Thank you for your feedback. We copied your comments and provided our responses below.

Reviewer 1

The manuscript draft “Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream” describes a rare opportunity to investigate the basic reach scale effects of beaver colonization over a gradient of dam influence. The others opportunistically leverage a fantastic dataset collected by Schmadel et al 2010 before the stream reach was colonized, by collecting data for several more years as beavers built at least 10 dams over a 750 m distance. Overall the topic is interesting, and the text quite well-written. The type of data collected are fairly basic, but as the authors note there is little “quantitative” study of beaver dam impacts to date. Beaver impoundment will have varied pros and cons in regard to stream restoration efforts that will be highly influenced by the morphological attributes of the degraded system and restoration goals (both physical and biological). There is an amazing opportunity to improve degraded streams, particularly incised channels in the USA western states, by simply allowing beaver to return (not trapping them), and perhaps actively helping them get a foothold. With the USA state of Utah actively including beaver management in their statewide stream management strategy, studies such as this are strongly needed.

1. Although I generally agree with the overall approach taken here, some things should be better quantified and clarified for this data to be more thoroughly interpreted in the context of seasonal variability. It seems 2010, the “beaver impact” end-member presented here, was perhaps unusually dry (Figure 2), and may have led to complicating human hydrological effects such as enhanced irrigation near the study reach.

   2010 was indeed drier year due to less snowfall. The snow water equivalent at its peak was about 500 mm in 2008 and 2009, and 300 mm in 2010. However, precipitation accumulation in 2010 increased in late spring/ summer, and the cumulative amounts were comparable with that of 2008 at the end of the water year (October). While the discharge in 2010 could have been influenced by irrigation practices in the nearby field, irrigation usually occurs only from mid-May to mid- or late-July at the latest and therefore only had a potential impact during this time. However, water rights require irrigation in this area to stop when the flow in Blacksmith Fork reaches a minimum instream flow. Because of low flows in 2010, irrigation stopped earlier than usual (likely early July, personal communication, Kelly Pitcher, Hardware Ranch operations). It is also important to note that the trend of gaining conditions persist past the irrigation season (with more beaver dams being built) (Figure 3). This suggests that reach gains in 2010 were due primarily to groundwater influences rather than irrigation influences. In our opinion, the human impact is likely not a driving factor of the hydrologic and temperature changes we observed. We have also added explanation in the discussion – page 854, L5.

   > *“While the discharge in 2010 could have been influenced by irrigation practices in the nearby field, irrigation usually occurs only from mid-May to mid- or late-July at the latest and therefore only had a potential impact during this time. However, due to drier conditions in 2010 and water right requirements, irrigation stopped earlier than usual (likely early July). The dominant hydrologic processes influencing the study reach clearly changed over the period of three years and the trend of gaining conditions persisted past the irrigation season (Fig. 3). This suggests that reach gains in 2010 were due primarily to groundwater influences rather than irrigation influences.”*

2. Further, no attempt is seemingly made to normalize stream temperature results to atmospheric temperature patterns of a given year, making conclusions based on inter-annual comparison less certain.

   Additional subplots of air temperature and solar radiation have been added to Figure 4 for 2008, 2009, and 2010 to show the relative differences of weather between years. The one-way ANOVA comparison of air temperature showed no statistically significant differences between individual years ($p > 0.05$) which suggests that air temperature is not a driving factor of stream temperature observed over the years. In addition, ΔT normalized by air temperature showed a gradual increase from 2008 to 2010, similar to Figure 4, suggesting changes within the reach. When one-way ANOVA was applied to normalized daily ΔT values for the common days when both water and air temperature are available each year, we again found a significant difference from year to year ($p < 0.01$) suggesting that the between year variability in air temperature is not creating the differences observed within each year. Further, we applied a one-way ANOVA to ΔT normalized by flow at the upstream boundary to investigate the impacts of flow variability between years. We still found a significant difference ($p < 0.01$) between 2008 and 2010 suggesting that flow conditions are not the only factor influencing ΔT values.

   We chose to leave Figure 4 as a relative net change in temperature (normalized to the upstream control temperature) to illustrate changes within the study reach as this will make it easier to compare with other studies. We did, however, add the following text to page 851, L1 to clarify that the between year water temperature differences were not due to differences in air temperatures. Also similar text has been added to Methods section – page 849, L 19.

   "To determine if weather conditions were influencing the water temperature differences between years, we first compared air temperature conditions through a one-way ANOVA and found no statistical differences between individual years ($p > 0.05$). We further compared daily ΔT values normalized by air temperature for the common days when both water and air temperature were available. We found a significant difference in the average $\Delta T/Tair$ values ($p <0.01$) between years. This suggests that the between year variability in air temperature is not controlling the observed ΔT patterns."

3. Finally, no straight forward process-based explanation of why increased water levels and retention along this reach caused a system-wide transition from "losing" to "gaining" is presented.

   We have added the statement below regarding the losing-gaining transition in the manuscript – we added this near page 854, L29 (in HESSD). Note that we have updated a number of figures within the MS to address the reviewers' comments. The old figure number and "New" figure number will be provided within the responses below.

   > *"The significant increases in the groundwater table (Figure 8, which is now the New Figure 7) were likely due to increased water surface elevations in the beaver ponds for consecutive years. The localized increases in groundwater elevations are further elevated each spring due to high flows, inundation of the flood plain, and general high surface water elevations throughout the reach. As the flow and surface water elevations drop throughout each summer, there are positive groundwater gradients towards the stream throughout this season and, therefore, the reach gains water. These opposing results from dilution gaging and groundwater levels highlight the importance of temporal scales and repeated measurements considered in this present work. They also indicate that without this consideration, the differences between measurement techniques can lead to contradicting conclusions as discussed within Schmadel et al. (2014)."*

Major comments:

4. I assume local air and groundwater temperatures were monitored over the course of this experiment? The results presented here should be put in their context. Reduced peak flows are expected after beaver dams, but what was the avg snowpack each year? Precip? There is clearly much less water flowing through the reach in 2010 overall compared to previous years if one integrates under the Q curves (Figure 2); this "environmental" effect will likely impact peak flows, losing/gaining hydraulics, water temp, residence times. Also, this "dryer" year may have resulted in enhanced local field irrigation which is independent of beaver dam impacts. The authors refer to this loosely on pg 850 and elsewhere- and 80% increase in reach Q over two years is likely not driven primarily by a few ponded areas, unless a reasonable process-based explanation can be presented. As the paper stands it is difficult for the reader to parse direct effects of beaver colonization from inter-annual environmental variability and associated human impact (irrigation); this renders the results much less "quantitative" than the authors imply (eg pg 853, L20).

   Yes, air temperature was measured in the reach and has been incorporated into Figure 4. The groundwater temperature was not measured over time. The cumulative precipitation for each year is now shown in SI Figure 5 to provide a context for the differences in discharge between years. While there is a lot less water flowing through the reach in 2010, we are focusing on illustrating the change in discharge over the study reach (shown as differences between downstream (outflow, PT1252) and upstream (inflow, PT515) discharge (Figure 3)). We present the data in terms of differences and percent differences (i.e., normalized by upstream values) rather than absolute values to illustrate the potential groundwater influences during the three year study period (Figure 3, 5, 6, 9, 10, 11, SI1) and seasonal variability (Figure 2 and 4).

   The concerns regarding the explanation of the gaining/losing patterns are provided above in our response to comment 3.

5. The "window of detection" concept well detailed by Payn et al 2009 should be reviewed and commented on in the context of your results. Beaver dams seem to force surface and subsurface flowpaths outside of the main channel which cause strong variability when making closely spaced in-stream evaluations, but may integrate at larger scales (windows) to result in muted changes.

   Good point. We have added the following language to page 854, L22 in the HESSD.

   > *"The window of detection varies as a function of stream characteristics, including storage zone dimensions and exchange rates, and stream velocity and discharge (Harvey et al., 2000).In turn, it dictates which subsurface exchange flow paths are captured within tracer break through curves (e.g., Ward et al., 2013). Because the changes to the study reach between years influenced the window of detection and the reported mass recoveries, our conclusions are based on the net changes to flow (%ΔQ) that are insensitive to a changing window of detection."*

6. The local discharge patterns described at the top of pg 850 could be influenced by a series of "return flows" from upper impounded areas.

Reach scale flow conditions reflect year to year variability as well as beaver dam building activities (Figure 3). All of the side channels were initiated and returned to the main channel within the study reach. The variable local discharge patterns did influence the sub-reach scale results when comparing flow conditions for all three years and this was acknowledged within the text (see HESSD page 854, L17).

7. Similarly, it is noted on pg 854 that the up-gradient "control" reach lost more water each year of the study, while the impounded reach gained more water. Could something about the higher water table, increased capture area be forcing greater return flow from upstream? Is there any way to parse stream water from new GW inputs chemically based on already collected data?

This is a good question. Based on head gradients and prior work in the upper control reach, we believe that much of the gaining and losing in the upper reach is more perpendicular to the channel than parallel or down-watershed. There may, however, be longer flow paths from the control reach to the beaver impacted reach that are being rerouted to the surface due to changing groundwater elevations in the study reach. Unfortunately, we do not have any data to support or refute these ideas.

8. Tracer mass-recovery methods should be better defined, and a mass recovery of -103.7% does not make sense conceptually.

We have expanded the tracer recovery methods (HESSD, page 846, L12). There was a mistake in the original manuscript (HESSD p. 852, L11) stating the mass recovery %. The percentages reported are not mass losses, but % gross water losses. This has been corrected within the manuscript and some additional comments (see below) regarding error estimates have been included. Please see HESSD page 852, L11.

> *"To estimate tracer mass losses and gross stream losses, mass recoveries were quantified using (Payn et al., 2009):*
>
> $$M_R = Q_D \int C_D(t)dt \qquad (1)$$
>
> *"For 2008, the error in flow estimates for the individual sub-reaches was about 8% for both Q and %ΔQ. For 2010, the errors ranged from 6% to 28% for Q and 8% to 29% for %ΔQ. Most of the error was due to incomplete tracer mixing and larger errors in 2010 were attributed to higher variability in flow and flow paths. The mass recoveries showed that the percent of mass loss changed significantly from 2008 to 2010. In 2008, the mean percent mass losses for individual sub-reaches were sequentially -2.8, -12.9, -18.1, -18.8, and -4.7%. In 2010, the mean percent mass losses were -69.0, -0.2, -8.3, -62.0, -7.6% for the same sub-reaches." – page 852, L11*

9. There is discussion regarding the increase in residence times on Pg 852, but this does not include the residence times of unrecovered mass/water, so these increases in recovered mass residence time likely underestimate true increases in system residence time.

True. We have added a statement to Sub-reach Scale Responses acknowledging this. Please see HESSD page 852, L22.

> *"The residence time of unrecovered mass was not included in mean residence time estimates."*

10. Although alluded to in the discussion, the concept of patchiness could be more strongly presented/commented on here (see http://rsfs.royalsocietypublishing.org/content/2/2/150). Beaver dams likely increase system productivity by creating varied habitats in close physical contact with one another as the author's mention. This increase in "productivity" may be difficult to quantify with simple point temperature and water flux/head measurements, but they can perhaps be commented on.

    We agree that it is difficult to capture spatial heterogeneity (patchiness) with point temperature measurements. This is emphasized within page 856, L14-L26, page 857, L6-L12 in the discussion and further illustrated within Figure SI4D. SI4D highlights the importance of the spatial scale when one is studying the impacts of beaver on stream systems. However, we have expanded this section to provide further emphasis on this topic (page 856, L24).

    > *"Spatial heterogeneity (patchiness) and spatial patterns in heterogeneity change with spatial scale (Cooper et al., 1997). Since most of the ecological interactions in heterogeneous streams happen in conditions that are different from mean conditions, they cannot be captured with point measurements, or with models that focus on understanding average conditions (Brentall et al., 2003, Grünbaum, 2012). This highlights the need to concentrate on variables and processes that capture spatial patchiness at different spatial scales in stream ecosystems."*

11. It is not clear why a 2006 image is used in Figure 1 to show a post-dam world, and the beaver ponding is digitized (?) from some other unknown image. Either both images should be directly presented or the 2010 image should be used for this figure. The text/symbol size in this figure needs to be increased.

    We have updated Figure 1 by combining the previous Figure 1 with Figure 7. The text size in Figure 1 has been increased. Also, Figure SI4 was changed to include aerial imagery from multiple years.

12. Consider shifting Figure 10 to supplemental, and including the current Supplemental IR figure as new Figure 10.

    Based on the response to comment 11 above, we believe that Figure 10 should remain in the text. While we understand the value of thermal image in understanding the spatial variability on temperatures, we decided to only include it in the SI because it is from a different time period. We felt it was important to have a consistent representation of study time period (2008-2010) and changes that occurred within that period. This led us to only using the thermal image to illustrate differences in temperature between sections with and without beaver dams.

13. Figure 4: Can you plot all of these panels together? They are difficult to compare as-is.

    These data could be plotted together, but the overlap of the time series will make much of it indistinguishable. We have added solar radiation and air temperature for each year to this plot to help with the between year comparison.

<u>Minor comments:</u> (next time please use a continuous line numbering system)

The line numbering was formatted by journal.

14. pg 840 l2- delete "increasing"

    Deleted.

15. l15-mean temperature in the outgoing thalweg? Try to be more specific with these important conclusions. state some conclusions here on local GW heads.

    Yes, the temperature increase at the reach scale in the outgoing thalweg. We have added the following sentence about groundwater in the abstract – HESSD p. 840, L14.

    > *"In addition, we observed an increase in groundwater elevation in the sub-reaches."*

16. 841- perhaps mention that beaver dams break up the average stream slope into a series of punctuated head drops. Overall this intro is in great shape.

    Thank you. We have added the following statement in our Introduction – p. 841, L4.

    > *"Within the stream channel, beaver dams break up the average hydraulic gradient into series of disrupted head drops and flat ponded sections. This change in average hydraulic gradient increases the potential for hyporheic exchange (Lautz and Siegel, 2006)."*

17. 843 L19- how old are the relic surfaces?

    We do not know exactly and have decided to remove this text.

18. 844 L1- The underlying goals of the restoration project should be clearly stated L4-"roughly around 2005?" surely somebody knows the correct timing

    This effort was not clearly documented and the availability of information is limited. Based on prior conversations with people within the Division of Natural Resources, the primary goal was to move the stream away from the buildings and horse pastures.

19. L12- Beaver dam height measured how? (eg top to base below water?)

    Beaver dam heights were measured at the downstream face as a difference between channel bottom right below the dam and top of the dam at the crest.

20. L19-extrapolaton seems a bit weird here- 13.3 dams/km based on 10 dams over 750 m- as you arbitrarily defined the reach length, and if the upper control section was included this number would fall

    The upper section is only a "control" reach for the discharge comparison. There is no beaver activity (at least in period of 2008 to 2010 presented here) in this section. Our intention was only to provide an estimate of dam density within the study reach which resulted in 10/0.75km = 13.3 dams/km.

21. 845 L15- where were these pressure transducers installed relative to channel morphology? In a side pool?

    The upstream pressure transducer (PT515, inflow) was installed close to river bank (RR) in a section between two bends with an average bed slope of 0.017. Based on 2009 data, the average depth recorded at the inflow (PT515) was 0.13 m and minimum and maximum values were 0.08 m and 0.57 m, respectively. The downstream pressure transducer (PT1252, outflow) was installed near a foot bridge about 1.5 m from river left with an average bed slope of 0.0239. Based on 2009 data, the average water depth recorded at the outflow (PT1252) was 0.16 m and minimum and maximum *values were 0.08 m and 0.32 m, respectively. The pressure transducer at the upstream end of the control reach (PT0) was installed about 1.0 m from river right with an average bed slope of 0.018. Based on 2009 data, the average depth recorded was 0.21 m and minimum and maximum values were 0.09 m and 0.37 m, respectively.*

22. L18- what is this full range of flow conditions?

    We have added the following information about specific flows measured (min and max). – page 845, L19.

    > *"The lowest flow measured was 157.4 L* s^{-1} *at PT1252 and the highest flow measured was 1509.6 L* s^{-1} *also at PT1252."*

23. L20- FloMate 2000?

    Yes, 2000. Changed within the text.

24. L28- are these return flows surface or subsurface? this seems like a "result"

    These were surface return flows – small side channels created either by beaver or due to overland flows from the beaver ponds. We have clarified this in the text. (HESSD page 845, L28).

25. 846 L3 include range of injected masses. Na+ also effects conductivity.

    We have included ranges of NaCl in the manuscript (HESSD page 846, L5). Also please see text added below.

    > *"Tracer injection masses ranged from 600 to 3300 g as NaCl and were varied to achieve large enough responses in electrical conductivity above background for dilution gauging and mass recovery purposes."*

26. L11ish- introduce the mass recovery, concurrent gains/losses methods here presented by Payn et al 2009, mass recovery is later determined but it is not stated how this was done

    We have included the following information (with equation) about mass recovery in our Data Collection section of the Methods – HESSD page 846, L13.

    > *"To estimate tracer mass losses and gross stream losses, mass recoveries were quantified using (Payn et al., 2009):*
    >
    > $$M_R = Q_D \int C_D(t)dt$$ *"*

27. L23- where were these temp measurements made? 0.6 m depth? attached to stake in water column?

    We have added this specification in the manuscript (HESSD page 846, L26). Also, please see below.

    > *"The temperature sensors were attached to metal stakes, placed in the middle of the channel, approximately halfway through the water column. Individual sensors were wrapped in aluminum foil to reduce solar radiation influence in slower moving waters."*

28. 847 L10- ice buildup influenced by dams? This can effect winter SW/GW exchange

    We agree that the ice buildup in the beaver ponds can influence surface/ground water exchange. But the major reason for excluding data from the winter months was ice buildup around pressure transducers themselves which could influence the data accuracy. We have added the following clarification in the manuscript (HESSD page 847, L10).

    > *"Data from the winter months were excluded from the analysis because they were influenced by ice buildup around the pressure transducers."*

29. L17- how is error on parameters a and b determined? Some main details should be stated here so the paper can stand alone without Schmadel et al 2010.

    We have added the following statement about a and b parameters in the manuscript (HESSD page 847, L15).

    > *"The regression parameter, a and b, were estimated through nonlinear regression and were the minimum sum of squares occurred. Uncertainty in these parameters was assessed from values within the 95% joint confidence region (Schmadel et al., 2010)."*

30. L20** are these changes normalized to local air temps somehow??

    Please see response to comment 2 above.

31. 849 L5- Make sure to state temp data were collected above the impounded water upstream of dams, not just right above a dam and right below which would make less sense

    Good point. We have corrected this in the Data Collection and Data Analysis sections (page 846, L24; page 849, L6) and added more detailed description of sensor placements.

    > *"The temperature sensors were initially placed in the flowing water to ensure well mixed flow. The sensors downstream from the beaver dams were placed outside of the scour pool. The temperature sensors were attached to metal stakes, placed in the middle of the channel, about halfway through the water column. Individual sensors were wrapped in aluminum foil to reduce solar radiation influence in slower moving waters."*

32. L25- how did snowpack/melt differ between years?

    We have added Figure 5 to the SI to show the differences in snow water equivalent and precipitation accumulation for all three years. Please see our response to comment 1 above.

33. 850 L4- include error estimates on these values, the coauthors previous work clearly indicates this should be done

    We have included error estimates on flow Q and dQ in the manuscript, as well as added error envelopes in Figure 2 and Figure 3.

34. 851 L12-14 move to Discussion section

Great point. We have moved this statement to discussion (page 855, L24).

35. L18 "in the end" too casual

    We have deleted it.

36. L20 what about the lateral transect info form Subreach 5?

    We have added the following statements in the results and discussion sections (page 852, L3; page 855, L3).

    > *"The head gradients from the cross-section of wells in sub-reach 5 show an increase in groundwater elevation over time and depict a positive gradient on one side of the channel and negative gradient on the other."*
    >
    > *"The positive head gradients on river left (facing downstream) shown in Figure SI 2 illustrates why sub-reach 5 is gaining water as shown in Figure 7. It is important, however, to also note that this sub-reach is also losing water on river right. However, sub-reach 6 is gaining water due to the main and side channels meeting again (Fig.1, Fig. 8)."*

37. 852 L2 note these patterns show a potential for water flux, not flux itself- you may be comparing pressure from two different flow paths

    We agree that there is a potential for different flow paths in our study reach. However, our intent is to use head gradients to illustrate relative changes over time in relation to surface water elevations. To make this clear, we edited a statement in methods (page 848, L19) and added a sentence to the discussion (page 854, L29).

    > *"To further understand hydrologic impacts of beaver dam construction and to illustrate the channel and groundwater elevation gradient changes over time, these data were grouped by each sub-reach were evaluated for 2008, 2009, and 2011."*
    >
    > *"Although, there is a potential for different flow paths in our study reach and head gradients do not necessarily translate into fluxes, we use the groundwater elevations to illustrate the relative changes in relation to channel surface water elevations over time."*

Review #2 (Megan Klaar)

The manuscript by Majerova et al. entitled "Impacts of beaver dams on hydrological and temperature regimes in a mountain stream" reports on the fortuitous investigation of beaver colonisation on a small tributary in Northern Utah. The occurrence of an earlier investigation on the Creek by Schmadel provides baseline hydrological and temperature data prior to beaver colonisation, allowing a before-and-after comparison of thermal and hydrological regimes over the course of beaver dam construction.
Given the current focus of river restoration and 're-wilding' of landscapes, the manuscript is very topical and has the potential to add important information to help river managers understand the impacts and benefits of restoration efforts, and in particular beaver management as adopted by the state of Utah, on the river environment.

The manuscript does a good job of making the most of the rare opportunity to study this event, and is generally very well written and engaging. However, I feel there are a few clarifications and limitations to the methodology which should be addressed to provide perspective to the results.

1. Generally, my comments are in line with Reviewer 1 with respect to tracer recovery results and methods and I am also of the opinion that differences in climate and hydrological conditions between years, and resultant changes in water resource management (i.e. irrigation) should be addressed to ensure that these factors are not compounding perceived beaver dam effects.

We have expanded the tracer methods and added the explanation of mass recoveries and error estimates. There was a mistake in original manuscript (p. 852, L11 in HESSD) stating the mass recovery %. The percentages reported are not mass losses, but % gross water losses. The MS has been updated with the following near HESSD page 852, L11.

> *"To estimate tracer mass losses and gross stream losses, mass recoveries were quantified using (Payn et al., 2009):*
>
> $$M_R = Q_D \int C_D(t)dt \qquad (1)$$
>
> *For 2008, the error in flow estimates for individual sub-reaches was about 8% for both Q and %ΔQ. For 2010, the errors ranged from 6% to 28% for Q and 8% to 29% for %ΔQ. Most of the error was due to incomplete mixing and larger errors in 2010 were attributed to higher variability in flow and flow paths. The mass recoveries from the dilution gaging showed that the percent of mass loss and gain changed significantly from 2008 to 2010. In 2008, the mean percent mass losses for individual sub-reaches were -2.8, -12.9, -18.1, -18.8, and -4.7%. In 2010, the mean percent mass losses were -69.0, -0.2, -8.3, -62.0, -7.6% for the same sub-reaches."*

To address the concerns regarding the differences in climate and hydrologic conditions between years, we have made a number of changes to the MS. First, air temperature and solar radiation for all three years has been incorporated into Figure 4. To illustrate climate differences and to provide a context for differences in discharge between years, we have added cumulative precipitation and snow water equivalent for each year in SI Figure 5. As explained in our responses to Reviewer 1 comments, 2010 was drier year due to less snowfall. The snow water equivalent at its peak was about 500 mm in 2008 and 2009, and 300 mm in 2010. However, precipitation accumulation in 2010 increased in late spring/ summer, and the cumulative amounts were comparable with that of 2008 at the end of the water year

(October) (SI Fig. 5). While the discharge in 2010 could have been influenced by irrigation practices in the nearby field, irrigation usually occurs only from mid-May to mid- or end-July at the latest and therefore only had a potential impact during this time. However, water rights require irrigation in this area to stop when the flow in Blacksmith Fork reaches a minimum instream flow. Because of low flows in 2010, irrigation stopped earlier than usual (likely early July, personal communication, Kelly Pitcher, Hardware Ranch operations). It is also important to note that the trend of gaining conditions persists past the irrigation season (with more beaver dams being built) (Figure 3). This suggests that reach gains in 2010 were due primarily to groundwater influences rather than irrigation influences. In our opinion, the human impact is likely not a driving factor of the hydrologic and temperature changes we observed.

2. In addition, I feel that the use of a single temperature and pressure logger at locations used to represent overall reach and sub-reach conditions may be stretching the data and conclusions reached; particularly so when no detail of how the locations were chosen, or in what conditions (depth of water, location in the channel) they have been placed within. For example, why are there differences in upstream and downstream logger locations between dams, as reported in Table 2?

We understand this concern and have added more detail regarding sensor placement. We have added the following explanation –page 846, L26.

> *"At the finer, beaver dam scale, temperature measurements were collected upstream of ponded water of beaver dams and downstream of individual beaver dams at 10-minute intervals using Onset® HOBO® Temp Pro V2 (Bourne, Massachusetts) deployed from September 2 to October 15, 2010 (Fig. 1, Table 1, Table 2). The temperature sensors were initially placed in the flowing water to ensure well mixed flow. The sensors downstream from the beaver dams were placed outside of the scour pool. The sensors were attached to metal stakes and placed in the middle of the channel about halfway through the water column. Individual sensors were wrapped in aluminum foil to reduce solar radiation influence in slower moving waters."*

To further clarify, temperature data were gathered above the backwater of the ponded areas (see responses to Reviewer 1 comments). The temperature sensors for our beaver dam scale study were initially placed in the flowing water above the ponded area or below the beaver dam. We tried to choose locations where flow was well mixed (e.g., in areas with multiple channels below the dam, we placed the logger downstream where the flow converged to ensure it was well mixed flow from both channels (BD4)). Also, loggers placed below the dams were placed outside of the scour pool where temperatures could be cooler due to upwelling. There is a possibility that due to beaver activity, some of the sensors were caught in slow/stagnant water for short periods of time. Regardless, as discussed within the paper, we believe that the variability in temperatures observed at the beaver dam scale is due to different surface flow paths, individual beaver dam characteristics such as their size and subsequently the size of the beaver pond, and residence times in the ponds.

As for the pressure transducers, the upstream pressure transducer (PT515, inflow) was installed close to river bank (RR) in a section between two bends with an average bed slope of 0.017. Based on 2009 data, the average depth recorded at the inflow (PT515) was 0.13 m and minimum and maximum values were 0.08 m and 0.57 m, respectively. The downstream pressure transducer (PT1252, outflow) was installed near a foot bridge about 1.5 m from river left with an average bed slope of 0.0239. Based on 2009 data, the average water depth recorded at the outflow (PT1252) was 0.16 m and minimum and maximum values were 0.08 m and 0.32 m, respectively. The pressure transducer at the upstream end of the control *reach (PT0) was installed about 1.0 m from river right with an average bed slope of 0.018. Based on 2009 data, the average depth recorded was 0.21 m and minimum and maximum values were 0.09 m and 0.37 m, respectively. It is important to note that the pressure transducer locations bounded the entire reach influenced by the beaver dams. Therefore, these data provided reach scale information to be made as the number of dams increased.*

3. There appears to be large differences in the distance the loggers were placed away from the dams, ranging for example from 8m to 81m upstream of dams. Would the differences in placement and location of the loggers not have an effect on the temperature data collected, and hence conclusions reached? Without an explanation of why and how the loggers were placed where they were, I do not have confidence that they are representative of the temperature conditions found in these locations, and hence provide sufficient information on the effects of beaver colonisation on hydrologic and temperature regimes.

This comment relates to our response in comment 2. We understand the variability is somewhat drastic, but we did focused on placing the sensors in flowing water above the ponded area or below the beaver direct influences of the dams. The large differences in the distances where loggers were placed are due to different size of beaver dams and channel geometry resulting in smaller/larger beaver ponds.

4. As stated by Reviewer 1, given the incomplete data and explanation of hydrological conditions and methods, I feel the current draft of the manuscript is more of a 'qualitative' study, which although interesting, does not meet the expected aims of the manuscript as it stands.

We hope that our clarifications and changes to the MS have provided the information necessary to see the quantitative value in the data collected. Our intent in saying this study is "quantitative" is to point out that we have collected a significant amount of data at different spatial and temporal scales representing actual responses due to beaver colonization.

Minor comments:
5. Please state the units of the stream bed slope on page 843, line24 (I assume %?).

The slope is the ratio of vertical and horizontal distance where units cancel out (meter/meter).

6. An explanation of how subreaches were determined would be beneficial on page 845, line 24.

The individual sub-reaches were chosen so the requirement for complete mixing for dilution gaging was met. Initially, the sub-reaches were equally spaced but later adjusted to provide good locations for injections that resulted in complete mixing. We have added the following statement to the manuscript – HESSD page 846, L1.

> *"The boundaries for the sub-reaches were chosen to ensure completely mixed conditions necessary for dilution gaging."*

7. How often were groundwater surface levels monitored, as detailed on page 846, line 20-23? Were these the only measures of groundwater, or were pressure-level loggers used as well?

The groundwater levels were measured 4 times in 2008 (June, July – 2x, August), 5 times in 2009 (June, July, August – 2x, November), and 4 times in 2011 (April, June, July, November). We have included this information in the MS – page 846, L22.

> *“The groundwater levels were measured four times in in 2008 (June, July (twice), August), five times in 2009 (June, July, August (twice), and November), and four times in 2011 (April, June, July, and November).”*

8. What is the n of the data presented in Figure 8?

Please see previous response to comment 7.

9. If groundwater was only manually measured using a dip meter, was sampling equal throughout the years and seasons?

Please see response to comment 7.

10. More detail on methods please. Without a better explanation of the locations of the loggers, I do not currently have confidence that the data shown in Figure 10 represents the variability in temperature differences between dams, as stated by the authors, but instead, could be a relict of logger placement; more detail is needed to qualify this statement.

Please see response to comment 2.

11. Air temperature and data from a ‘control’ location (e.g. upstream) of the beaver dams should be added to Figure 11 if possible to put the data in context with the atmospheric and hydraulic conditions during this study period.

We have added the air temperature and stream temperature from the inflow (PT515) to New Figure 10.

12. The authors may wish to consider using more descriptive rather than numerical names for their upstream and downstream temperature loggers (PT515 and PT1252) to help improve the flow of the manuscript and assist readers in immediately grasping their locations.

We have added “inflow” and “outflow” description to the existing nomenclature in the manuscript.

Relevant changes made in the manuscript:

1. We have added information regarding differences in climate and hydrological conditions between years and showed they have no effect on our final results. The information about normalization of stream temperature by the air temperature was added with additional statistics provided and showing no significant difference ($p>0.05$) in air temperature between individual years. Also, some additional plots of air temperature and solar radiation have been added in Figure 4.

2. We have added information regarding possible human effects (irrigation) on the hydrology and explained the timing of irrigation and changes observed during our study. The irrigation stopped earlier in 2010 and could not influence the gaining trend that persisted past the irrigation season (Fig. 3).

3. We have added more information regarding the losing-gaining transition in the manuscript and provided explanation why the increase in the groundwater levels likely occurred.

4. We have expanded on the tracer recovery methods and added information about the error in flow estimates. Also, the range of injected masses was added in the manuscript. The error envelopes have been added to Figure 3 as well.

5. We have expanded the discussion section by discussing spatial heterogeneity (patchiness).

6. We have added more detailed description of locations of pressure transducers and temperature sensors.

7. We have added a statement about the cross-sectional head gradients in the sub-reach 5.

8. The stream inflow temperature and an air temperature have been added to Figure 10.

Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream

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Abstract

Beaver dams affect hydrologic processes, channel complexity, and stream temperature by inundating riparian areas and influencing groundwater-surface water interactions. We explored the impacts of beaver dams on hydrologic and temperature regimes at different spatial and temporal scales within a mountain stream in northern Utah over a three-year period spanning pre- and post-beaver colonization. Using continuous stream discharge, stream temperature, synoptic tracer experiments, and groundwater elevation measurements we documented pre-beaver conditions in the first year of the study. In the second year, we captured the initial effects of three beaver dams, while the third year included the effects of ten dams. After beaver colonization, reach scale discharge observations showed a shift from slightly losing to gaining. However, at the smaller sub-reach scale, the discharge gains and losses increased in variability due to more complex flow pathways with beaver dams forcing overland flow, increasing surface and subsurface storage, and increasing groundwater elevations. At the reach scale, temperatures were found to increase by 0.38°C (3.8%), which in part is explained by a 230% increase in mean reach residence time. At the smallest, beaver dam scale, there were notable increases in the thermal heterogeneity where warmer and cooler niches were created. Through the quantification of hydrologic and thermal changes at different spatial and temporal scales, we document increased variability during post-beaver colonization and highlight the need to understand the impacts of beaver dams on stream ecosystems and their potential role in stream restoration.

Keywords: beaver dams, Castor canadensis, stream discharge, stream temperature, stream restoration

1. Introduction

Beaver dams create ponds that change surface water elevations, alter channel morphology, and decrease flow velocities (Gurnell, 1998; Meentemeyer and Butler, 1999; Pollock et al., 2007; Rosell et al., 2005). These ponds and the overflow side channels are forced by high dam crest elevations and generally increase water storage, water residence time, and depositional areas for sediments. The increased storage attenuates hydrographs (Gurnell, 1998) and can increase base flow (Nyssen et al., 2011). Specifically in the beaver ponds, water infiltration through the bed and adjacent banks influences local groundwater elevations (Hill and Duval, 2009). Within the stream channel, beaver dams break up the average hydraulic gradient into series of disrupted head drops and flat ponded sections. This change in average hydraulic gradient increases the potential for hyporheic exchange (Lautz and Siegel, 2006). Such changes in channel morphology and hydrology alter stream temperature regimes. Warming due to solar radiation can be a key factor due to increased water surface area (Cook, 1940). Further, foraging and extensive inundation can lead to loss of riparian vegetation that decreases riparian canopy and the associated shading influences (Beschta et al., 1987). Changes in groundwater-surface water interactions can also impact the overall temperature regime (e.g., upwelling zones decrease temperatures below beaver dams (Fanelli and Lautz, 2008; White, 1990)). Regardless of this implied connection between hydrologic and stream temperature changes due to beaver dam construction, most studies have investigated these changes separately. Furthermore, the temporal and spatial scales considered within individual studies vary widely, leading to inconsistent conclusions regarding beaver dam impacts on stream systems (Kemp et al., 2012).

When considering hydrologic influences at the beaver dam scale (which includes the beaver dam structure, the upstream ponded area, and the section below the dam), Briggs et al. (2012) found a connection between streambed morphologies formed upstream of a beaver pond and the hyporheic flow patterns. Similarly, Lautz and Siegel (2006) showed that beaver dams promoted higher infiltration of surface water into the subsurface. Janzen and Westbrook (2011) found enhanced vertical recharge between stream and underlying aquifer upstream of the dams. They also found that the hyporheic flowpaths surrounding beaver dams were longer than expected. Nyssen et al. (2011) studied impacts of beaver dams at a larger reach scale and throughout a series of beaver dams. Similar to other literature (Gurnell, 1998; Burns and McDonnell, 1998), they found that a series of beaver dams retained water during high flows and increased low flows through drier periods. The authors found that the recurrence interval for major floods increased over 20 years and peak flows were decreased and delayed by approximately a day. In contrast, some argue that while beaver dams affect downstream delivery, they provide minimal retention during extreme runoff events (Burns and McDonnell, 1998).

The documented impacts of beaver dams on temperature are more variable. Some studies found that beaver dams and beaver ponds cause overall increases in downstream temperatures (Andersen, 2011; Margolis et al., 2001; Salyer, 1935; McRae and Edwards, 1994; Shetter and Whalls, 1955) with reported values as high as 9^{o}C during summer months (Margolis et al., 2001). Fuller and Peckarsky (2011) also observed increases in temperatures below low-head beaver dams, but a cooling effect below high-head beaver dams. At the longer reach scale (22 km), Talabere (2002) found no significant influence of beaver dams on stream temperature. A recent literature review regarding the impacts of beaver dams on fish further summarizes such inconsistent findings. Kemp et al. (2012) cited 13 articles that argued beaver dams provided thermal refugia and 11 articles that argued negative impacts from altered thermal regime (i.e., detrimental increases in summer temperatures). Interestingly, this review also pointed out that of the 13 articles claiming temperature benefits of beaver dams, only seven were data driven and the remaining six were speculative. By contrast, of the 11 articles showing temperature impairments, only one was data driven while the rest were speculative. Another recent literature review regarding the effects of beaver activity in stream restoration and management further revealed that a majority of studies cover small spatial scale areas (e.g., small reach scales), are mainly qualitative, and many hypotheses are supported only by anecdotal or speculative information (Gibson and Olden, 2014). Particularly in the context of stream management, where beaver have recently been considered as a potential restoration tool (e.g., Utah Beaver Management Plan), a more quantitative understanding based on field observations of the hydrologic and thermal impacts of beaver within stream systems is critical.

Variability in hydrologic and thermal responses in streams with beaver dams and the subsequent inconsistent conclusions found in the literature highlight the need for more data driven studies across multiple spatial and temporal scales. In an effort to link hydrologic and temperature responses due to beaver dam development, we present data from different spatial (reach, sub-reach, and beaver dam) and temporal scales (instantaneous to continuous three-year time series) that span a period prior to and during the establishment of 10 beaver dams. We illustrate how the development of beaver dams shifts instream hydrologic and thermal responses. More specifically, a losing reach (pre-beaver) was transformed to a gaining reach (post-beaver) while simultaneously increasing stream temperatures.

Site Description

Curtis Creek, a tributary of the Blacksmith Fork River of Northern Utah drains a portion of the Bear River Range. Curtis Creek is a first-order perennial mountain stream with intermittent tributaries. The mountainous watershed includes a combination of hard sedimentary rock, Paleozoic and Precambrian limestone bedrock that is strongly indurated. The valley broadens in the lower portion of Curtis Creek and is primarily dominated by remnant low-angle alluvial fans. The valley bottom is comprised of a mix of longitudinally stepped floodplain surfaces and channel that are both partly confined by coarse-grained alluvial fan deposits with gravel, cobble, boulders and some soil development. These stepped floodplains are infrequently inundated by the modest spring-snowmelt flow regime, and reflect surfaces created by relic beaver ponds and beaver dam flooding.

Data were gathered in a 750 m long study site on the lower portion of Curtis Creek that is located about 25 km east of Hyrum, Utah at Hardware Ranch (an elk refuge operated by the Utah Division of Wildlife Resources (UDWR)). In 2001, the UDWR conducted a stream relocation project within the study reach and some segments of the channel were moved and reconstructed, leaving portions of the original channel abandoned. The study reach has a relatively steep streambed slope of 0.035, supporting a bed of coarse gravel to large cobble with some man-made boulder vortex weirs placed within the new channel with a meandering planform. The banks of the realigned channel were stabilized with boulders, root wads, logs, and erosion control blankets.

The riparian area surrounding the channel prior to and following relocation was heavily grazed by elk and did not support woody riparian vegetation. Roughly around 2005, grazing pressure was lessened and the area was fenced (though some grazing was still allowed). This facilitated some modest recovery of the riparian woody vegetation which was enough to attract beaver. In early summer of 2009, beaver colonization began with beaver dam 7 being constructed in the middle of the study reach (Fig. 1). Beaver dams 4 and 5 were also completed during the summer of 2009. New beaver dams (3 and 8) were established early-summer 2010 and by the late summer-early fall, dams 2, 6, 9, and 10 were completed. By the end of fall 2010, beaver dam 1 was built at the upstream end of the study reach resulting in a total of 10 beaver dams with an average height of 1 m (measured at the downstream face of a dam as the difference between the channel bottom and the top of the dam crest). In addition, two small (less than 0.5 m in height) beaver dams were constructed in the old channel (Fig. 1, dams without numbers). Beaver built seven of their dams using the artificial restoration structures as foundations. By the end of fall 2010, the channel consisted of sections with flowing water (main channel and side channels), ponded water (beaver ponds), and beaver dam structures (Fig. 1). The resulting dam density by 2010 was 13.3 dams/km.

2. Methods

The field site was originally instrumented with pressure transducers, temperature sensors, and groundwater observation wells to investigate groundwater-surface water interactions in the absence of beaver. After one year of data collection, beaver colonization occurred within the study reach, changing the objectives of the study. In short, it produced the perfect accidental experiment and a unique opportunity to quantify fundamental hydrologic and thermal impacts of beaver dam construction on stream systems. In an effort to specifically investigate these impacts, three primary data types were collected over a three-year period spanning pre- and post-beaver colonization (Table 1, Fig. 1). Flow information was collected at the reach and sub-reach scale to compare influences of individual beaver dams and cumulative impacts. In addition, groundwater levels were observed within the floodplain of the study reach. To explore the corresponding impacts of dams on thermal regimes, stream temperature data were collected and analyzed at the reach, sub-reach and beaver dam scales. Both the hydrologic and temperature data collection took place over different temporal scales and the frequency varied from instantaneous measurements to continuous data throughout the three-year period.

2.1 Data Collection

The study reach boundaries were set following a previous study (Schmadel et al., 2010) and locations along the reach were denoted by distance downstream from an arbitrary datum set upstream of the study reach (Fig. 1). Water level and temperature were measured using KWK Technologies® SPXD™ 610 (0-5 psig) (Spokane, Washington) pressure transducers (PT) with vented cables and Campbell Scientific® CR-206 data loggers (Logan, Utah) at the upstream, inflow (PT515, Fig. 1) and downstream, outflow study reach limit (PT1252, Fig. 1). Both pressure transducers were installed in the flowing water close to the bank with an average bed slope of 0.017 and 0.024 for inflow (PT515) and outflow (PT1252), respectively. Water level and temperature were measured at 30-second intervals and five-minute averages were recorded. Discharges were measured at each PT under the full range of flow conditions using the velocity-area method to establish rating curves. The lowest flow measured was 157 L s^{-1} at PT1252 and the highest flow measured was 1510 L s^{-1} also at PT1252. The flow velocity was recorded with a Marsh McBirney Inc. ® Flo-Mate™ (Model 2000, Frederick, Maryland). To provide a local comparison of hydrologic responses due to beaver activity, continuous discharge data were similarly collected at the bounds of a control reach approximately 535 m long without any beaver activity located immediately upstream from our study reach (PT0).

The study reach was further divided into six sub-reaches, ranging from 56 to 168 m and numbered sequentially downstream (Fig. 1). The six sub-reaches spanned individual dams (e.g., sub-reach 4), multiple dams (e.g., sub-reach 2 and 5), and a non-impounded sub-reach that received surface return flows via small side channels or overland flow from an upstream beaver pond (sub-reach 3). The boundaries for the sub-reaches were chosen to ensure completely mixed conditions necessary for dilution gaging (Schmadel et al., 2010). Dilution gaging was conducted at the sub-reach scale on July 16, 2008 (pre-beaver) and July 19, 2010 (post-beaver) to provide a longitudinal understanding of flow variability. As described within Schmadel et al. (2010, 2014), chloride (from NaCl) was used as a conservative tracer (Zellweger, 1994) and rhodamine WT was used as a visual indicator for a qualitative assessment of mixing. Tracer injection masses ranged from 600 to 3300 g as NaCl and were varied to achieve large enough responses in electrical conductivity above background for dilution gauging and mass recovery purposes. Tracer responses were measured following an instantaneous tracer injection starting at the downstream end of the study reach and then moving upstream to individual sub-reach limits. Each response was measured with specific conductance (SC) (electrical conductivity normalized to 25 °C as a surrogate to chloride concentrations) at one-second intervals using YSI® sondes (models 600 LS and 600 XLM, Yellow Springs, Ohio) calibrated in the field. The background SC was corrected to zero (Gooseff and McGlynn, 2005; Payn et al., 2009) and each corrected response was correlated to chloride concentrations with calibration regressions. To estimate tracer mass losses and gross stream losses, mass recoveries were quantified using (Payn et al., 2009):

$$M_R = Q_D \int C_D(t)\,dt \tag{1}$$

To capture changes in groundwater levels throughout the reach, groundwater observation wells were installed in June 2008 (Fig. 1). These wells were constructed from half inch polyvinyl chloride (PVC), 2 m in length with 40 cm of perforation covered with 2 mm flexible nylon screen to exclude soil. Elevations were established for individual wells using a total station and later using differential rtkGPS (Trimble® R8, Global Navigation Satellite System, Dayton, Ohio). Groundwater levels were determined by measuring the distance from the top of each well to the groundwater surface level in each well using a Solinst® electronic well sounder (Model 101 Mini, Georgetown, Ontario, Canada). The groundwater levels were measured four times in 2008 (June, July (twice), August), five times in 2009 (June, July, August (twice), and November), and four times in 2011 (April, June, July, and November).

At the finer beaver dam scale, temperature measurements were collected upstream of ponded water of beaver dams and downstream of individual beaver dams at 10-minute intervals using Onset® HOBO® Temp Pro V2 (Bourne, Massachusetts) deployed from September 2 to October 15, 2010 (Fig. 1, Table 1, Table 2). The temperature sensors were placed in the thalweg of the flowing channel entering the pond to ensure well mixed flow. The sensors downstream from the beaver dams were placed downstream of the scour pool, but in the completely mixed portion of the channel. The temperature sensors were attached to metal stakes, placed in the middle of the channel, approximately halfway through the water column. Individual sensors were wrapped in aluminum foil to reduce solar radiation influence in slower moving waters.

Aerial imagery was used to delineate and compare pre- and post-beaver colonization flowing and ponded water area. Pre-beaver colonization conditions (2006) were captured with high resolution aerial imagery available through the Utah Automated Geographic Reference Center (AGRC). Post colonization, NIR (Near Infrared) and RGB (Red-Green-Blue) aerial imagery were collected using Aggie Air UAVs (Unmanned Aerial Vehicle) in 2010. Aggie Air flights that additionally included thermal aerial images were completed in 2011-2013.

2.2 Data Analysis

At the reach scale, the five-minute continuous stage and temperature data recorded at the study reach boundaries were averaged to daily values to illustrate changes over the three-year study period. Data from the winter months were excluded from the analysis because they were influenced by ice buildup around the pressure transducers. Rating curves were developed from the measured discharges and continuous stage from PTs in the form (Cey et al., 1998; Rantz, 1982):

$$Q = aZ^{b} \tag{2}$$

where Q is the predicted discharge (L s^{-1}), a and b are the regression parameters, and Z is the stage measured by the pressure transducer (m). The regression parameters, a and b, were estimated through nonlinear regression and were the minimum sum of squares occurred. Uncertainty in these parameters was assessed from values within the 95% joint confidence region (Schmadel et al., 2010). The continuous discharge estimates provided continuous estimates of net change in stream discharge (ΔQ) at the reach scale (downstream discharge minus upstream discharge). To illustrate percent net change (%ΔQ), ΔQ was normalized by upstream discharge (Q at the upstream reach boundary). The error for the reach scale discharge was estimated directly from the rating curve where the 95% confidence interval was generated (Schmadel et al., 2010). The net change in stream temperature (ΔT, downstream temperature minus upstream temperature) and %ΔT were also calculated at the reach scale. To determine if weather conditions were influencing the water temperature differences between years, we first compared average daily air temperatures for each year through a one-way ANOVA (p=0.05). We then compared daily ΔT values normalized by air temperature for the days when both water and air temperature were available within each year (p= 0.01).

At the finer, sub-reach scale, stream discharge was calculated at each sub-reach limit from dilution gaging using (Kilpatrick and Cobb, 1985):

$$Q = \frac{M}{\int_0^\tau \left(C(t) - C_b(t)\right)dt} = \frac{M}{\int_0^\tau C(t)dt} \tag{3}$$

where Q is the stream discharge (L s^{-1}), M is the mass of solute tracer injected (mg), $C(t)$ is the tracer concentration (mg L^{-1}), $C_b(t)$ is the background tracer concentration (corrected to zero) (mg L^{-1}), t is time (s), and τ is the measurement time period from tracer injection to last detection (s). The net ΔQ was also estimated at the limits of each sub-reach (Fig. 1). The net ΔQ for each sub-reach was again normalized by the discharge at the corresponding upstream sub-reach limit resulting in a net $\%\Delta Q$ to allow for direct comparison between sub-reaches. Uncertainty in the estimates was quantified using the same technique presented in Schmadel et al. (2010) and provided the 95% prediction interval around the discharge estimate. Tracer mass recovery through each sub-reach was calculated to provide information regarding flow diversions within and possible returns to some sub-reaches. In addition, mean residence times (μ_t) for individual sub-reaches were estimated from the first temporal moment or expected value of each recovered tracer response as:

$$\mu_t = \frac{\int_0^\tau tC_D(t)dt}{\int_0^\tau C_D(t)dt} \tag{4}$$

where $C_D(t)$ is the recovered tracer response at the downstream sub-reach limit (mg L^{-1}).

To further understand hydrologic impacts of beaver dam construction and to illustrate the channel and groundwater elevation gradient changes over time, these data were grouped by each sub-reach and were evaluated for 2008, 2009, and 2011. The groundwater elevation data collected in 2010 were limited and thus post-beaver colonization period was represented by the 2011 data. Due to the established groundwater observation wells not being distributed evenly throughout the study reach, changes in groundwater over the study period are only available for sub-reaches 2, 3, and 5.

The temperature impacts at the beaver dam scale were quantified from the data collected upstream of ponded waters and downstream of individual beaver dams (3, 4, 5, 7, and 8) from fall 2010 (Fig. 1 and Table 2). In case of beaver dam 7 and 8, the ponded water from beaver dam 8 extended to beaver dam 7. Therefore, we used data upstream from dam 7 and downstream from dam 8. A 24-hour moving average was calculated from the data to detect temporal trends other than diurnal patterns. The net temperature change, ΔT, for each individual beaver dam was calculated by subtracting the temperature upstream of the beaver dam from the temperature downstream of the beaver dam. A positive change represented net warming, while a negative change represented net cooling downstream from the beaver dams. The area of flowing water (represented by the stream channel) and ponded water from the beaver dams was digitized and calculated from the 2006 (pre-beaver conditions) and 2010 (post-beaver colonization conditions) imagery (Table 3). The main channel water volume for pre- and post-beaver dams were also estimated based on one-dimensional HEC-RAS hydraulic model built to replicate the two different states (Table 3).

3. Results

3.1 Reach Scale Responses

At the reach scale, the average daily discharge (Fig. 2) illustrates the seasonal variations and changes in flow conditions at the inflow (PT515) and outflow PT1252 for 2008 through 2010. The 2008 and 2009 flows were fairly comparable with peak flows at PT1252 of 1698 L s^{-1} and 1549 L s^{-1}, respectively. The 2010 flows were, however, one third of peak flow in comparison to previous years (592 L s^{-1} at PT1252). This difference is also illustrated with snow water equivalent and precipitation accumulation from nearby a SNOTEL site (SI Fig. 1). The impacts of beaver dam building activities are directly reflected in the reach scale flow conditions and in the year-to-year variability in net ΔQ and $\%\Delta Q$ (Fig. 3). Negative changes indicate a net losing reach while positive values indicate net gains in flow. The daily average value for March-October of 2008 (pre-beaver) was -5.6 L s^{-1} for ΔQ and -4.4% for $\%\Delta Q$. As the beaver dams were built and increased in number, the average values of ΔQ and $\%\Delta Q$ increased to 51.2 L s^{-1} and 13.2% in 2009 and to 81.2 L s^{-1} and 53.1% in 2010, respectively.

Across shorter temporal scales, variability within each season of each year was also apparent. Even though data are only available for short portion of the spring period in 2008, the reach was gaining. In July 2008, the $\%\Delta Q$ became negative suggesting that the reach was losing after the spring flood recession. In early spring of 2009, the reach shifted from losing to gaining. However, the reach did not switch back to losing conditions during lower flows and gains were approximately 10% during the months of June, July, and August. In September 2009, the $\%\Delta Q$ further increased to 30% over one week and was followed by a slow decrease of approximately 20% the following two weeks before increasing again. Similar gaining conditions continued throughout 2009 and into 2010. In 2010, another increase in $\%\Delta Q$ was observed in April at the beginning of snowmelt and reached up to 60%. The greatest $\%\Delta Q$ occurred at the end of June 2010 reaching approximately 80% (Fig. 3). This drastic change may be partially affected by irrigation patterns in nearby fields during the summer months (mid-May through July).

At the reach scale, stream temperatures consistently increased during the summer with peaks occurring at the end of July and beginning of August with some periods of cooling within the reach in the fall and winter for all three years (Fig. 4). Net and percent changes in temperature (ΔT and $\%\Delta T$) show a warming trend from 2008 to 2010 corresponding to the increase in the number of dams (Fig. 5). In 2008, the average daily ΔT was 0.22°C and in 2010 the average ΔT was 0.43°C. The average increase from 2008 to 2010, with differences based on the daily ΔT (not on their yearly averages), was 0.38°C ($\%\Delta T = 3.8\%$). The maximum difference in ΔT between these years was 0.77°C ($\%\Delta T = 8.5\%$) and occurred on August 1st (Fig. 5).

The one-way ANOVA for air temperature comparison showed no statistical difference between individual years ($p > 0.05$). Further comparison of daily ΔT values normalized by air temperature showed a significant difference in the daily average values ($p < 0.01$) between years. This suggests that the between year variability in air temperature is not controlling the observed ΔT patterns.

Reach scale data from a smaller temporal scale (a five-day period in July) illustrates the links between discharge and temperature patterns associated with beaver dam construction (Fig. 6). Comparison of ΔQ and $\%\Delta Q$ show similar trends to those in Fig. 3 (i.e., an increase in the amount of water gained over the reach each year), but with diurnal patterns. The $\%\Delta Q$ for 2010 shows approximate 80% increase in discharge when compared to 2008 (Fig. 6B). The transformation from losing in 2008 to gaining in 2010 is also more pronounced at this shorter five-day scale. Similarly, when comparing ΔT and $\%\Delta T$ values there is an average increase of 0.6 °C and 4.6% from 2008 to 2010, respectively. The data also contain a diurnal pattern with a maximum difference of 1.1^{o}C (8%) between 2008 and 2010 (Fig. 6C-D). The ΔT values show that the range of temperature differences during the day doubled in 2010. In 2008, the flowing water surface area was estimated to be 1776 m^2 with no ponded area (Fig. 1, Table 3). In 2010, the flowing water surface area decreased to 1211 m^2 with the ponded area covering about 2830 m^2. The water surface area in 2010 had more than doubled.

3.2 Sub-reach Scale Responses

With an increase in the number of beaver dams for each consecutive year, the groundwater elevation increased in sub-reaches as shown by the changes in the annual distribution and median values (Fig. 7, Fig. SI2). The response was greatest for sub-reach 2, where median groundwater levels increased approximately 0.03 m during the first year (2008-2009) and by another 0.34 m from 2009 to 2011. For sub-reaches 3 and 5, median groundwater levels increased by 0.02 m and 0.12 m from 2008 to 2009, respectively. From 2009 to 2011, these levels increased further by 0.10 m in sub-reach 3 and by 0.15 m in sub-reach 5. Based on the positive head gradient between groundwater and surface water, sub-reach 2 and sub-reach 3 is primarily gaining. However, sub-reach 5 is generally neutral in 2008 and is more commonly losing in surface water in 2009 and 2010 (Fig. 7, SI Fig. 2). The head gradients from the cross-section of wells in sub-reach 5 show an increase in groundwater elevation over time and generally depict a positive gradient on one side of the channel and negative gradient on the other (SI Fig. 2).

Groundwater-surface water exchanges in the study reach prior to beaver dam influences were documented in Schmadel et al. (2014). Discharge estimated at various locations longitudinally illustrates the variability in flows prior to beaver dam influences (Fig. 8A) and the sub-reach scale $\%\Delta Q$ showed some sub-reaches gaining while others losing (Fig. 8B). The 2010 discharge values showed greater variability after beaver dams were constructed in the reach (Fig. 8A). In contrast with the yearly average head gradient (Fig. 7), the net $\%\Delta Q$ in sub-reach 2 shows a transition from gaining in 2008 to losing in 2010, sub-reach 3 from neutral to gaining, and sub-reach 5 from neutral to losing in 2010 (Fig. 8B). In 2008, the error in flow estimates for the individual sub-reaches was about 8% for both Q and $\%\Delta Q$. In 2010, the errors ranged from

6% to 28% for Q and 8% to 29% for %ΔQ. Most of the error was due to incomplete tracer mixing and larger errors in 2010 were attributed to higher variability in flow and flow paths. The mass recoveries showed that the percent of mass loss changed significantly from 2008 to 2010. In 2008, the mean percent mass losses for individual sub-reaches were sequentially -2.8, -12.9, -18.1, -18.8, and -4.7%. In 2010, the mean percent mass losses were -69.0, -0.2, -8.3, -62.0, -7.6% for the same sub-reaches.

Mean residence times estimated from the 2008 and 2010 tracer studies show an increase for all sub-reaches containing beaver dams (Table 4). The biggest change was observed in sub-reach 2 where beaver dam 4, with the largest pond area, was located (Fig. 1). The second greatest increase occurred in sub-reach 5 where a series of dams and ponds covered approximately 50% of the sub-reach length. The increase in sub-reach scale residence times translates into an overall reach scale increase of 62 minutes or 230%. The residence time of unrecovered mass was not included in mean residence time estimates.

3.3 Beaver Dam Scale Responses

The spatial and temporal temperature differences observed between individual beaver dams from a two-day period show that each dam influences the system differently throughout each day (Fig. 9). A comparison of absolute temperatures above and below individual beaver dams, where a positive change represents net warming and negative change represents net cooling below the beaver dam, illustrates a general downstream warming trend which cumulatively propagated downstream below beaver dam 8 (SI Fig. 3). Although, the temperature increase for each dam was generally within the accuracy of the temperature sensor (+/- 0.2^{o}C), the cumulative impact of multiple dams showed more significant downstream warming.

Based on the data shown within Fig. 9, daily ranges (daily maximum minus daily minimum values) of temperature differences below and above each beaver dam (ΔT) provide additional information regarding the spatial variability among individual dams within each day (Fig. 10A). However, when looking at 24-hour moving averages (Fig. 10B), ΔT values fall within the accuracy of the sensors and highlight the importance of the temporal scale (frequency) of measurements when determining the impacts of beaver dams on stream systems.

4. Discussion

While many studies exist regarding the influence of beaver dams on the local hydrologic and temperature regimes, the majority of these studies lack sufficient field measurements across appropriate spatial (beaver dam to reach scale) and temporal scales (instantaneous to continuous over a period of years) to draw meaningful conclusions (Kemp et al., 2012; Gibson and Olden, 2014). Furthermore, the results are often inappropriately generalized beyond the scales of the observations. Our observations provide an opportunity to quantify the influences of beaver dams on stream flow and temperatures while demonstrating how beaver dams impact stream hydrologic and temperature regimes at different spatial and temporal scales.

The reach scale results of our study suggest an overall increase in Δ*Q* from 2008 to 2010 based on changes in flow conditions due to beaver dam building activity (Fig. 2). The increases in gains during the spring can be attributed to surface and subsurface lateral inflows. However, the impacts of the beaver dams are more apparent during low flow conditions when the study reach slowly transitions from losing in 2008 to gaining in 2010 (Fig. 3). As the number of beaver dams increases, the impact on reach scale discharge is more evident. In summer and fall of 2008, the reach is in equilibrium or slightly losing water. In contrast, the reach is gaining water during these same summer and fall months of 2009. This trend continues and is more pronounced as beaver dams continue being built and the cumulative impact of multiple beaver dams results in constant gains in 2010 (Fig. 3B). While the discharge in 2010 could have been influenced by irrigation practices in the nearby field, irrigation usually occurs only from mid-May to mid- or late-July and therefore, only had a potential impact during this time. However, due to drier conditions in 2010 and water right requirements, irrigation stopped earlier than usual (likely early July). This suggests that the dominant hydrologic processes influencing the study reach changed over the period of three years as the trend of gaining conditions persisted past the irrigation season (Fig. 3). Groundwater elevations further illustrate the relative changes in relation to channel surface water elevations over time. Although, there is a potential for different flow paths in our study reach and head gradients do not necessarily translate into fluxes, there were notable increases in the groundwater table (Fig. 7). These changes were likely due to increased water surface elevations in the beaver ponds for consecutive years. The localized increases in groundwater elevations are further elevated each spring due to high flows, inundation of the flood plain, and general high surface water elevations throughout the reach. As the flow and surface water elevations drop throughout each summer, there are positive groundwater gradients towards the stream throughout this season and, therefore, the reach gains water. To provide a comparison, we can use baseline Δ*Q* and %Δ*Q* from the control reach just upstream for the same three-year period (Table 3). These data show that the control reach was losing water for all three years except for summer of 2008. In contrast to the beaver impacted study reach, the losing trend in the control reach is more pronounced with each year and it is at its maximum in 2010.

When considering the smaller spatial scales (sub-reach, beaver dam) there is great variability in terms of losses and gains that are not fully understood from the reach scale observations in the study reach with beaver dams (Fig. 7 and 8, Table 4). This variability is due to many different mechanisms occurring in and around beaver dams, including groundwater-surface water exchanges (Lautz and Siegel, 2006; Janzen and Westbrook, 2011). However, the sub-reach scale variability in this study (Fig. 8) was primarily due to high crest dams forcing year round overbank flow. Much of the overbank flow was either returned to the main channel through side channels or was diverted to the off-channel beaver ponds. These changes in flowpaths influenced the mass recovery in our tracer study in 2010 and the highest mass loss occurred in sub-reaches with big beaver dams and multiple side channels. The window of detection for the tracer experiment (i.e., the time over which the tracer is measurable) varies as a function of stream characteristics such as transient storage zone dimensions and exchange rates, and stream velocity and discharge (Harvey et al., 2000). In turn, it dictates which subsurface exchange flow paths are captured within tracer break through curves (e.g., Ward et al., 2013). Because the changes to the study reach between years influenced the window of detection and the reported mass recoveries, our conclusions are primarily based on the net changes to flow (%ΔQ) that are less sensitive to a changing window of detection.

The dynamic activity of beaver, through construction and maintenance of dams, and natural seasonal changes in flow led to a diverse range of hydrologic responses resulting in the spatial and temporal variability of gains and losses through the study reach. The dilution gaging results show that at the two points in time we sampled, sub-reach 2 transitioned from gaining to losing (Fig. 8). However, if groundwater and channel surface water elevation data are aggregated over a year, the same reach was shown to be dominantly gaining over the study period (Fig. 7). These differing results from dilution gaging and groundwater levels highlight the importance of temporal scales and repeated measurements considered in this present work. They also indicate that without this consideration, the differences between measurement techniques can lead to contradicting conclusions as discussed within Schmadel et al. (2014). It is also important to note that the positive head gradients on river left (in a downstream direction) shown in Figure SI 2 illustrate why sub-reach 5 is gaining water as shown in Figure 7. However, it is also likely losing water on river right. Sub-reach 6 is gaining water due to both the main and side channels meeting again (Fig.1, Fig. 8).

Our temperature results demonstrate the considerable spatial and temporal variability in stream temperature caused by beaver dams. We captured the warming effect at the reach scale over a period of three years (Fig. 4 and 5). However, the data at this scale do not portray the thermal heterogeneity illustrated by the beaver dam scale temperatures (Fig. 9 and 10). Similarly, the temporal scale is of importance when determining impacts of beaver dams. For example, the 5-minute temperature data captured temperature fluctuations during the day that may play an important role in fish habitat management and restoration (Fig. 6C-D). This daily variability would not be captured if only daily averages or instantaneous measurements were recorded. The lag times in peak temperatures from 2008 to 2010 (more apparent at shorter temporal scales (e.g., SI Fig. 4) are likely due to different flow conditions, air temperatures, solar radiation, precipitation, and channel morphology.

To understand the significance of simultaneously considering the spatial and temporal scale of measurements, Fig. 9-10 illustrate the temperature variability for five beaver dams while providing a comparison between the dams. Individual beaver dams introduce more variability than that observed at the reach scale with warming and/or cooling effects during different times of the day. These individual responses are likely due to the diverse beaver dam morphology, size of the beaver dam, and size of the beaver pond (Fuller and Peckarsky, 2011; McGraw, 1987). However, considering a longer temporal scale, the temperature variability associated with a 24-hour moving average falls within a measurement error (+/- 0.2°C) (Fig. 10B).

With the transition from a losing to gaining reach, one might expect a decrease in temperature during the summer due to the addition of colder groundwater. However, we observed increased warming over the study reach. Based on this expectation that a gaining reach should be cooling, it is important to discuss the different heat transfer mechanisms influencing instream temperature responses. It is well established that surface heat fluxes (shortwave radiation, incoming and outgoing longwave radiation, conduction/convection, and evaporation/condensation) and bed processes (bed conduction, groundwater/ hyporheic exchanges) are the primary factors dictating stream temperature responses (e.g. (Cardenas et al., 2014; Evans et al., 1998; Moore et al., 2005; Neilson et al., 2010a; Neilson et al., 2010b; Sinokrot and Stefan, 1993; Webb and Zhang, 1997; Westhoff et al., 2007; Younus et al., 2000). When considering the transition between pre and post-beaver colonization, the doubling of the channel surface area is critical because surface heat fluxes are scaled with the area (Neilson et al., 2010a). The influence of these fluxes on temperature is also dependent on the difference in the volume of water in the channel and the residence time within the study reach. Based on the observed temperature increases, the doubling of the surface area (Fig. 1, Table 3) and the tripling of the residence time (Table 4) negate the buffering effects of an almost quadrupled main channel water volume (Table 3) and the cooling effects associated with groundwater inflows. As found within other prior studies, the general downstream warming is due primarily to influences of solar radiation (Cook, 1940; Evans et al., 1998; Johnson, 2004; Webb and Zhang, 1997).

Regardless of the larger scale downstream trends, it is critical to consider smaller scale thermal heterogeneity. To illustrate the thermal heterogeneity and complexity of flow paths resulting from beaver colonization, a thermal image of surface stream temperature in May 2012 shows that temperatures range from 11^{o}C to 18^{o}C along the study reach (SI Fig. 5C). It is most important to note the difference in the temperature ranges in areas with and without beaver ponds. Such thermal heterogeneity is typically overlooked or averaged out when larger scale (e.g., reach scale) measurements are collected. From a stream restoration point of view, when beavers are used to restore riparian areas (Albert and Trimble, 2000; Barrett, 1999; Shields Jr. et al., 1995) and/or enhance fish habitat (Billman et al., 2013; Pollock et al., 2004), small spatial scales (e.g., sub-reach, beaver dam, and even microhabitat units) are key for understanding the influences on the aquatic ecosystem (e.g., Billman et al., 2013; Westbrook et al., 2011). Spatial heterogeneity (patchiness) and spatial patterns in heterogeneity change with spatial scale (Cooper et al., 1997). Since most of the ecological interactions in heterogeneous streams happen in conditions that are different from mean conditions, they cannot be captured with point measurements, or with models that focus on understanding average conditions (Brentall et al., 2003, Grünbaum, 2012). This highlights the need to concentrate on variables and processes that capture spatial patchiness at different spatial scales in stream ecosystems.

This study emphasizes the need to understand the variability in flow and temperatures at different spatial and temporal scales. Furthermore, these data begin to provide an explanation as to why the current literature provides inconsistent information regarding the influences of beaver colonization. Although it is difficult to make any generalizations about the hydrologic and thermal impacts of beaver dams (e.g., beaver dams increase temperature), we measured an increased variability in flow and temperature that have been qualitatively discussed in previous studies. Our quantification of the variability across different spatial and temporal scales provides a context for better interpreting the inconsistent information found in the literature. In a given locality or under specific circumstances, we contend that the patterns of increasing variability in flows and temperatures should create and maintain more heterogeneous habitat that has a greater probability of providing multiple niches and supporting greater biodiversity. We believe that this observed hydrologic and thermal variability is an important and more generalizable attribute of beaver dams. Variability in temperature, flow properties, and the associated increase in microhabitat complexity are often restoration goals. However, if beaver is being considered as a restoration tool (e.g., Utah Beaver Management Plan), the importance of further understanding and predicting their impacts on stream systems at different spatial and temporal scales is a necessity. Based on these findings, future efforts in understanding the impacts of beaver dams on hydrologic and temperature regimes should begin by identifying the spatial and temporal scales of data required to address specific questions and/or restoration goals. Ultimately, more quantitative field and modeling studies are needed to fully understand impacts of beaver on stream ecosystems for the potential use of beaver as a restoration tool.

5. Conclusion

This study quantifies the impacts of beaver on hydrologic and temperature regimes, and highlights the importance of understanding the spatial and temporal scales of those impacts. Based on the flow and temperature data collected over period of pre- and post-beaver colonization, we found a general increase in stream discharge and stream temperatures at the reach scale. The reach transitioned from slightly losing in 2008 (pre-beaver colonization period) to gaining in 2010 (post-beaver, second year into beaver colonization). Similarly, we observed a downstream warming effect over the 3-year study period. We found that the reach scale hydrologic and temperature changes do not reflect the variability captured at smaller sub-reach and beaver dam scales. For example, temperature measurements at finer temporal scales (5- to 10-minute records throughout each day) revealed significant within-day variability at smaller spatial scales that was not captured at the reach scale. Our most important and likely transferable findings are with regards to the increase in hydrologic and thermal variability that beaver dams produce. We captured natural variability of hydrologic and thermal processes at the sub-reach scale prior to beaver dam influences and show how this variability increased after beaver colonization. While some sub-reaches showed gaining trends from 2008 to 2010, some began losing due to flow being rerouted by dam construction. In addition, daily stream temperature variability increased from 2008 to 2010. Furthermore, these data illustrate the influence of individual beaver dams that can cumulatively contribute to the downstream warming and/or cooling. Such hydrologic and temperature variability would be lost if only reach scale measurements were collected. In the context of ecosystem impacts and potentially using beaver as a restoration tool, where habitat heterogeneity and increased system resilience is achieved through higher rates of biodiversity, we argue that quantifying the range and increase in variability may be far more important than measuring a minor and often inconsistent change in mean conditions.

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Table 1.

	Temporal Scale		Spatial Scale		
	Measurement Type	Measurement Time	Reach	Sub-reach	Beaver Dam
Discharge	Instantaneous	2008*		X	
		2010*		X	
	Continuous	2008-2010	X		
Temperature	Instantaneous	2008		X	
		2010		X	
	Continuous	Sept-Oct 2010			X
		2008-2010	X		
Ground Water Levels	Instantaneous	2008	X	X	
		2009	X	X	
		2011	X	X	

*Based on flows calculated from dilution gaging

Table 2.

Distance From Beaver Dam (m)			Description (for period September 2 to October 15)
Beaver Dam	Temperature Sensor Upstream	Temperature Sensor Downstream	
3	15	9	Upstream sensor was initially in the flowing water near the transition to the ponded area, later in slowly flowing water, downstream sensor is at the boundary of flowing water and ponded water from BD4
4	60	49	Upstream sensor is same as BD3 downstream, downstream sensor is in a flowing well mixed portion of the channel
5	81	21	Upstream sensor is in flowing water near the transition to the ponded area, downstream sensor is same as BD7 above
7	47	9	Upstream sensor is in flowing water near the transition to the ponded area, downstream sensor is same as BD8 above
8	8	6	Upstream sensor is in flowing water near the transition to the ponded area, downstream sensor is in flowing well mixed portion of the channel

Table 3.

		2008	2009	2010
Study Reach (with beaver dams)	ΔQ (L s^{-1})	-5.60	51.20	81.20
	%ΔQ	-4.40	13.20	53.10
	ΔT (°C)	0.22	0.17	0.43
	%ΔT	2.10	1.10	4.40
	Flowing Water Area (m^2)	1776	-	1211
	Ponded Water Area (m^2)	0	-	2830
	Water Volume (m^3)	636 *	-	2449 *
Control Reach (no beaver dams)	ΔQ (L s^{-1})	-24.30	-55.90	-92.50
	%ΔQ	-7.70	-19.80	-42.50

* The water volume is an estimate from a one-dimensional model where pre- and post-beaver dams flow conditions were captured. The 2010 volume includes only main channel water without any side channels or off-channel beaver ponds.

Table 4.

			2008		2010
Sub-reach	Stream distance (m)	Stream length (m)	Mean residence time (min)	Beaver Dam	Mean residence time (min)
2	692 to 877	185	8	3, 4	36
3	877 to 995	118	4		5
4	995 to 1087	92	4.5	5	15
5	1087 to 1235	148	6.5	7, 8	29
6	1235 to 1291	56	4		4
Total (min)			27		89

Figure 1. Aerial image from 2006 (pre-beaver period) and beaver dams constructed between 2009 and 2010. The main beaver dams are numbered from 1 to 10 from upstream to downstream and the time of dam construction is noted in the table. The study reach was further divided into 6 sub-reaches. The spatial scales investigated are illustrated below the map. The most downstream beaver dam and beaver pond are located in the old channel but overlap in the Beaver Dam Scale schematic in this figure. The 2006 channel is outlined in black while flowing and ponded water area from 2010 are represented by different shades of blue.

Figure 2. Daily average discharge estimated from continuous pressure transducer records spanning 2008-2010 (A-C). The black dashed line represents upstream, inflow conditions at PT515 and the red solid line represents downstream, outflow conditions at PT1252. The individual 95% confidence intervals around discharge estimates are represented by grey shading. Note that the inflow bounds are very small and are therefore, not visible in the figure.

Figure 3. A) Change in discharge over the study reach calculated from daily average flows where ΔQ is the discharge at outflow (PT1252) minus the upstream discharge at inflow (PT515). Positive values represent increases in discharge and negative values represent decreases in discharge. B) $\%\Delta Q$ is the percent change relative to the discharge at inflow (PT515). The 95% confidence interval in three different shades of grey correspond with each individual year. Arrows represent time of individual beaver dam construction. Blue and red arrows correspond with year 2009 and 2010, respectively, while the arrow size is proportional to size of the dam.

Figure 4. Average daily temperature (absolute) representing reach scale responses at inflow (PT515, black dashed line) and outflow (PT1252, red solid line) during 2008 (A), 2009 (B), and 2010 (C). Average daily air temperature (D) and average daily solar radiation (E) show similar weather patterns for all three years.

Figure 5. A) Reach scale change in temperature (ΔT) calculated from temperatures at the reach outflow (PT1252) minus the temperature at the reach inflow (PT515). B) $\%\Delta T$ is the percent change relative to the temperature at the inflow location (PT515). Positive values represent warming throughout the reach and negative values represent cooling relative to the upstream inflow temperature at PT515. Arrows represent time of individual beaver dam construction. Blue and red arrows correspond with year 2009 and 2010, respectively, while the arrow size is proportional to size of the dam.

Figure 6. Change in discharge (Δ*Q*) and temperature (Δ*T*) over the study reach from 2008 to 2010. This five day period in July illustrates variability over shorter temporal scales. The %Δ*Q* and %Δ*T* are relative to the discharge and temperature at the upstream inflow location (PT515). The %Δ*Q* were averaged over a one hour interval, while the %Δ*T* represents 5-minute temperature values.

Figure 7. Groundwater elevations grouped by individual sub-reaches and shown with channel water surface elevations. The groundwater elevations were measured four times in 2008, five times in 2009, and four times in 2011. The water surface elevation in the channel represents the average yearly value for each sub-reach. There is a gradual increase in groundwater elevation and channel water surface elevation in all sub-reaches over the years.

Figure 8. Sub-reach stream discharge (*Q*) estimates for 2008 and 2010 representing longitudinal flow variability before and after beaver colonization. %Δ*Q* is calculated from flow at the end of the sub-reach minus the flow at the beginning of the sub-reach relative to the upstream value.

Figure 9. Spatial variability in stream temperature throughout individual beaver dams (BD). Temperature differences (Δ*T*) were calculated based on 10-minute temperature records from locations downstream and upstream of the beaver dam and pond. These data illustrate that there is a time lag between air temperature and stream temperature and that there can be measurable differences in temperatures at the beaver dam spatial scale that vary diurnally. It further shows the variability in temperature differences between the dams.

Figure 10. A) Daily range of temperature differences (Δ*T*) (downstream temperature minus upstream temperature) of each beaver dam (BD) based on 10-minute temperature records. Beaver dam 7 and 8 were considered to be one complex. The air temperature (blue line) and stream temperature at the inflow (PT515, black dashed line) illustrate the diurnal patterns. B) 24-hour moving average of Δ*T*.

Table 1. Discharge, temperature and ground water level observations made at different spatial and temporal scales throughout the study reach.

Table 2. Distance for temperature sensors located above and below individual beaver dams (BD) during September 2 to October 15, 2010 (Fig. 1).

Table 3. Annual change in flow (ΔQ) and annual percent net change ($\%\Delta Q$) for the study reach impacted by beaver dams (shown in Fig. 1) and for an adjacent, upstream control reach with no beaver dams present. Change in stream temperature (ΔT), percent change ($\%\Delta T$), and area of flowing water and ponded water area for the study reach impacted by beaver dams is listed as well. Change in flow and temperature and their percentages (ΔQ, $\%\Delta Q$, ΔT, $\%\Delta T$) were calculated as an average of daily Δ values for each year (Fig. 3 and Fig. 5).

Table 4. Sub-reach scale mean residence times for 2008 and 2010.