<u>Comments from Reviewer 2 and Authors' replies</u>

We thank Reviewer 2 for their helpful comments. The original comments are listed below, and our comments are provided in bold.

Comment 1: In my opinion, this is an incredibly well written and well presented paper that is a great addition to the stream temperature literature. Kurylyk et al present a series of equations that can be used to consider the impact of changes to shallow aquifer and groundwater temperature on stream temperatures, presenting many useful examples.

Reply to Comment 1: We appreciate the interest in this topic and hope that this will be a helpful contribution to the stream temperature community. We agree that the point of the paper was to (1) present equations for calculating groundwater warming and (2) show examples of how these equations can be applied.

I only have minor comments, but a few broader questions:

Comment 2: It seems as though snow or particularly cold weather makes some of these equations more useful or less useful in certain places. Are any of these solutions more or less suited to other places based on their physical setting, for instance warmer climates, complex aquifers, aquifers of variable materials, very deep/very shallow aquifers?

Reply to Comment 2: These are valid points. Generally speaking, snowpack does not limit the utility of the solutions (except perhaps Stallman's equation); however, surface temperature trends cannot be assumed to follow air temperature if snowpack evolution occurs. Thus in these cases, surface temperature changes should be obtained from air temperature changes using a land surface heat flux model. As we note in our comments to Reviewer 1, surface energy flux models are generally easy to use and require less expertise, data, and time to run than numerical subsurface heat transport models. Thus, the solutions are still useful, but an additional step is required.

Probably the most relevant concern addressed above is with regard to deep or shallow aquifers. Very shallow aquifers (e.g., depth < 3m) can be assumed to be in equilibrium with the land surface temperature, at least on a mean annual basis, and thus the solutions are not overly helpful. On the other hand, very deep aquifers (e.g., > 40 m) are influenced strongly by the geothermal gradient, and thus the solution forms presented in this paper may not be appropriate. These can be modified to include the geothermal gradient, but the solutions do become a bit more complex. Thermal heterogeneity likely plays a more minor role, as the variability in thermal properties is orders of magnitude less than that for hydraulic properties. These thermal properties can be averaged out as in Menberg et al. (2014, http://www.hydrol-earth-syst-sci.net/18/4453/2014/hess-18-4453-2014.pdf). The

equations are valid in warm and cold climates provided that the surface temperatures used to drive the solutions are reasonable. Complex flow regimes in aquifers may potentially invalidate some of the equation assumptions.

<u>Changes</u>: We will include a sentence in Section 3.5 that discusses the ideal depth range for which to apply these solutions. We will also include a statement regarding the averaging of thermal properties. We will also include a statement regarding complex flow regimes (e.g., fractured rock) in the limitations.

Comment 3: I found Table 1 to be very helpful. A second table that lists the variables a researcher would need to extract for each equation (beyond the obvious, air temperature, stream temperature, etc) would be very helpful. Data limitations may make some equations more or less useful in certain places. There is still a disconnect in my mind between the equations and the figures, and something to help that translation may be useful for readers.

Reply to Comment 3: We agree that such a table would be very helpful for researchers wishing to apply these equations.

<u>Changes</u>: This will be added to Section 3.5.

Comment 4: The subsurface is still relatively unmeasured, making some values needed for these equations difficult to estimate or measure (for instance, Darcy velocities for upward and downward movement). How would you propose researchers address these and other subsurface values?

Response to Comment 4: We agree with this to an extent. Certainly thermal diffusivities for different types of soils are generally reported in literature (e.g., Table 1). The two parameters having the most uncertainty are depth *z* and *U* (related to Darcy velocities). Recharge estimates can be obtained by using heat as a tracer, measured water table fluctuations, instruments such as lysimeters or previously published recharge maps (e.g., P12604, L3-6). However, sometimes none of these are available, and in this case, we recommend that a range of reasonable recharge rates are considered (e.g., 5 to 25 cm/yr) to generate an envelope of calculated groundwater warming (see Comment 5). The depth to the aquifer can be obtained from wells, geophysical surveys, or regional depth to groundwater map.

<u>Changes</u>: We will include more text in Section 3.5 to briefly list alternatives for obtaining groundwater recharge and will cite the recent text devoted to this topic (Healy, 2010). Also, we will explain approaches for estimating the depth to the groundwater table and advocate that a range of values be considered to generate an envelope of results.

Healy R.W. 2010. Estimating Groundwater Recharge, Cambridge University Press.

Comment 5: Given the inherent uncertainty within the subsurface, would an uncertainty framework (ranges of values) be a more acceptable approach as opposed to choosing just a single value? Is this a way to move beyond limitations regarding homogeneity?

Response to Comment 5: We agree that this is a good approach.

<u>Changes:</u> We will propose this in a revised version of this paper in section 3.5.

Minor comments:

Comment 6: Throughout: the authors use the term ‘For example’ quite liberally throughout the text! Consider revising. Many times it is used, the sentence could stand alone without it.

Response to Comment 6: We agree, and this will be removed in many locations.

Comment 7: P 12599: line 28: illustrate not illustrates and P 12600: line 11: indicate not indicates

Response to Comment 7: Thank you for noting these two typos.

<u>Changes</u>: They will be fixed in the revision.

Comment 8: P12600, Line 15-17: found this sentence a little confusing! Would rise approximately 90% of expected value? So, expected value would only overestimate by a small amount?

Response to Comment 8: We agree that this was worded confusingly. The point is that the groundwater warms 90% of the surface warming over this period, not 90% of the expected groundwater warming. Note that the accuracy of assuming that the magnitude of the groundwater warming equals the magnitude of the land surface warming will increase over time because the thermal sensitivity begins to approach 1 (see Figs. 8c and 8d). However, this assumption may be very unrealistic for the first few decades depending on the depth, thermal properties, etc.

<u>Changes</u>: We will remove the word ‘expected’ to clarify this sentence.

Comment 9: p. 12601: line 6: You get at this a little bit later, but I think it might be helpful to define the concept of ‘short term’ here. I think that what you think of as short term is very different than what the average person thinks of as short term!

Response to Comment 9: We agree and will insert a parenthetical statement here (e.g., weeks, months, or even years) to indicate what we mean by short term.

Comment 10: p. 12601: lines 11:14: Feels like this is missing a word: maybe, changes to the thermal sensitivities will still be significant?

Response to Comment 10: We will modify this to 'groundwater warming at depths > 10 m may still be significant…'.