from the dataset as to whether confluences significantly modify grain transport or not, in particular the tail of transport distances. In many places, the author’s statistical analysis of the data should be more rigorous (see detailed comments below). Given the data presented, it is not clear that grain dispersion is actually increased in confluences, or that confluences significantly (in a statistical sense) affect grain transport beyond differences in the spatial likelihood of deposition.

As stated by reviewer #2, I think the paper would actually be much better and will have more impact if the discussion of the heavy or thin-tailed nature of the right tails was omitted or at least significantly reduced. Simply because, the dataset (and in particular the limited range in transport distance which is essential to explore tail behaviour) does not permit examining this aspect rigorously enough.

Similar to reviewer #2, the authors should improve and discuss more thoroughly “how the transport statistics within the confluence differ from the control reach, as it currently seems that they are more similar than different” (i.e., fig. 7-8-9-10). In detailed comments below, I highlight some assertions in the text that are not enough supported by the data shown in the figure.

Improving on the statistical analysis of the data, and/or removing some unnecessary parts would strengthen the MS. It might however lead to significantly rewriting the discussion and in particular the conceptual model which assume that confluences affect grain transport while a proper demonstration of this phenomenon has not been given. The authors should close more rapidly their discussion and avoid conceptualizing too much given the data available to do so. Or they should introduce some quantitative modelling of the problem, but I think that would be a completely different paper.

For the above reasons, I recommend major revision with possible re-review.
Detailed comments

#340 – figure 6: Particles are less frequent in the scour hole, but according to fig 6, they are not more likely deposited on area mapped as depositional bars flanking the channel than elsewhere in the bed. Either you need to change in fig.6 the way you map depositional bars, or you need to rephrase.

WE HAVE REPHRASED THE TEXT REFERRING TO FIGURE 6 AS follows:
“Within the confluence particles tended to be deposited towards channel margins and were less-frequently deposited within the scour hole (Figure 6).”

# section 3.2: I find that the comparison with EHS and GEM actually weakens the paper. The data dispersion (related in part to the small number and short distances travelled by the particles) make any model fit-able (even a simple power-law would probably fit better most of the distribution, or at least as well as the EHS and GEM). The only thing I gather from fig 7 is that particle displacement distributions are not significantly different in the control section than in the confluences. In the end, if you remove fig 7 and the associated text I don’t think the paper’s conclusion would be changed.

WE HAVE DELETED FIGURE 7 AND THE ASSOCIATED TEXT REGARDING THE EHS AND GEM COMPARISON. THIS INCLUDES EDITS TO 2ND PARAGRAPH OF INTRODUCTION, 2.3 OF METHODS, 3.2 OF RESULTS, AND DISCUSSION.

# 373- Fig. 8: The cumulative distribution is an interesting graph, but I think the interpretation of the data is not rigorous enough. In fig. 8a, the presence of a distinct step must also be compared to the initial distribution. For Moose creek I agree that there is an enhanced transport in the confluence (i.e. a steeper part on the cumulative area, but also slightly before (look at the difference in the slope of the cumulative distribution before and after). You also start from a relatively continuous initial distribution which helps in documenting spatial gradient in transport distances. The problem is that Moose Creek is not fundamentally different from the control section (e.g., max transport distance are of the same magnitude, and you also have some small step in the distribution). For Martin Creek, the step in the post-distribution also corresponds to a step in the pre-distribution: if you simply translate the pre curve by about 5 m, you get almost exactly the post-curve. It would indicate no effect of the confluence (or very marginal).

In the end, only Martin Creek, in the lower confluence, seems to exhibit a conclusive evidence of an increased transport efficiency (and potentially dispersion) in the confluence: you start from an initial uniform distribution, and you have clearly a reduced likelihood of deposition within the confluence and an increased one downstream.

All of this is to say, that interpreting these 3 figures (8a,8b,8c), which are very interesting (because they do not entail any a priori model nor specific statistical treatment) and central to the paper deserve more than a simple paragraph.

WE HAVE ELABORATED THE TEXT INTERPRETING THIS FIGURE (NOW FIGURE 7) IN THE FIRST 3 PARAGRAPHS OF SECTION 3.2, INCORPORATING DR. LAGUE’S COMMENTS AND PROVIDING ADDITIONAL EXPLANATION OF OUR INTERPRETATIONS.

# 381- Fig 9: this figure is indeed essential, but the interpretation offered by the author is a bit too simplistic. What it shows, as hinted by reviewer #2, is that the control section does not significantly
differs from the lower confluence. One could certainly consider that the main trend is given by an exponential with a lower characteristic slope (not necessarily going through 1 at Xn=0) and that Moose and Martin Creek (upper) have some kind of reduced transport efficiency/ increased trapping efficiency. This is just to highlight that there’s nothing conclusive here regarding the effect of confluences and the heavy-tailed/thin-tailed nature of transport given the limited range in normalized transport distances.

WE HAVE REVISED THE TEXT DESCRIPTION OF THIS FIGURE, AS DESCRIBED ABOVE. THE REVISED TEXT APPEARS IN THE 4TH PARAGRAPH OF SECTION 3.2 OF THE NEW VERSION; THIS NOW REFERS TO FIGURE 8.

# Fig 10: this is probably the most risky and less convincing figure of the paper because the authors are trying to fit log-log tails over less than 20 % of a decade...to be valid, the estimate of alpha should have at minimum an uncertainty, and I suspect that it would be so large that nothing conclusive could be drawn from it...or more precisely, that the tail behaviour of confluences are not statistically different from the main control section at the ... % confidence interval. I think fig. 10 could actually be removed (or the fits) as most of the paper’s conclusion can be drawn from fig 8 and 9.

WE HAVE REMOVED THIS FIGURE; WE AGREE THAT THE PRECEDING FIGURES ARE MORE CONVINCING AND THAT THE STATISTICS UNDERLYING THIS FIGURE WERE TOO TENUOUS.

#Fig.11 : I have trouble understanding what is the physical meaning of a negative intercept. There is something odd here, as X/D should be equal (or very close) to zero for I* =0. Here again, the lack of error bars on the data and statistical analysis limits the conclusion that can be drawn from the data and weakens the paper.

THE NEGATIVE INTERCEPT WAS AN ERROR. WE HAVE RECALCULATED THE FITS AND REVISED THE FIGURE ACCORDINGLY. THIS NOW REFERS TO FIGURE 9.

Discussion:

#465 : you would not need the comparison with EHS and GEM to reach the conclusion that transport distance are likely thin tailed. Fig. 9 gives you this result.

TEXT REGARDING EHS AND GEM COMPARISON HAS BEEN DELETED.

#478: it all depends where you put your exponential fit. Moreover the control section has the same tail behaviour than the lower confluence.

WE HAVE ADDED TEXT COMPARING THE TAIL BEHAVIOUR OF THE CONTROL SECTION AND THE LOWER CONFLUENCE, AT THE END OF SECTION 3.2.

#4.3 : this is interesting conceptually, but probably too far fetched given the uncertainty on the effect of confluences on sediment dispersion and transport. I would consider shorten this part significantly to stick with what the data can really tell.

WE HAVE REWRITTEN THIS SECTION, SHORTENING THE DISCUSSION OF CONFLUENCE EFFECTS ON ROUTING, ADDING REFERENCES/DISCUSSION OF ADDITIONAL WORK ON NETWORK SEDIMENT
ROUTING, AND ELIMINATING THE FORMER FIGURE 12 THAT ILLUSTRATED THIS CONCEPTUAL DISCUSSION. WE FEEL THAT SOME DISCUSSION OF SCALING UP TO BASIN SEDIMENT ROUTING IS MERITED AND PROVIDES A NICE WAY TO END THE DISCUSSION AND POINT TOWARD FUTURE STUDY.
Coarse bedload routing and dispersion through tributary confluences

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Abstract

Sediment routing fundamentally influences channel morphology and propagation of disturbances such as debris flows. The transport and storage of bedload particles across headwater channel confluences, which may be significant nodes of the channel network in terms of sediment routing, morphology, and habitat, are poorly understood, however. We investigated patterns and processes of sediment routing through headwater confluences by comparing them to published results from lower-gradient confluences and by comparing the dispersive behavior of coarse bedload particles between headwater confluence and non-confluence reaches. We addressed these questions with a field tracer experiment using passive-integrated transponder and radio-frequency identification technology in the East Fork Bitterroot River basin, Montana, USA.

Within the confluence zone, transport occurred along tracers tended to be deposited ion was skewed towards scour-hole and channel margins, and suggesting in narrow, efficient transport corridors that mirror those observed in prior studies, many of which are from finer-grained systems. Coarse particles entering confluences in some confluence reaches experienced reduced depositional probabilities relative to a control reach within the confluence relative to upstream and downstream of the pre and post-confluence channel. Analysis of the distribution of particle transport lengths suggested that variation in the spatial distribution of coarse sediment particles was may be enhanced by passing through confluences, though further study is needed to evaluate confluence effects on dispersive regimes and sediment routing at broader spatial and temporal scales. The effect is minor at the scale of individual flood events. We suggest
that equilibrium confluences can may therefore enhance sediment transport enact unique dispersive regimes on coarse sediment routing through headwater networks.
1 Introduction

The transport and storage of mobile sediment particles through channel networks, i.e., sediment routing (Swanson and Fredriksen, 1982), link sediment supply, flow, and channel morphology and thereby regulate channel evolution (Church, 2002; Church 2006). In headwater regions, where hillslope-channel connectivity is strong, storage and downstream routing of sediment inputs reflect the influence of spatially and temporally variable forcing by hillslope (e.g., debris flows) and fluvial processes (Montgomery and Buffington, 1997; Brooks and Brierley, 1997; Prosser et al., 2001; Lancaster and Casebeer, 2007). Discrete pulses of coarse sediment delivered to streams can travel downstream as a translating bedload wave, by dispersion, or by a combination of translation and dispersion (Lisle et al., 2001; Sklar et al., 2009).

Analyses of dispersion based on the premise that particle motion is a random walk have represented downstream transport as a series of intermittent steps and rests (Einstein, 1937). This approach has informed flume and field studies seeking to identify characteristic probability distributions of step length and rest periods (e.g., Hubbell and Sayre, 1964; Yang and Sayre, 1971; Bradley et al., 2010). Various statistical distributions (e.g., including exponential, gamma, and Pareto functions), have been found to approximate spatial distributions of bedload-particle displacements in flume and field conditions (e.g., Hassan et al., 1991; Bradley and Tucker, 2012; Martin et al., 2012; Haschenburger, 2013, Phillips et al., 2013). These statistical models have been used to approximate dispersive regimes in various gravel-bed channel morphologies, including plane-bed (Bradley and Tucker, 2012), pool-riffle (Liébault et al., 2012; Milan, 2013), and braided systems (Kasprak et al., 2014). Many model functions may be applicable, however, because morphologic features and hydraulics can produce characteristic local dispersive regimes (Pyrce and Ashmore, 2003). Long-term tracer experiments have noted evolving spatial distributions of bedload particles, suggesting that best-fit statistical distributions may differ depending on the degree of vertical mixing, often a function of time (Haschenburger, 2013). Downward advection of particles into the streambed can reduce the probability of re-entrainment and thus slow streamwise advection (Pelosi et al., 2016). As a result, dispersion models predicting a smooth spatial distribution therefore may not adequately capture the true dispersive behavior of bedload particles across multiple channel morphologies.
The dispersive behavior of coarse sediment particles has also been considered in terms of changes in the variance of particle displacements with time (e.g., Phillips et al., 2013). Sediment dispersion is thus treated as analogous to one-dimensional diffusion in the downstream direction, with potential diffusion dynamics that include normal diffusion, where the variance of particle displacements increases linearly with time, and anomalous diffusion, which includes both superdiffusion and subdiffusion, when variance increases more quickly or more slowly with time than the linear case, respectively (Metzler and Klafter, 2000; Nikora et al., 2002; Olinde and Johnson, 2015). Improved understanding of variability in dispersive regimes among channel types and other controls on sediment dispersion is needed, however, to facilitate sediment-routing predictions.

Nodes of the channel network that may be especially important with respect to sediment routing are tributary confluences, where point sources of flow and sediment connect tributary to trunk streams (Rice et al., 2008; Rice, 2016). The importance of confluences in sediment routing, as well as their morphologic significance, may depend on factors including drainage densities (i.e., frequency of confluences; Benda et al., 2004a), the magnitude and frequency of disturbances such as debris flows (Benda and Dunne, 1997; Hoffman and Gabet, 2007), and the relative differences in flow, sediment caliber, and load between tributaries and the trunk streams they enter (Figure 1) (Knighton, 1980; Richards, 1980; Ferguson et al., 2006; Swanson and Meyer, 2014; Rice, 2016). Morphological effects stemming from disturbance-derived confluence deposits may extend spatially, well beyond the area of flow convergence, and temporally, persisting for ~10^2 – 10^4 years (Lancaster and Casebeer, 2007). Study of confluences in light of disturbance deposits and morphological heterogeneity has led to the Network Variance Model Dynamics Hypothesis (NVMNDH, Benda et al., 2004a,b), which considers the spatial arrangement of confluences in river networks and how they affect local and non-local channel morphological characteristics. Channel confluences also represent biological “hot spots”, forcing spatial heterogeneity in habitat types and in various habitat metrics and influencing longitudinal distributions of aquatic organisms (Rice et al., 2001; Gomi et al., 2002; Clay et al., 2015).
Whereas sediment dynamics and morphology of headwater confluences can be primarily influenced by disturbances such as debris flows (Benda and Dunne, 1997), what we refer to as “equilibrium” confluence morphology, reflecting feedbacks between flow hydraulics, sediment transport, and morphology, can also develop and persist (Figure 1). Such confluences are well-studied in sand and gravel-bed river systems and typically feature a central scour hole, tributary-mouth bars, and bank-attached bars at areas of flow recirculation and stagnation (Best, 1987; Rhoads, 1987; Best, 1988; Roy and Bergeron, 1990; Biron et al., 1996; Boyer, 2006; Rhoads et al., 2009; Ribeiro et al., 2012). Physical controls on confluence hydraulics and associated morphology include junction angle (Θ), bed discordance (zd), discharge ratio (Qr) (Figure 1), and upstream planform curvature (Ashmore and Parker, 1983; Best, 1987; Biron et al., 1996; Rhoads and Sukholodov, 2004; Boyer et al., 2006; Constantinescu et al., 2012; Ribeiro et al., 2012).

Sediment transport through equilibrium confluences, however, is poorly understood (Best and Rhoads, 2008), limiting understanding of how confluences influence local and network-scale patterns of sediment routing.

In this study we assess how coarse bedload particles are routed through equilibrium confluences in a mountain river headwaters. We address two questions: i) How do sediment routing patterns through headwater equilibrium confluences compare to those described in other, primarily lower-gradient gravel-bed river systems? ii) How do equilibrium confluences affect the dispersive behavior of coarse bedload particles compared to non-confluence reaches? We address these questions with a tracer experiment conducted through two headwater confluences and a non-confluence control reach. We compare stochastic models of sediment transport and dispersion (Einstein, 1937; Hubbell and Sayre, 1964; Yang and Sayre, 1971) and compare spatial distributions of mobilized particles among study sites and apply a dimensionless impulse framework (Phillips et al., 2013) to observed tracer behavior to explore the effects of confluences on sediment routing. We also evaluate our results and their implications in the context of theory regarding confluences and sediment routing through headwater networks. Our study contributes to the growing body of work on particle dispersion and transport dynamics in mountain rivers and is, to our knowledge, the first to investigate these topics with respect to sediment routing through confluences in a field setting.
Here we describe our study area and the preparation, deployment, and measurement of coarse-bedload tracer particles. We then describe the analyses we conducted that allow comparison of particle displacement through the study confluences to that of the control reach and prior transport studies in gravel-bed river systems. This involved assessment of displacement distributions and a dimensionless impulse, with the goal of evaluating and comparing dispersive regimes. Additional details on these analyses, beyond what is provided below, are in Supplemental Information and Imhoff (2015).

2.1 Study area

We selected a study area in the East Fork Bitterroot (EFB) River basin in western Montana, USA (Figure 2) that is typical of semiarid, snowmelt-dominated, montane headwater systems. This location lacks recent physical disturbances (e.g., post-wildfire debris flows) and contains confluences exhibiting characteristics of the equilibrium morphology described above. The field site drains 298 km$^2$ of forested and alpine mountainous terrain, in both the Sapphire Mountains and Pintler Range, ranging in elevation from 1584 m to 2895 m. Sediment supplied to channels is comprised of quartzite, argillite, siltite, and feldspathic granitic rock, eroded from metasedimentary Belt Supergroup and Idaho Batholith sources. Annual precipitation is about 0.6 m yr$^{-1}$, based on data from the Tepee Point weather station 1.4 km from the EFB (Western Regional Climate Center Remote Automated Weather Station, 2015). Runoff is dominated by spring snowmelt, with flows capable of mobilizing coarse bedload typically occurring in similar streams between March and July. Human influences from roads and other land uses are minimal in the study area.

Two tributary confluences mark the upstream and downstream extent of the study area. These are herein referred to as the upper confluence, where Moose Creek and Martin Creek combine, and, 1 km downstream, the lower confluence, where Martin Creek enters the EFB. The tributary and mainstem stream of each study confluence are considered as separate reaches, for the purpose of separately considering incipient motion and transport behavior of tracers starting in
each. Between the study confluences is a plane-bed control reach. Combined discharge in the 
upper confluence is approximately half that of the lower confluence.

Because the site is ungauged, we installed HOBO-U20 water level loggers to record stage at 15-
minute intervals during the 2014 study period. One transducer was placed along a surveyed-cross 
section of the bed at each study reach. We also periodically manually measured water surface 
elevations and, during wadeable conditions, stream velocities. Above-average flows during the study period reflected that year’s large snowpack. Snow water equivalent at SNOTEL sites within 50 km of the study area registered above 150% of normal on 1 April 2014 (http://www.wcc.nrcs.usda.gov/snow/). We estimated the spring 2014 peak flow to have a 3.5 to 4-year recurrence interval, based on transducer data, flood-frequency regression equations developed for western Montana streams (Parrett and Johnson, 2004), and analysis of a downstream US Geological Survey gage. Flood flows peaked between 25 May and 4 June 2014 (Figure 3).

To characterize study-reach morphology, we completed topographic surveys and grain-size measurements. Topography was surveyed using a Leica TS06 total station during the initial tracer deployment (March 2014), before spring runoff high flows, and the summer (July-September) recovery campaign. Topographic surveys entailed longitudinal profiles, to determine slope, and cross-sections at the location of pressure transducers, for use in the incipient motion estimates described below. We also surveyed bedform extents to produce a bedform map. Surface grain size distributions were measured using Wolman pebble counts across each study reach. Channel slopes, dimensions, grain sizes, and confluence characteristics are shown in Table 1 (also see Supplemental Information).

2.2 Bedload tracer preparation, deployment, and measurement

Our study employed passive-integrated transponder (PIT) and radio-frequency identification (RFID) technology for tagging and tracing bedload particles. PIT tags are highly recoverable, durable, and cost-effective relative to other particle tracing methods (e.g., Lamarre et al., 2005; Bradley and Tucker, 2012; Chapuis et al., 2015). Moreover, PIT-tagging allows for analyses of
transport of both bed-material populations and specific subsets of the grain population (e.g., by size, shape, lithology), displacement distributions and their evolution over time, and other aspects of transport dynamics.

We collected gravel and cobble particles from Moose Creek, upstream of our study reaches, in January 2014 for tagging. Using a 1-hp drill press, holes 8 mm wide by 30 mm long were drilled using a ~0.8 mm diamond-tipped drill bit. We tagged cobbles with median axes mostly between 60 and 130 mm (Figure 4, Table 2). Many of the tracer particles were larger than the bed D$_{50}$ (Table 1), because particles with b-axes below 45 mm often fractured during drilling. We assumed our tracer particles, which fell within the D$_{37}$ to D$_{70}$ size fraction of bed materials, to be representative of the coarser fraction of mobile bedload particles. The results and interpretation of our sediment tracers thus do not apply for the entire mobile bedload population in this system.

The PIT tags used in this study are 12 mm and 23 mm half-duplex, read-only tags from Oregon RFID. Vertical read range varies based on tag orientation, battery level, noise proximity, and other factors, but is generally 0.25 to 0.5 m. Previous work has identified horizontal and vertical detection ranges at 0.5 m (Lamarre et al., 2005) and 0.25 m (Bradley and Tucker, 2012). Chapuis et al. (2014) assessed RFID detection ranges and observed higher uncertainty in radial detection distance than reported in other studies. Uncertainty in tracer position is highest for solitary, buried tracers, which are not visible via snorkel survey and have the largest detection radius; clusters of buried tracers, in contrast, have reduced detection ranges via tag interference. We oriented the antenna parallel to the surface of the bed, at a height of about 0.2 m (after Chapuis et al., 2014). For our analysis, we considered tracer movement below the threshold of detection as immobile and assigned a travel distance of 0 m (after Phillips and Jerolmack, 2014). Particles moving beyond the threshold of detection were labeled the “mobile” fraction. In total, 428 cobble and gravel tracers were prepared for deposition into the three study reaches (Table 2).

We installed the PIT-tagged tracers before the onset of the spring snowmelt, in late March and early April 2014. Our seeding method involved loosely seeding tracer particles on the bed surface near the channel thalweg in a grid (Figure 5). Mimicking the arrangement of fluvially-deposited gravels and minimizing the influence of the initial condition of particle deployment is
a challenge in tracer studies, but a regular grid such as ours provides a reproducible initial
condition and is consistent with previous work (Ferguson and Wathen, 1998). A sparse grid like
the one employed here minimizes disturbance to the bed and flow field (Bradley and Tucker,
2012) while simultaneously avoiding “confusing” the PIT tag detection equipment, which
encounters issues when dealing with clusters of particles (Chapuis et al., 2014). The gridded
surface ranged from 7–13 m wide. We deployed PIT-tagged tracers at equal distances upstream
from the confluence in each tributary. Initial tracer positions were recorded using the total
station.

Field recovery campaigns to detect tracer locations and measure particle displacement took place
after recession of high flows, once the streams were wadeable. The bed was scanned with a 0.5
m diameter loop antenna in conjunction with a backpack reader. Once a tracer was located, the
loop antenna was brought towards its detection field from all directions. This helped to identify
other tracers in a cluster by reading different tags first, depending on the direction the cluster is
approached. Each tracer’s position was recorded using the total station. The uncertainty
associated with individual total station measurements of tracer position and travel distance is
±0.20 m (Bradley and Tucker, 2012). We also employed a snorkel survey to identify if tracers
were buried or clustered together. Visible tracers were occasionally surrounded by other tracers
in shallow pockets. At all sites, we scanned with the loop antenna for 200 m downstream of the
last detected particle to limit omission of any far-traveling tracers, which influence the tail
character of displacement distributions. The position of far-traveling tracers was recorded with a
Trimble GEOXH 6000 GPS.

2.3 Particle-displacement distributions Analyses of tracer behavior

To investigate how tracers routed through confluences compared to those in our plane-bed
control reach, we compared the spatial distribution of tracers at initial deployment and after the
2014 flood among sites by plotting the distribution of tracers versus streamwise distance.
Differences in the pre- and post-flood distributions are indicative of transport distances and of
changes in depositional probability; e.g., a reduction in the slope of the distribution from pre-
flood to post-flood conditions indicates reduced depositional probability and enhanced transport
To evaluate observed particle displacement distributions across our study site, we tested the applicability of two stochastic models of sediment transport and dispersion: the Einstein-Hubbell-Sayre (EHS; Hubbell and Sayre, 1964) and Gamma-Exponential models (GEM; Yang and Sayre, 1971). These models were chosen following previous tracer experiments, particularly Bradley and Tucker (2012), who tested the fit of the EHS and GEM functions to displacement distributions measured using PIT tags in Halfmoon Creek, Colorado, USA. Halfmoon Creek has similarities in terms of slope, grain size, width, plane-bed morphology, and snowmelt hydrology to our study sites and is thus suitable for comparison with our results. The EHS and GEM models differ by modeling step lengths using either exponential (EHS) or gamma (GEM) distributions, resulting in step length distributions that decrease monotonically (EHS) or vary more flexibly (GEM), as described in more detail in Bradley and Tucker (2012) and in our Supplemental Information. We compared EHS and GEM fits to our confluence and non-confluence transport data, with the goal of comparing bulk routing characteristics between the two reach types. In doing so we apply models that approximate step length to test against observed displacement, which for an individual particle may include multiple steps across the 2014 hydrograph.

To further investigate displacement distributions, we non-dimensionalized also assessed dimensionless transport distances of each tracer by scaling each tracer’s transport distance \((X_i)\) by its median b-axis diameter \((D_i)\). We then calculated normalized transport distance, \(X_n\) (after Phillips et al., 2013):

\[
X_n = \frac{X_i}{D_i} <\frac{X}{D}>
\]

(1)

where \(<X/D>\) is the mean displacement length for the 2014 flood at each study reach. The variance of dimensionless transport distances was also calculated (after Phillips et al., 2013):

\[
\sigma^2 = <\left(\frac{X_i}{D_i} - <\frac{X}{D}>\right)^2 >
\]

(2)

where \(\sigma^2\) is the variance for the 2014 flood for each tracer population.
In addition, we analyzed cumulative exceedance distributions of tracer travel distance for each study reach to assess tail character (after Hassan et al., 2013). This was achieved by measuring the rate of decay of the exceedance distribution tail, \( P(X>x) \), where \( X \) is a travel distance beyond the user-determined start of the tail, \( x \). The log-log slope of decay (\( \alpha \)) distinguishes between heavy-tailed (\( \alpha < 2 \)) and thin-tailed (\( \alpha > 2 \)) distributions (Metzler and Klafter, 2000; Olinde and Johnson, 2015). We considered \( <X/D> \) to be a suitable parameter to test in the context of comparing our tracer data to thin-tailed transport models. These analyses offer a comprehensive approach to investigating whether the overall distribution of particles evolves in a significantly different way when being routed through confluences, as opposed to the plane-bed control reach.

### 2.4 Dimensionless impulse

We also analyzed tracer displacement data with respect to a cumulative dimensionless impulse \( I^* \), which provides a measure of the time-integrated fluid momentum links particle displacement to the duration of flow above the threshold of particle motion (Phillips et al., 2013), as follows:

\[
I^* = \int_{t_i}^{t_f} \frac{(U^*_e)dt}{D_{50}} 
\]

where \( t_i \) and \( t_f \) are start and end times, respectively, for flow above a critical threshold of motion of bed materials, and \( U^*_e \) is excess shear velocity, which is the difference between the shear velocity (\( U^* = \sqrt{gRS} \), where \( g \) is gravitational acceleration, \( R \) is hydraulic radius, and \( S \) is channel slope) and the critical shear velocity (\( U^*_c \)) associated with initial motion of bed particles. Flume studies have identified that a mobilized sediment particle shows a total displacement that is proportional to \( U^*_e \) (Lajeunesse et al., 2010; Martin et al., 2012). In addition, analysis of channels across climatic settings and channel types found that morphology is adjusted in a manner whereby \( U^*_c \) is typically slightly exceeded during floods, allowing bed-material transport while maintaining channel stability (Phillips and Jerolmack, 2016). Shear velocity is equal to (\( gRS \)^{0.5} where \( g \) is gravitational acceleration, \( R \) is hydraulic radius, and \( S \) is channel slope. For the critical condition (\( U^*_c \), \( R_c \) is critical hydraulic radius associated with the mobilization of the
average-sized tracer particle and can be back-calculated from critical Shields number \( \tau_c^* \), a non-dimensional shear stress associated with incipient motion of particles in a flow:

\[
\tau_c^* = \frac{\rho g R_c S}{(\rho_s - \rho_w) g D_{50}}
\]

where \( \rho_s \) is sediment bulk density (assumed to equal 2650 kg m\(^{-3} \)) and \( \rho_w \) is water density (1000 kg m\(^{-3} \)).

We used \( I^* \) to compare tracer transport distances against the cumulative \( U_{\text{e}}^* \) excess shear velocity imparted on grains. We determined \( I^* \) for each of our five seed reaches and, as a means of comparing confluence and non-confluence reaches, evaluated the extent to which each data set deviated from a linear relationship between \( \langle X/D \rangle \) and \( I^* \), which can be considered indicative of a difference in dispersive regimes (Phillips et al., 2013).

Because our tracer equipment could not directly detect initial motion conditions, we estimated \( U_{\text{e}}^* \) by back-calculating \( R_c \) (critical hydraulic radius associated with the mobilization of the average-sized tracer particle) from critical Shields number \( \tau_c^* \), a non-dimensional shear stress associated with incipient motion of particles in a flow:

\[
\tau_c^* = \frac{\rho g R_c S}{(\rho_s - \rho_w) g D_{50}}
\]

where \( \rho_s \) is sediment bulk density (assumed to equal 2650 kg m\(^{-3} \)) and \( \rho_w \) is water density (1000 kg m\(^{-3} \)). We determined \( \tau_c^* \) using two different empirical approaches, which we selected based on their derivation in gravel-bed systems similar to our study sites and our ability to measure required inputs. For the first estimate, we used Mueller et al.’s (2005) reference dimensionless shear stress relation for steep gravel and cobble-bed rivers:

\[
\tau_{c,\text{Mueller}}^* \approx \tau_r^* = 2.18 S + 0.021
\]
where $\tau^*_r$ is a reference shear stress, which we assume is similar to $\tau^*_c$ (after Mueller et al., 2005). Mueller et al.’s (2005) relation is derived from field, rather than laboratory, data, including a study site that is similar to the EFBour study site in terms of slope, grain size, width, plane-bed morphology, and snowmelt hydrology, as described above. For a second estimate of $\tau^*_c$, we used Recking’s (2013) mobility shear stress ($\tau^*_m$) equation, which was empirically developed using bedload transport data from gravel-bed transport studies in mountain streams:

$$\tau^*_{c,Recking} \approx \tau^*_m = (5S + 0.06)\left(\frac{D_{84}}{D_{50}}\right)^{4.4}\sqrt{S^{-1.5}}.$$  \hspace{1cm} (56)

Analogously to Eq. (5), we assume $\tau^*_m$ approximates $\tau^*_c$ (after Recking, 2013).

These two estimates for $\tau^*_c$ were paired with stage data to estimate the cumulative duration of flow above the threshold of motion, which is difficult to measure directly (Charru et al., 2004). At each seed reach, we used pressure transducer data to identify the critical flow depth ($h_c$) that corresponds with the $R_c$ for initiating sediment motion, thus linking stage data to estimates of channel-averaged $U^*$ during the 2014 flood hydrograph. Estimates of $U^*_c$ were then integrated across the 2014 hydrograph to estimate $I^*$. Because Eq. (23) is restricted to flow above the threshold of sediment motion, $I^*$ limits the frequency-magnitude distribution of $U^*$ to conditions relevant to estimated sediment transport and only considers the momentum excess imparted by the flow on sediment particles. This approach adopts the simplifying assumption of a constant $U^*_c$ for a given field site (after Phillips et al., 2013; Phillips and Jerolmack, 2016), although we recognize that $U^*_c$ likely varies in both space and time (e.g., Turowski et al., 2011).

### 3 Results

#### 3.1 Field observations of tracer displacement

We recovered 68–86% of the seeded tracers, depending on the reach (Table 2). Recovery was greatest within study reaches with low $D_{84}$ values and short transport distances, including the control reach and Moose Creek (Table 2). Our recovery rate is comparable to recent tracer...
studies using RFID technology have found comparable recovery rates: 25–78% (Liébault et al., 2012), 93–98% (Bradley and Tucker, 2012), 62–100% (Phillips et al., 2013), 40% (Chapuis et al., 2015).

Similar percentages of recovered tracers (41, 39, and 50%) left each seed reach. At the upper confluence, tracer configurations within the seed reach retained the signature of their gridded streamwise spatial pattern in Moose Creek after movement but not in Martin Creek, which contained more boulders to facilitate trapping and clustering of particle tracers (Figure 5). Particles seeded in Moose Creek also constituted the majority of tracers exported into the confluence itself. Deposition within the confluence primarily correlated to depositional bars flanking the scour hole. Within the confluence, particles tended to be deposited towards channel margins and were less-frequently deposited within the scour hole (Figure 6). Particles deposited within the scour hole were segregated by contributing stream. Tracers from the upper confluence seed reaches had short travel distances and, even after being mobilized, remained within the confluence zone (Figure 6).

Particles recovered in the lower confluence largely retained the signature of the gridded arrangement of their initial positioning at both seed reaches, even after mobilization. The relative contribution of tracers into the confluence was more evenly distributed than in the upper confluence: 55% of deposited tracers came from the East Fork, with the remaining 45% from Martin Creek. Similar to the upper confluence, tracer particles remained segregated as they progressed through the confluence, stranding preferentially on bank-attached depositional bars. Deposition within the scour hole was limited and segregated, further agreeing with the upper confluence. An additional group of tracers, seeded at the upstream junction corner, were immobile. Similar to the upper confluence, large boulders were effective in trapping mobile tracer particles. Of the recovered tracers in the entire lower confluence, 23% left the confluence zone completely, with 58% of post-confluence tracers originating in the East Fork and 42% from Martin Creek. Recovered particles downstream of the lower confluence ceased to be segregated after about 30 m, and were recovered approximately in the channel center.

3.2 Particle displacement distributions
Tracers from the upper confluence. The Einstein-Hubbell Sayre (EHS) and Yang-Sayre (GEM) models provided similar-quality fits to each other in all study reaches (Figure 7). The Yang-Sayre GEM provides the most accurate fit, with a slight $R^2$ advantage ranging from 0.01 to 0.001. Both the EHS and GEM models accurately approximate the slowest moving tracer bins, generally overestimate the probabilities of mid-range bins, and underestimate the probabilities of fast-moving bins that correspond to the tail of the displacement probability distribution. In the control reach, fast tracer bins generally have a smaller residual than in the confluence study reaches. The models fit the lower confluence tracers better than the upper confluence tracers (Table 3). In all reaches but Martin Creek (lower confluence), the average transport distance of our data exceeded model estimates (Table 3). Upon entering the confluence, exhibited reduced depositional probabilities and enhanced particle transport (Figure 7a). This is demonstrated by changes in the shape of the overall distribution of tracers that correlate to entering the confluence. Slope reduction upon entering the confluence zone indicates a reduced depositional probability within the confluence (Haschenburger, 2013); in contrast whereas similar slopes among the pre- and post-flood distributions, a continued slope trend would indicate a consistent depositional probability in space. The reduced slope that indicates a reduced depositional probability correlates closely, though not exactly, to the point at which particles enter the confluence—this discrepancy is minor and likely the result of an erroneous field-delineation of the beginning of equilibrium confluence morphology. Although most of the particles seeded in Martin Creek did not enter the upper confluence, those that did experienced a similar reduction in depositional probability as the Moose Creek tracers. The stepped pre-flood distributions of Martin Creek upper-confluence particles (Figure 7a) reflected prevailing ice conditions that and likely translated to the post-flood distributions. Despite this Regardless, additional particles lie within the zone of reduced depositional probability post-flood, indicating enhanced transport within the confluence itself.

In the control reach, observed transport distances were comparable to those in the upper-confluence reaches (Figure 7a, 7b). This was in spite of considerably larger Recking-estimate impulse values, reflecting the fact that the upper-confluence reaches together provide the control reach’s component discharge (Table 3). Within the post-flood spatial position of tracers in the
control reach, small steps were present (e.g., at about the 40th percentile), which appear to correspond to steps present in the pre-flood distribution (e.g., near the 60th percentile), reflecting downstream translation of the curve across a portion of its distribution (Figure 7b). The post-flood distribution assumes the shape of a decay, suggesting constant depositional probability is relatively constant throughout the reach (Figure 7b), in The control reach’s relatively consistent decay contrasts to with the depositional probabilities pre and post-confluence at the upper confluence.

At the lower confluence, transport distances are greater than in the upstream reaches (Figure 7c). Evidence of enhanced transport within the confluence is strong for Martin Creek; depositional rates upstream and downstream of the confluence exceed those within the confluence, and there is no relic pattern carried over from the pre-flood spatial distribution of tracers (Figure 7c). Confluence effects are less clear among The East Fork tracers, largely because shows a similar pattern, albeit not as developed as in Martin Creek. The tracers seeded at the upstream junction corner in the East Fork did not enter the confluence and are visible as a near-vertical line in the pre- (>80th percentile) and post-flood (20th – 40th percentile) flood spatial distributions (Figure 7c). Other than these tracers the East Fork tracers show, we observe a similar pattern as in Martin Creek. Overall, the dispersive growth of the lower-confluence tracers assumes a thin-tailed decay similar to that of the control, though the altered depositional probability within the confluence, especially among Martin Creek tracers, differentiates the control and lower-confluence distributions stands out.

At the upper confluence, mobile tracers entering the confluence zone exhibited a distinct step in the spatial distribution of tracer positions, denoting enhanced transport and reduced depositional probabilities (Figure 78, after Haschenburger, 2013). Enhanced transport is also evident for tracers routing through the lower confluence reaches (Figure 78): a distinct step is evident for tracers entering the confluence, where the probability of deposition decreases for the duration of time spent within the confluence zone. The control reach lacks significant steps and instead features a smooth decay indicative of consistent depositional rates with distance downstream.

Dimensionless displacement distributions for both confluence and non-confluence reaches are reasonably characterized by an exponential distribution (Figure 8). This further suggests that
particle dispersion at the site is thin-tailed during the 2014 flood. Front-running particles at the upper confluence reaches travel relatively shorter distances beyond the population average compared to the lower confluence. This, along with far shorter transport distances, suggests that larger cumulative excess shear stresses (i.e., larger $I^*$ values) correlate to increased transport and greater dispersive growth, as asserted by Phillips et al. (2013). The control reach plots similarly to the lower confluence in Figure 8, despite comparable tracer transport metrics to the upper confluence (Table 2; Figure 7) – far fewer particles exceed the average transport distance for the population than at the upper confluence.

Dimensionless displacement distributions deviate from a best-fit exponential distribution at distances beyond approximately twice the average normalized transport distance (Figure 89). In evaluating $X_n$, tracers in the upper confluence reaches do not travel as far relative to the population mean as those in other seed reaches. Tail character in confluence populations generally showed smaller $\alpha$ values than the control reach, corresponding to heavier tails and greater dispersive growth (Figure 10). The point of origin of the tail is user-defined, however, and varying the start point changes the resulting slope of the exceedance tail. We therefore assessed tail character at multiple points above the 75th percentile of tracer displacement distance, to test the sensitivity of tail designation. None of the study reaches cross the thin-heavy threshold ($\alpha=2$) by varying the tail start point. We thus chose to define the tail as beginning at the 80th tracer percentile. Only Moose Creek shows a thinner tail in the exceedance probability distribution than the control reach. Martin Creek (at both the upper and lower confluences) exhibits a heavy-tail, while Moose Creek, the control reach, and East Fork Bitterroot are thin-tailed. The data do not distinguish whether transport through confluences is thin or heavy-tailed, rather suggesting that distributions of tracers moving through confluences are generally “heavier” and exhibit a higher proportion of tracers traveling far distances than in the plane-bed reach.

### 3.3 Dimensionless impulse

Our estimates of critical Shields number ranged from 0.056 to 0.119 (Table 34), slightly larger than often-assumed values of $\tau_c^*$ (e.g., $\tau_c^*=0.045$; Church, 2006). For all study reaches, $\tau_c^{*,\text{Mueller}}$
values (Eq. 45) were lower than the $\tau_{c, Recking}^*$ values (Eq. 56), resulting in correspondingly lower $U_c^*$ values. These calculations indicate that flow exceeded the threshold of motion for 8–37 ($\tau_{c, Mueller}^*$) or 1–17 ($\tau_{c, Recking}^*$) days, with the lower confluence experiencing the longest duration above the critical level. The distribution of $U^*$ and $I^*$ scale with channel dimensions and peak discharge, with the upstream confluence seed reaches experiencing smaller $U^*$ and $I^*$ values than the control reach and lower confluence (Table 34). Moose Creek, for example, is wider and shallower than Martin Creek at the upper confluence, and requires a larger discharge increase to move from the Mueller to Recking incipient motion threshold estimate. This results in reach-specific variation in sensitivity to the estimation method for incipient motion. We found that $I^*$ scaled well with tracer displacement (Table 34), substantiating its applicability confirmed its usefulness for assessing coarse particle transport at the EFB.

We found $<X/D>$ to conform to a linear relation to $I^*$ (Figure 9a), and the variance ($\sigma^2$) of dimensionless transport distances showed a power-law relationship to $I^*$ function (Figure 9b). These relationships are consistent with, in agreement to, the predictions and findings of Phillips et al. (2013) and Phillips and Jerolmack (2014) regarding the broad applicability of normalized travel distances and impulse for characterizing bedload transport (Figure 11). The occurrence of a linear fit between $<X/D>$ and $I^*$ supports the notion that $I^*$ may be used to correlate flow strength with travel distance across multiple sites. Between confluence reaches, greater impulse values correlated to larger average and maximum transport distances as well as dispersive growth (Table 3). However, a linear fit through the origin was far less appropriate than provided a similar quality-of-fit to that found by Phillips et al. (2013). Fits could be greatly improved when improved by only considering the relationship between confluence reaches: the control reach has similar displacement but higher $I^*$ values than reaches at the upper confluence, giving it the highest residual from the best-fit curve in both cases. We did not Normalization of $I^*$ by frictional resistance, as it did not prove to significantly improve the collapse of our tracer data.

## 4 Discussion

### 4.1 Coarse sediment routing through confluences
Our study used PIT / RFID technology to provide novel insights into the effect of investigate coarse sediment transport across tributary confluences on sediment routing through of mountain streams. Maximum transport distances along scour-hole flanks and segregation are similar to the findings of Mosley (1976) and Best (1988). Because we detect no tracers beyond the extent of the upper confluence, we take the depositional pattern in Figure 6 to reflect a tendency of our tracers to route along, rather than through, the scour hole. We see similar depositional patterns for tracers that were detected within the lower confluence and posit that similar transport corridors apply. We consider these transport patterns to reflect the controlling influences of Θ and Qr; the simple upstream planform geometry and minimal bed discordance (zd) at our sites suggest that those factors exert little influence on morphodynamics in our study confluences. Observed discordance between scour and tributary mouth bars at our study confluences (0.6 and 1.4 m, respectively) exceed that of Roy and Bergeron (1990; ~0 m at Θ=15), supporting observations that scour is largely absent at low Θ values (Benda and Cundy, 1990).

Our data also agree with the assertions of Best (1988) and others as to how the position and orientation of the scour hole is influenced by Qr. Increased penetration of flow from the tributary at the upper confluence, due to higher Qr, forced the scour hole towards the middle of the confluence, as opposed to the lower confluence where the scour was shifted by greater discharge from the East Fork Bitterroot. Observed feedbacks between confluence morphology and particle transport suggest similar confluence morphodynamics as observed in past studies (e.g., Mosley, 1976; Best, 1987; Boyer et al., 2006; Rhoads et al., 2009), though in a higher-gradient, more headwaters setting than previous work.

4.2 Effects of confluences on dispersion

Fit quality of the EHS and GEM models support Bradley and Tucker’s (2012) assertion that a gamma or exponential distribution can approximate the compound Poisson distribution of coarse tracer displacement in headwater systems. Differences between the EHS and GEM at our site are almost indistinguishable, whereas Bradley and Tucker (2012) found that the GEM described observed step lengths than the monotonically decreasing EHS. The strong fits of the EHS and GEM may reflect the short duration (one flood) of our study; Bradley and Tucker (2012)’s study
spanned four flood events. The quality of these fits is likely to weaken over time as particles become vertically integrated with the bed (Haschenburger, 2013).

General accordance to the EHS and GEM models suggests that a

Our comparison of the pre- and post-flood spatial distributions of bedload tracers provides evidence of suggests that, within confluences themselves, reduced depositional probability decreases and enhanced transport within confluences occurs (Figure 7). This is most evident in Moose Creek, at the upper confluence, and the Martin Creek, at reach in the lower confluence. Where the pre-flood spatial distribution of particles is not continuous, such as the upper Martin Creek reach and the East Fork, these patterns are less evident. The spatial distribution of tracers in the control reach does not radically substantially differ from the lower-confluence reaches, even when the confluence zone is clearly transport-efficient. This may be because the confluence zone in the lower-confluence reaches represents a minor portion of the total tracer transport distances, which are greater here than in upstream reaches, muting confluence effects on transport. Thus, the effects of enhanced confluence transport would be muted when the entire distribution of tracers is considered and as tracer transport becomes more influenced by plane-bed morphology than confluence effects. At this differs from the upper confluence, in contrast, where the confluence zone occupied a much larger portion of the transport reach, and, consequently, the post-flood distribution differs more from the control. A muted signal in the lower confluences indicates that these effects may quickly dissipate once particles return to the plane-bed channel morphology in which the confluence is located.

In Figure 8, Exceedance probabilities of normalized transport distances show a steeper form in the upper-confluence reaches feature a steeper linear form than the control reach and lower confluences (Figure 8). The steeper trend ensures that front-running tracers travel a relatively shorter distance beyond the population average, though a greater proportion of the tracer population travels near or beyond the average distance. This is a distinctive difference from the control reach which, despite similar average and maximum tracer transport distances as the upper-confluence reaches, shows more similar distributions to more closely aligns with the lower-confluence reaches. We assert that This difference is suggestive of further supports the enhanced transport hypothesis within the equilibrium confluence; We when tracers entering the confluence
are able to continue transporting downstream, a greater proportion of tracers will reside in the front of the plume, past the average transport distance, as we see with the upper confluence. Because the trend is absent for the lower confluence, we postulate that the confluence effect (enhanced transport, reduced deposition) is muted once particles have transported a sufficient distance beyond the confluence zone. Despite evidence suggesting confluence effects on transport, our study lacks sufficient spatial and temporal resolution to differentiate in a statistically rigorous manner between confluence and non-confluence reaches—these differences, we lack enough confluences or years of observation to greatly distinguish between our study confluences and the control reach—all study reaches may be considered as exhibiting a thin-tailed dispersive growth pattern, given their linear form in semi-log space. Recent works suggest that thin-tailed dispersion is dominant for coarse bedload particles (e.g., Hassan et al., 2013), and our work is no exception. A thin-tailed model may be reasonable for describing particle displacement distributions through confluences as well as in our control reach. The linear collapse in semi-log space observed in Figure 89 further supports this view, indicating that normalized transport distance (Eq. 1) may serve as an appropriate single-parameter approach to describe tracer displacement at the scale of individual floods. However, the tail of the distribution diverges from the model fits and exponential regression. This divergence is evident in our other analyses, which suggest relatively heavy-tailed displacement distributions and reduced depositional probabilities for coarse sediment within the confluence zone. Enhanced transport is further suggested by larger transport distances for a given impulse (Table 34; Figure 10). We therefore assert that coarse particles entering the confluence zone are less likely to deposit than in the preceding plane bed reach, and that particles exposed to the greater dimensionless impulse beyond the confluence travel farther distances than those that do not enter the confluence.

4.3 Confluences and large-scale sediment routing

We therefore propose a conceptual model where equilibrium confluences have the effect of enhancing coarse bedload transport and dispersion downstream. Tracers moving through confluences show greater transport distances for a given $I^*$ and reduced depositional
probabilities in the confluence itself. This would distort the spatial distribution of a population of coarse particles in the Lagrangian field perspective, where front-runner tracers are preferentially routed through confluences and the overall spatial distribution distorted in the downstream direction. Tracer transport dynamics were reasonably well fitted by thin-tailed models, but not for far traveling tracers. The differences we observe between confluence and non-confluence reaches are subtle, but this effect may increase as particles are routed through successive confluences.

This conceptual model applies to confluence morphology that is governed by hydraulics and sediment supply typical of snowmelt-dominated hydrographs, as opposed to confluences influenced by recent disturbance. We consider our model within the context of Benda et al.'s (2004b) Network Variance Model Dynamics Hypothesis to consider the effects of confluences at the scale of headwater river networks. The NVMNDH considers that the likelihood of morphologically significant perturbations to mainstem channels, in the form of large sediment deposits, increases in the vicinity of confluences due to upstream disturbance. Our sites, where recent tributary disturbances are absent, diverge from this model, such that sediment can propagate, unhindered by recent sediment deposits, through confluence zones, and indeed, transport is enhanced rather than impeded across our equilibrium confluences. Our work expands, rather than refutes, the NVM by suggesting that confluences play morphologically important roles with respect to sediment routing both in and outside of disturbance-dominated headwater systems.

To develop a more complete understanding of how dispersive patterns observed at the scale of We hypothesize, based on our findings above, that sediment routing through individual equilibrium confluences influences sediment connectivity and routing at the larger basin scale in mountain watersheds. Longer-term studies across a larger number of confluence sites and channel morphologies are needed. As the equilibrium confluence is contingent on high $Q_r$, $\Theta$, and other physical controls, we would expect such work could test, for example, how confluence effects on sediment routing are dependent on both confluence (e.g., $Q_r$, $\Theta$) and basin certain basin types to accumulate confluence effects to a greater extent than others, according to basin (e.g., shape, drainage density, and network geometry) characteristics (Benda et al., 2004a; Rice, 2016).
Such studies could also further test Benda et al.’s (2004ab) Network Dynamics Hypothesis (NDH), which considers that the likelihood of morphologically significant perturbations to mainstem channels, in the form of aggradational sediment deposits, increases in the vicinity of confluences due to upstream disturbance and may be cumulatively more significant in compact basins (also see Rice, 2016). Additional field measurement of sediment transport across confluences would complement recent application of remote, automated methods of predicting tributary-driven aggradation at confluences and testing of the effect of basin shape on confluence aggradation (Rice et al., 2016).

Network structure, in terms of both geometry and variations in sediment transport capacity, has been found to influence how sediment inputs in headwaters propagate downstream through basins (e.g., Czuba and Foufoula-Georgiou, 2014; Gran and Czuba, 2016) and relates to the questions raised in the NDH about basin shape and associated confluence effects (Benda et al., 2004a,b). In our study area and in semiarid mountain watersheds in general, for example, post-fire erosion is an important sediment source with implications for humans and aquatic ecosystems; downstream propagation of post-fire sediment inputs may vary depending on basin shape and confluence effects. For example, propagation of sediment routing may differ between unglaciated, compact basins with dendritic channel networks (as are present in our study area and the surrounding Sapphire Mountains) compared to formerly glaciated, elongate basins with trellis drainage networks (as are present in the Bitterroot Range ~30 km to the west of our study sites) (Benda et al., 2004a). Discontinuity in coarse sediment transfer can emerge when competence is reduced and particles enter long-term storage (e.g., Tooth et al., 2002; Fryirs, 2013; Bracken et al., 2015), including where the morphology of landforms surrounding confluences create sediment buffers between tributaries and trunk streams (Fryirs and Gore, 2014) or as a result of downward advection into the streambed (Pelosi et al., 2016). These points highlight the importance of understanding the dispersive behavior of coarse bedload particles. As an illustrative example, we compare the EFB basin to a similarly sized basin (Tin Cup Creek), 35 km to the west in the Bitterroot Range (Figure 12). The morphology of basins in the Bitterroot versus Sapphire Mountains differs considerably as a result of differences in erosive history and lithology. The Bitterroot are formerly glaciated and have granitic rock, with U-shaped valleys, elongate basins, and trellis drainage networks. The unglaciated Sapphires, in
contrast, have V-shaped valleys, compact basins, and dendritic networks. Comparing these basin types, basins such as those in the Sapphire Range (e.g., the upper EFB basin) have larger tributary channels of increasing order (Strahler, 1952), where tributary discharges scale with increased mainstem flow, and a greater number and downstream extent of equilibrium confluences than the elongate basins (Benda et al., 2004a) that largely define basins such as the Bitterroot. This suggests that basin shape, itself a function of lithology and climate, may inform the dispersive behavior of a coarse bedload population, including in various basin shapes and in locations both lacking recent disturbance, and with equilibrium confluence morphology, and in disturbance-driven, aggradational confluences corresponding confluence deposits. This would determine the setting where confluences would (Benda et al. 2004b) be expected to enact a cumulative and significant effect on coarse sediment transport, if such an effect does indeed persist at these locations. Even if equilibrium confluences are not significantly different than the channel morphologies in which they are nested, they likely enact a unique dispersive regime than the aggradational setting described in the NDH. This will need to be characterized in future efforts to accurately model and predict patterns of sediment routing. Ultimately, further investigation into equilibrium confluences should test (a) whether a statistically-significant effect on sediment dispersion occurs and (b) the spatial and temporal scales in which the effect alters patterns of sediment routing in mountainous river networks.

Understanding the extent to which equilibrium confluences affect basin-scale routing requires further insight into coarse bedload connectivity in mountain rivers. Our conceptual model assumes steady progression of coarse sediment downstream in a plane bed morphology; however, discontinuity in coarse sediment transfer can emerge when competence is reduced and particles enter long-term storage (e.g., Tooth et al., 2002; Hooke, 2003; Fryirs, 2013; Bracken et al., 2015). Certain channel morphologies exhibit bedload particle displacements between morphologic units (e.g., bars; Pyrce and Ashmore, 2003), which can result in disconnectivity if bedform-scale aggradation exceeds rates of removal (Hooke, 2003). The unique dispersive patterns we observe at the scale of individual confluences must be analyzed across multiple confluences, over multiple floods, and within other channel morphologies, to quantify the extent of their influence over large-scale patterns of sediment routing.
Our tracer study, the first to date of coarse-sediment routing through mountain-river confluences, showed that in gravel-bed headwater systems, equilibrium tributary confluences are representative geomorphically unique locations that locally affect patterns of sediment routing within riverine systems that may affect local patterns of sediment transport and deposition routing. Our study is the first to date of tracer-based coarse-sediment routing through mountain-river confluences. We observed that at the reach scale, coarse sediment is routed through confluences along the flanks of a well-defined scour hole, in agreement with observations and flume studies from other gravel-bed systems. Certain equilibrium-confluence reaches showed evidence for enhanced transport during a single snowmelt flood, although understanding whether confluences influence bedload dispersion in a geomorphically significant manner at larger spatial and temporal scales would require further study at the scale of individual floods, suggesting that over multiple floods and confluences, equilibrium confluences may enact geomorphically-significant dispersive regimes to bedload particles. The dimensionless impulse metric (Phillips et al., 2013) was shown to correlate to tracer transport and dispersion over a single flood event, further supporting its use in future sediment transport studies. Transport distance of mobilized clasts through the confluence zone is less dependent on grain size than in the plane-bed channel morphology, especially for larger grains. Distributions of particle displacement were along the thin-heavy tail threshold; longer-term monitoring would elucidate the evolution of tail characteristics. Regardless of thin or heavy-tailed transport, confluence reaches generally featured a “heavier” distribution of displacement distances and a greater proportion of tracers in the tail. We therefore found confluence reaches to impart greater transport distances and dispersive growth compared to the plane-bed channel morphology, even when particles did not progress beyond the downstream extent of the confluence itself. Our study also illustrates the utility of tracer studies using PIT / RFID technology for providing field-based insights into sediment transport dynamics.

We proposed a conceptual model where equilibrium Equilibrium headwater confluences may alter patterns of dispersion and enhance downstream transport. According to the sediment cascade framework of Fryirs (2013), this would classify equilibrium confluences as an enhanced
longitudinal linkage compared to the plane-bed channel morphology. Combined with the work of Benda et al. (2004a,b) and others, we suggest that the location of confluences influences sediment routing patterns and, in the case of upstream disturbances, responses to sediment pulses, in headwater systems both with and without disturbance-derived sediment deposits. Longer-term sediment transport studies across confluence and non-confluence reaches, combined with analysis of changes in bed elevation and texture in intervening reaches to place the work in a mass conservation framework, would further clarify sediment routing patterns in mountain channel networks and thus inform a range of problems. These include understanding of how confluences influence sediment cascades and connectivity (Fryirs, 2013); links among confluences, sediment routing, and basin morphology (Benda et al., 2004a, b; Rice, 2016); and applied problems, including solid-phase contaminant transport (Bradley et al., 2010), cosmogenic radionuclide accumulation (Gayer et al., 2008), sediment budgeting (Malmon et al., 2005), and the duration and topographic impact of pulses on aquatic habitat (Lisle et al., 2001).
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Table 1: Channel morphology and bed-material grain-size characteristics at each study reach. Width and depth values are bankfull dimensions, as measured along surveyed cross-sections; $Q_r$, $\theta$, and $z_d$ are illustrated and defined in Figure 1. Upper and lower confluences reaches are denoted with (U) and (L), respectively.

<table>
<thead>
<tr>
<th>Study Reach</th>
<th>$S$</th>
<th>Width (m)</th>
<th>Depth (m)</th>
<th>$D_{50}$ (m)</th>
<th>$D_{84}$ (m)</th>
<th>$Q_r^a$ (avg)</th>
<th>$\Theta$</th>
<th>$z_d$ (m)</th>
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<tbody>
<tr>
<td>Moose Creek (U)</td>
<td>0.018</td>
<td>11</td>
<td>0.76</td>
<td>0.05</td>
<td>0.10</td>
<td>0.63</td>
<td>8</td>
<td>0.16</td>
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<tr>
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<td>0.029</td>
<td>7</td>
<td>0.94</td>
<td>0.06</td>
<td>0.15</td>
<td></td>
<td>6°</td>
<td></td>
</tr>
<tr>
<td>Control Reach</td>
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<td>15</td>
<td>0.78</td>
<td>0.06</td>
<td>0.13</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>Martin Creek (L)</td>
<td>0.017</td>
<td>15</td>
<td>0.80</td>
<td>0.07</td>
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<td>0.45</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
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<td>16</td>
<td>1.03</td>
<td>0.07</td>
<td>0.14</td>
<td>0.45</td>
<td>1°</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a$ calculated by dividing the smaller trunk stream by volume over the mainstem. $Q_r = Q$(Moose)/$Q$(Martin) in the upper confluence, and $Q$(Martin)/$Q$(East Fork) in the lower confluence.
Table 2: Tracer recovery and transport statistics by study reach

<table>
<thead>
<tr>
<th>Study Reach</th>
<th>(n^a)</th>
<th>(n_{rec}^b)</th>
<th>Recovery (%)</th>
<th>(D_{50}) (m)</th>
<th>((X \pm \sigma)_{tot}) (m)(^c)</th>
<th>((X \pm \sigma)_{mob}) (m)</th>
<th>(X_{max}) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moose Creek (U)</td>
<td>65</td>
<td>53</td>
<td>82</td>
<td>0.077</td>
<td>7.4±6.6</td>
<td>8.5±6.4</td>
<td>24.5</td>
</tr>
<tr>
<td>Martin Creek (U)</td>
<td>62</td>
<td>42</td>
<td>68</td>
<td>0.081</td>
<td>3.8±4.1</td>
<td>4.4±4.1</td>
<td>20.6</td>
</tr>
<tr>
<td>Control Reach</td>
<td>97</td>
<td>83</td>
<td>86</td>
<td>0.080</td>
<td>4.2±5.3</td>
<td>4.9±5.4</td>
<td>22.7</td>
</tr>
<tr>
<td>Martin Creek (L)</td>
<td>103</td>
<td>71</td>
<td>68</td>
<td>0.082</td>
<td>14.6±22.9</td>
<td>16.4±24</td>
<td>133</td>
</tr>
<tr>
<td>East Fk. Bitterroot (L)</td>
<td>101</td>
<td>74</td>
<td>73</td>
<td>0.080</td>
<td>47.4±56.3</td>
<td>49.4±56.6</td>
<td>211</td>
</tr>
</tbody>
</table>

\(^a\) number of tracers deployed

\(^b\) number of tracers recovered

\(^c\) \(X\) is average transport distance, \(\sigma\) is standard deviation

* “tot” and “mob” describe (1) the total tracer population and (2) tracers moving beyond 0.5 meters
Table 3: Tracer statistics derived from two stochastic models of tracer transport and dispersion: Einstein-Hubbell-Sayre (EHS) and the Yang-Sayre Gamma Exponential Model (GEM).

<table>
<thead>
<tr>
<th>Study Reach</th>
<th>EHS</th>
<th></th>
<th></th>
<th>GEM</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>σ</td>
<td>CV*</td>
<td>X</td>
<td>σ</td>
<td>CV</td>
</tr>
<tr>
<td>Moose Creek (U)</td>
<td>6.7</td>
<td>5.7</td>
<td>0.86</td>
<td>6.6</td>
<td>5.7</td>
<td>0.87</td>
</tr>
<tr>
<td>Martin Creek (U)</td>
<td>3.8</td>
<td>3.8</td>
<td>1.0</td>
<td>3.8</td>
<td>3.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Control Reach</td>
<td>4.2</td>
<td>4.6</td>
<td>1.1</td>
<td>4.2</td>
<td>4.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Martin Creek (L)</td>
<td>15.6</td>
<td>24.6</td>
<td>1.6</td>
<td>16.2</td>
<td>25.4</td>
<td>1.6</td>
</tr>
<tr>
<td>East Fk.</td>
<td>43.9</td>
<td>61.4</td>
<td>1.4</td>
<td>43.7</td>
<td>61.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*coefficient of variation

The values presented here incorporate estimates of critical Shields stress calculated from Eq. 4 (Mueller et al., 2005); results are nearly identical if Eq. 6 is used instead.

Table 4: Critical shear velocity ($U^*_c$) and dimensionless impulse ($I^*$) at each study reach.

<table>
<thead>
<tr>
<th>Study Reach</th>
<th>$\tau_c^{\mu}$</th>
<th>$U^*_c$ (m/s)</th>
<th>$I^*$</th>
<th>$\tau_c^{R}$</th>
<th>$U^*_c$ (m/s)</th>
<th>$I^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moose Creek (U)</td>
<td>0.06</td>
<td>0.23</td>
<td>602000</td>
<td>0.08</td>
<td>0.27</td>
<td>14900</td>
</tr>
<tr>
<td>Martin Creek (U)</td>
<td>0.08</td>
<td>0.29</td>
<td>310000</td>
<td>0.11</td>
<td>0.34</td>
<td>37600</td>
</tr>
<tr>
<td>Control Reach</td>
<td>0.06</td>
<td>0.23</td>
<td>425000</td>
<td>0.07</td>
<td>0.25</td>
<td>88400</td>
</tr>
<tr>
<td>Martin Creek (L)</td>
<td>0.06</td>
<td>0.25</td>
<td>1200000</td>
<td>0.09</td>
<td>0.31</td>
<td>86000</td>
</tr>
<tr>
<td>East Fk. Bitterroot (L)</td>
<td>0.06</td>
<td>0.25</td>
<td>1900000</td>
<td>0.07</td>
<td>0.29</td>
<td>577000</td>
</tr>
</tbody>
</table>
Figures

Figure 1: Flow (top left) and morphology (bottom left) in a gravel-bed confluence (after Best, 1987). Key variables influencing hydraulics and morphology include discharge ratio ($Q_r$), junction angle ($\theta$), bed discordance ($z_d$), and upstream planform geometry (not pictured).
Figure 2: Study area, including location within the East Fork Bitterroot River’s headwaters (upper left) and three study sites: upper and lower confluences and a control reach, outlined in yellow; individual reaches in which PIT-tagged particles were seeded are outlined in red.
Figure 3: Stage hydrograph during spring 2014 runoff period at lower confluence (East Fork Bitterroot River) study site. Estimated bankfull level, based on cross-section topography surveyed at transducer location, is shown as horizontal dotted line.
Figure 4: Grain size distribution of tagged tracers (red) and streambed (black) composite over all study sites.
Figure 5: Tracer positions at initial installation (left) and following the 2014 flood (right) at (A) the upper confluence, (B) control reach, and (C) lower confluence reaches.
Figure 6: Digitized patch map of bedforms and tracer recovery positions at the (A) upper and (B) lower confluences.
Figure 7: Einstein-Hubbell-Sayre (EHS) and Yang-Sayre (GEM) model fits for (A) Moose Creek, (B) Martin Creek (upper), (C) the control reach, (D) Martin Creek (lower), and (E) the East Fork Bitterroot River. $R^2$ fit differences between the two models were < 0.01, so we present their shared fit values here.
Figure 78: Spatial distribution of tracer positions at the time of initial deployment (pre) and after the 2014 flood (post) for (A) the upper confluence, (B) the control reach, and (C) the lower confluence. The confluence zones are bracketed with dotted vertical lines. Note the altered x-axis scale in (C).
Figure 8: Normalized transport distances ($X_n$; Eq. 1) in all five study reaches, with exponential fit plotted for comparison.

Figure 10: Cumulative exceedance distributions of travel distance for the upper confluence, lower confluence, and control reach.
Figure 1: Linear and power-law relations between dimensionless impulse and (A) mean displacement length ($<X/D>$) and (B) variance ($\sigma^2$; Eq. 2) for each tracer population.
Figure 12: Typical basin shapes and tributary sizes in the (A) Sapphire Mountains (East Fork Bitterroot River) and (B) Bitterroot Range (Tin Cup Creek). These basins are of similar drainage area, but differ in lithology, erosional history, basin morphology, and potential sediment routing.