Dear Dr. Wood:

We very much appreciate the detailed and helpful comments from both reviewers as well as your summary report. We have extensively revised the paper based on these comments, and believe that the revised version is a significant improvement on the original *HESSD* paper. Most of the changes have been concentrated in the introduction, discussion, and conclusions.

We have separated the original reviews into distinct, enumerated comments to facilitate our replies. The reviewer comments are listed below, and our comments (including changes to the text) are provided in bold. Unless otherwise noted, all citations refer to papers referenced in our *HESSD* paper. Due to the number of changes made, the page numbering herein refers to the tracked changes version of manuscript (i.e. the manuscript included at the end of this document).

Sincerely,

Barret Kurylyk, Kerry MacQuarrie, Daniel Caissie, and Jeffrey McKenzie

<u>Comments from Editor and Authors' replies</u>

Comment 1: Both Reviewers make useful comments, and your responses generally address them well. However, underlying reviewer #1's concerns are some points that perhaps did not come out clearly in the review and reply. I will outline these in more detail separately.

Response to Comment 1: Thank you for highlighting these additional points where there was a lack of clarity in our original public response. We have revised several of our original comments and also reply to your specific concerns on a point by point basis below.

Non-public comments to the Author:
Comment 2: As noted by Reviewer #1, and discussed in your response, please ensure that you clearly distinguish the focus of this paper from the other two (also with lead author Kurylyk) that have recently appeared.

Response to Comment 2: We have inserted new paragraphs/sentences into the introduction and conclusions that places this paper in the context of the two previous papers noted by Reviewer 1 (P24,1-10; P50, L18-P25). We acknowledge the contribution of the previous papers but also establish the novelty and importance of the present study.

Comment 3: Some of the sentences in this manuscript lean more towards using the analytical solution to demonstrate how warming air temperatures will affect groundwater-dominated streams. However, the manuscript does not include any validation of the analytical model for this problem, so it is speculative to claim that the equations can be used to demonstrate real-world phenomena. The authors need to make the case for why the reader should trust the analytical results when they come from a simplified model. Sentences such as "Despite these limitations, these analytical solutions can be employed to obtain reasonable estimates ..." require some form of supporting evidence or logic, not just an assertion.

Response to Comment 3: As noted in our response to Reviewer 1 (Comment 1), these methods have been used to reproduce real-world phenomena in that they have been applied to reproduce observed multi-decadal groundwater warming in Germany (Menberg et al., 2014). It is very difficult to obtain such data (e.g. 40 years of regularly measured groundwater temperature), and hence such studies are presently limited. This oversight has now been recognized, and the U.S. Geological Survey is now continuously recording groundwater temperature station at wells near some current stream gauging stations. Nevertheless, the uncertainties associated with climate change studies remain difficult to quantify (for both surface water and groundwater temperatures). This is why we believe models can provide insightful results of such future projections.

Changes: We have now added a citation and explanation for the Menberg et al. paper following the sentence noted in this comment (P49, L28-30). We have also deleted the last sentence of the limitations section ('The parsimonious approach proposed in this study is preferred to merely ignoring groundwater temperature evolution and the associated impacts to streambed heat fluxes in groundwater-dominated streams'). Finally, we have added a new sentence acknowledging the present lack of field-based studies (P51, L4-9).

Comment 4: You have the opportunity to make a stronger case for the value of an analytical solution. You mention the lower costs of data assembly and computation. Analytical models also provide insight gained from compressing the problem into a small number of degrees of freedom, enabling a comprehensive evaluation of all possible solutions, and exploring all interactions among inputs to the model.

Response to Comment 4: This is a very good point, and we have incorporated this thought (and much of the text) into section 2 (P26, L8-10).

Comment 5: You also need to point out situations where this analytical model would be unsuitable. For example, shallow aquifers with strong lateral heterogeneities.

Response to Comment 5: Our limitations section details several of the shortcomings of our approach. Also, based on the reviewers' comments, we have added new sentences to this sections describing limitations associated with flashy flow regimes (P48, L23-26) and the ideal depth ranges for which to apply these methods (P49, L19-25). Finally, we have added a sentence acknowledging that lateral heterogeneities may violate the assumptions of the conceptual model (P48, L30).

Comment 6: I think the authors need to choose whether this is a paper that uses an analytical solution as a convenient way to efficiently explore possible effects of warming on groundwater temperature, or whether they want to use the equations to quantify a real-world phenomena (in which case there is a much higher expectation that the equations you use will be validated against observations). As you said in your response, you may choose to make this more of a methods paper, in which case the conclusions need to be revised significantly.

Response to Comment 6: This is a good point, and we have decided to reframe the paper slightly as a methods paper. The modified objectives (Objective 2, P24) more clearly reflect that the intent of the paper is to derive, present, and demonstrate the analytical expressions. We agree that the conclusions warranted modification based on this rewording of the objectives, and this major revision to the conclusions has been made (P50-51).

Comments from Reviewer 1 and Authors' replies

Comment 1. This manuscript addresses the point that short-term analyses of stream temperature sensitivity do not account for long-term responses of groundwater (and discharge to streams) to increasing air temperatures. The manuscript nominally treats groundwater temperature sensitivity to climate change as an eventuality rather than sensitivity, drawing on the rough equivalence between shallow groundwater temperature and mean annual air temperature. This is probably an important point, given the number of papers saying that groundwater dependent streams might be less sensitive to climate change.

Reply to Comment 1: This statement generally summarizes the content of our paper, and we agree that the topic is important given the large number of emerging papers that do not consider groundwater warming when projecting future stream temperatures.

However, our *HESSD* paper did not suggest that mean annual air temperature and shallow groundwater temperature are equivalent. On the contrary, we note in several locations, that *land surface temperature* drives shallow groundwater temperature (e.g., P19, L33; P23, L7-10; P24, L16, 22; P26, L1; P31, L16-18). Furthermore, the presented solutions do not merely suggest an equivalency between land surface and groundwater temperature but rather account for both damping and lagging effects. We acknowledge that Figure 2 may

be a bit confusing in this context (i.e. air temperature trends are presented rather than surface temperature trends), but as we indicate on P31, L16,17, this approach is using air temperature trends to represent surface temperature trends. This is usually considered to be reasonable in the absence of snowpack evolution.

Also note that we use the term 'sensitivity' in the same manner as stream temperature analysts who have applied the concept of stream thermal sensitivity proposed by Kelleher et al. (2012, *HP*) to project decadal scale stream sensitivity.

<u>Changes</u>: We have included an additional statement in Section 2.4 (P31, L18-19) indicating that air temperatures are used as a proxy for surface temperatures in this context.

Comment 2: However, the point [see above] is not novel; it has been made before on several occasions, mostly by the same authors. Here are quotes from the abstracts of two of the papers (using the citations from the manuscript):

"The simulated increases in future groundwater temperature suggest that the thermal sensitivity of baseflow-dominated streams to decadal climate change may be greater than previous studies have indicated." (Kurylyk et al, 2013)

"Thus, the simulations demonstrate that the thermal sensitivity of aquifers and baseflow-dominated streams to decadal climate change may be more complex than previously thought. Furthermore, the results indicate that the probability of exceeding critical temperature thresholds within groundwater-sourced thermal refugia may significantly increase under the most extreme climate scenarios." (Kurylyk et al., 2014a)

Reply to Comment 2: We agree that the Kurylyk et al. (2013, *HESS*) and (2014a, *WRR*) papers also addressed groundwater warming in response to climate change. However, the thermal sensitivity of shallow groundwater to climate change remains a very under-researched topic in comparison to surface water warming. Although dozens of papers have been published that consider surface water warming in response to climate change, to our knowledge, only papers involving authors of this manuscript have directly addressed the potential of groundwater warming to produce additional stream warming. There is also a difference in focus between this study and the two studies listed above. For example, as the quote selected by Reviewer 1 indicates, the Kurylyk et al. (2014a, *WRR*) paper primarily addresses how groundwater-sourced thermal refugia (discrete groundwater discharge points) will warm in response to climate change and how those changes could influence thermal diversity in rivers. The Kurylyk et al. (2013, *HESS*) paper primarily considers (1) land surface temperature changes due to climate change and snowpack evolution and (2) the empirical relationship between seasonal surface and groundwater temperature. Only 1 short paragraph in Kurylyk et al. (2013, P2713) addresses the differences between short

term and long term groundwater sensitivities. This is the phenomenon that is the focus of the present study.

There are many unique facets of the present study. The most important are:

1. **This contribution presents and demonstrates the utility of analytical solutions that can be used by other researchers for different climates and aquifer configurations. The spreadsheet is provided as an electronic supplement to allow others to readily implement these solutions. Conversely, the results presented in the 2013 *HESS* and 2014 *WRR* papers are site specific. The methods suggested in these previous papers require either extensive monitoring of surface and subsurface thermal regimes (to parameterize the empirical function proposed in the 2013 *HESS* paper) or detailed numerical modeling that requires extensive hydrogeological expertise, numerical codes, and several months of pre-processing, simulations, and post-processing.**

   Thus, the two previous papers identified a weakness in stream temperature papers that did not consider groundwater warming. However, the results from those two papers are not easily transferable to other catchments. Here we provide a first-order approach for considering groundwater warming that can be applied without the limitations noted above. We expect that these solutions will be used in future studies to estimate groundwater warming and the associated changes to streambed heat fluxes in deterministic stream temperature models. These solutions can also be used to gradually adjust the coefficients found in empirical stream temperature models. For example, the possibility of altering coefficients in regression-based stream temperature models to account for long term groundwater warming is investigated in more detail in a recent paper by Synder et al. (2015).

   Snyder CD, Hitt NP, Young JA. 2015. Accounting for groundwater in stream fish thermal habitat responses to climate change. *Ecological Applications* Published online, DOI: 10.1890/14-1354.1.

2. **A large portion of this study (e.g. Section 1, 2.3, 2.7.1, and 3.2 as well as Figs. 3a, 3b, and 7) addresses the influence of land cover disturbances on groundwater temperature. Kurylyk et al. (2013, *HESS*) and Kurylyk et al. (2014a, *WRR*) do not include discussion on this important topic.**

3. **Although, the analytical solutions (Eqs. 5, 11, 13, and 15) are obtained or modified from previous publications, the analytical expressions for *groundwater thermal sensitivity* in response to long term climate change or land cover disturbance (Eqs. 16-19) have not been previously proposed. These expressions facilitate the comparison to short term (i.e., the seasonal damping factor, Eq. 8) and long term**

groundwater thermal sensitivity and thus very clearly illustrate the limitations of employing short term stream thermal sensitivity to infer long term stream warming. They also allow the user to investigate thermal sensitivity of groundwater to a few parameters (e.g. depth, time, thermal diffusivity, and groundwater velocity), and thus a range of results based on the parameter uncertainty can be readily obtained.

4. **This contribution contains far more discussion on streambed heat fluxes (e.g., Fig.1, first 2 paragraphs of introduction, and discussion), their influence on surface water temperature in upwelling streams, and their dependency on groundwater temperature. The intent of this text was to more clearly demonstrate the interrelationships between climate change, groundwater temperature, and stream temperature. This is also reflected in the title.**

<u>Changes</u>: Changes in response to Comment 2 are included within our response to Comment 3.

Comment 3: More thorough reading of the papers shows very similar discussion, figures, and conclusions about the inappropriateness of ignoring groundwater warming when considering climate change impacts.

Response to Comment 3: We agree that the text Sections 3.3 and 3.4 and the conclusions contains some concepts similar to previous papers, although we note that new ideas and comparisons to new studies are presented in this section. It could be argued that Figs. 1 and 2 review material that is similar to previous papers, but these are merely introduction/methods figures rather than results/discussion figures. The other figures presented are unique from previous contributions and demonstrate the utility of the analytical solutions and thermal sensitivity expressions.

<u>Changes</u>: We have altered the introduction to clearly explain how this contribution differs from the other papers noted by Reviewer 1. In particular, we have emphasized that the main objective is to present the analytical solutions and associated groundwater thermal sensitivity expressions and to demonstrate their utility (P24,L1-19). Portions of Sections 3.3.2 (P41, L25-P42,L11 and P42, L25-29), 3.3.3 (P43, L9-11), 3.4 (P44, L5-6, 15-17, 21-24; P45, L21-29) and 3.5 (P46, L7-10, P48,L13-18) have been removed to limit redundancy with these previous papers. The caption of Figure 2 has been amended to reflect that it is modified from a previous study. Finally, two paragraphs of the conclusions have been removed (P51, L10-25).

Comment 4: Note that the current manuscript still only simulates aquifer temperatures, not stream temperatures, so does not go much beyond these and the related earlier papers in pointing out the potential additional warming.

We agree that a study that considers the thermal regimes of aquifers and stream holistically would be a useful contribution. However, this manuscript is already long and we believe that there is sufficient content in this manuscript to warrant publication without considering surface water thermal regimes directly. This paper goes beyond earlier papers by providing surface water temperature modellers with a set of equations that can be applied to estimate future groundwater warming. Other unique aspects of this paper are listed in our response to Comment 2.

Comment 5: The arguments presented in the current manuscript rely on analytical solutions of the conduction-advection equation (the commonly used version with constant diffusivity and velocity), whereas previous papers have used numerical models to estimate the effects of climate change on groundwater temperatures. What new information is learned from applying analytical solutions instead of numerical solutions?

Response to Comment 5: To our knowledge, the Kurylyk et al. (2014a) paper is the only previous study to apply numerical methods to study shallow groundwater warming in response to climate change. A couple other studies have considered deeper environments or have investigated aquiver reactivation due to ice melt in permafrost regions, but the foci of these studies were very different than the present one. Thus, we do not believe that the present study addresses a scientific question that has been thoroughly investigated using numerical methods. Numerical models generally require extensive subsurface data for parameterization, modeling expertise, and time. For example, the modeling presented in the Kurylyk et al. (2014a, *WRR*) required very lengthy simulations, and even these were based on idealized aquifers. The findings of the *WRR* paper were valuable, but it is unlikely that these resources would typically be dedicated to a study of a stream temperature response to climate change. Conversely, the spreadsheet provided in the electronic supplement allows the user to quickly conduct a simple sensitivity study to consider a range of potential groundwater warming based on relatively few input parameters.

Also, the mathematical forms of the solutions allow for the derivation of the groundwater sensitivity formulae (Eqs. 16-19). These analytical expressions illustrate the difference between the subsurface thermal response to short term and long term surface temperature changes. These expressions can be applied to test how system conditions (depth, time, etc.) can influence subsurface thermal sensitivity.

Comment 6: There are some technical points that leave a little confusion as well. They briefly mention one issue with snowpack, where shallower snowpacks can actually lead to cooler ground surface temperatures in part of the season. In addition because of the latent heat of fusion, the snowpack pins temperatures to near 0°C for a portion of the season (getting shorter under a warming climate of course), and much water input (the downwelling contribution) still occurs at or near freezing. Wouldn't this mean that even if the winter temperatures are warmer, the "mean temperature" of the ground may not shift as much as the mean of the air temperatures for the year. Despite noting a few concerns with how one would factor snow cover into the proposed conceptual model for groundwater temperature, the authors are critical of work from areas with substantial snow cover. Is this really appropriate, or should the authors be a little clearer about where they can make such inferences and where they cannot?

Response to Comment 6: Some of this comment is beyond the scope of the present study, but we will attempt to address it herein. The boundary conditions for these solutions are at the ground surface not the atmosphere, and thus they must be driven by land surface temperature. In many areas, mean annual air temperature and surface temperature trends are coupled. In fact, the whole field of borehole paleoclimatology is predicated on this assumption. Reviewer 1 is correct in noting that snowpack evolution can decouple trends in mean annual air and ground surface temperature, and this is discussed in far more detail in Kurylyk et al. (2013).

In snowpack-dominated regimes, a surface energy flux model should be applied to consider the influence of changing air temperature and snowpack evolution on surface temperatures. These surface energy flux models are typically easy to run and can reproduce measured surface temperature data under snowpack conditions (see Fig. 4, Kurylyk et al. 2013, *HESS*). Surface energy models are parameterized/driven with more commonly available data (e.g., leaf area index, latitude, precipitation) than subsurface models. Each simulation in surface energy flux models can typically be performed in seconds as opposed to the days required to run each subsurface numerical model simulations presented in Kurylyk et al. (2014a).

Please see our response to Comment 7 that discusses the influence of the temperature of groundwater recharge.

<u>Changes:</u> **The text in Section 3.4 has been enhanced slightly (P46, 22-30) and Table 3 has been added to more clearly explain the approach for obtaining surface temperature trends in snowpack dominated regions. This process was only alluded to in the HESSD paper.**

Comment 7: There is a non-constant water velocity through the course of the year, and most of the analytical solutions (and the initial equation used) are derived based on a nominally constant velocity. In many places in the world, recharge is seasonal. In particular in snowpack dependent climates, the recharge is associated with near 0°C meltwater. This only means that the approximations are off, and does not broadly contravene the conclusions, but it would dampen the degree of effect in some situations.

Response to Comment 7: We agree, to an extent, and acknowledged this in the limitations. The primary author is currently conducting a study of how seasonal recharge impulses influence shallow groundwater temperature. The analytical solutions assume that recharge enters the subsurface at the mean annual land surface temperature. In regions where snowmelt dominates recharge, the mean annual recharge temperature is less than mean annual surface temperature. Conversely, in regions where recharge tends to be dominated by irrigation during the warm season, the recharge temperature is higher than mean annual surface temperature. However, preliminary numerical modeling results suggest that the resultant influence of recharge pulses on the seasonal groundwater temperature or the rate of shallow groundwater warming tends to be minimal. For example, numerical model (SUTRA) runs have been conducted assuming saturated sand thermal properties, a typical maximum basin recharge rate (25 cm/year), a seasonal range of surface temperature of 30°C, a linear surface warming of 5°C per century, and that the entire recharge pulse occurs during the coldest month. The difference in the groundwater warming produced by the numerical model compared to that predicted by the Taniguchi et al. (1999) solution (assuming constant recharge) is about 10% in the upper 40 m. The results are presented on the following figure.

Note these simulations were run for deeper conditions and thus contain a thermal gradient. This is the extreme case (i.e. assuming recharge only occurs during coldest month), and for most basins, the influence would be less as recharge events still occur in the summer and fall. Thus, this appears to exert minor control on the rate of groundwater warming, at least for typical basin conditions. This is because the conductive heat flux at the land surface tends to dominate the advective heat flux due. Thus the seasonal surface temperature cycle, rather than the groundwater recharge temperature, is the primary driver of shallow groundwater temperature.

We acknowledge that these results are simplified conditions. In more extreme settings (e.g. in karst aquifers or in alpine basins where 500 mm of snowmelt may infiltrate within a few weeks) there may be potential for enhanced seasonality of groundwater recharge to more strongly influence shallow groundwater temperature.

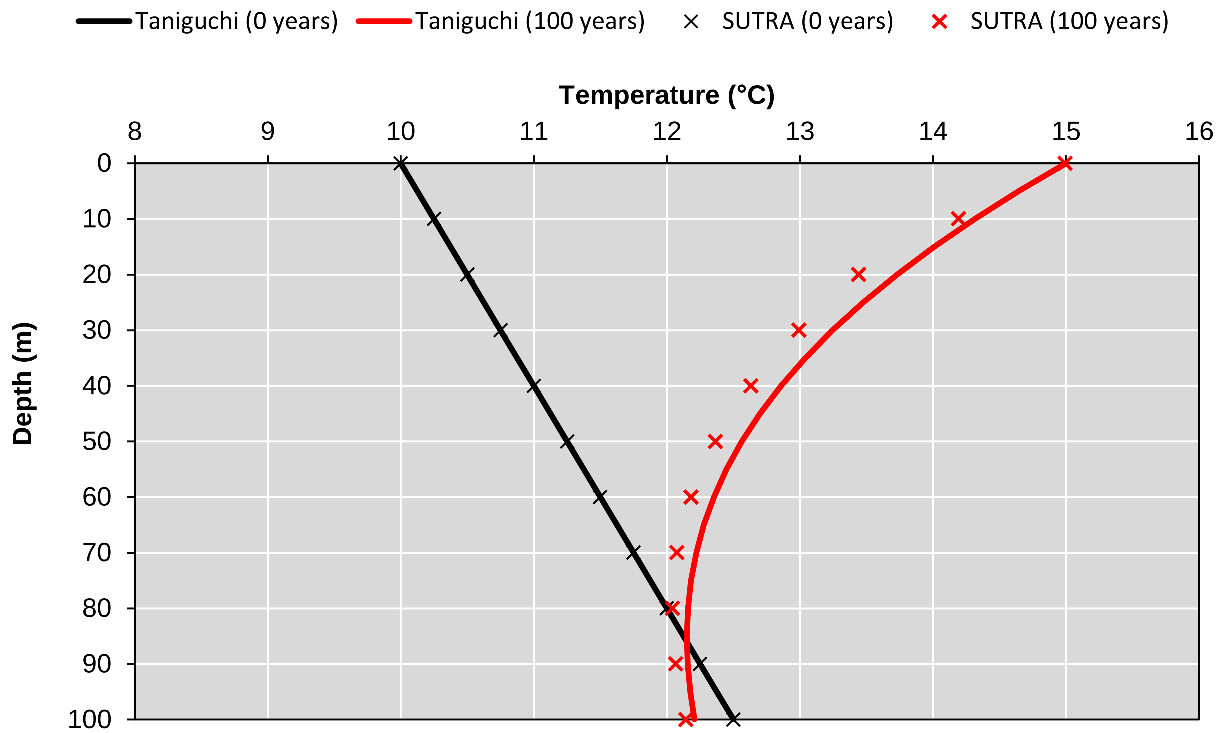

Figure: Temperature-depth profiles for 0 years and 100 years (due to 5°C per century linear warming) simulated with SUTRA and the Taniguchi et al. (1999) solution. The only difference between the results is that the Taniguchi et al. (1999) assumes constant recharge, whereas the SUTRA runs accommodate seasonal surface temperature and recharge at the ground surface (all recharge enters SUTRA domain during coldest month).

<u>Changes:</u> In flashy fractured rock aquifers, groundwater may not have time to thermally equilibrate with the surrounding rock, and hence recharge seasonality would have more influence on groundwater discharge temperature. We have included a sentence acknowledging this (and the implications for recharge seasonality) in our limitations sections (P48, L23-26).

Comment 8: Why did the authors apply a recharge rate of 0.2 m/yr to generate figure 5? Shouldn't this be on a par with runoff? Is this just an estimate of the recharge to deeper groundwater systems? If it were higher, deeper layers would respond more rapidly. This does not seem like it would be a substantial issue for the arguments presented, but the seemingly small recharge rate leaves one asking the question.

Response to Comment 8: This recharge rate was applied for all results (Figures 5-8). This is a typical basin recharge rate. In fact, for many surficial aquifers the recharge rates are much lower than this. For example, Döll and Fiedler (2008) estimated global (minus Antarctica) terrestrial recharge to be 12,666 km^3/yr. Dividing through by the land area of

135,000,000 km^2 (149,000,000 – 14,000,000) yields a mean annual recharge rate of about 10 cm/yr.

We agree that faster recharge rates would lead to more rapidly transmitted surface temperature signals. However, it is uncommon for recharge rates to greatly exceed 20 cm/yr except during intense irrigation or when water is sourced from a draining surface water body.

<u>Changes:</u> We have included a statement and a reference to Döll and Fiedler (2008) and Healy (2010) to justify our choice of recharge (P37, L17-18).

Döll, P. and Fiedler, K. 2008. Global-scale modeling of groundwater recharge. *Hydrol. Earth Syst. Sci.* 12: 863-885.

Comment 9: An additional point of noting these approximations used by the authors is that the models they apply have error as well. So if the work ignoring the groundwater effects is an approximation to some order, then the authors are not, per se, correcting these, but improving the order of error of the approximation (one hopes that is the case, in any event, but it has only been argued not demonstrated). In the context of improving projections of future temperature, then, is the additional effect noted here a small term in the overall uncertainty in future stream temperatures or a large term?

Response to Comment 9: Any thermal modeling of hydrologic systems invokes assumptions. Also, introducing model complexity (e.g. such as considering groundwater temperature warming in stream temperature models) never eliminates error but only improves the approximations. We agree with this point, but the same statement could be made of most (if not all) modeling studies of river, stream, or aquifer thermal regimes that incorporate some degree of increased complexity in comparison to previous studies.

The degree to which ignoring groundwater warming influences the overall uncertainty in stream temperature projections is dependent on many things such as the stream canopy, local climate, degree of groundwater contribution to stream, and time. Thus, this must be investigated using stream temperature models and is outside the scope of this study.

Comment 10: In summary, the general point is good to note, but it seems repetitive considering earlier work by the same authors. The current manuscript almost seems to present a weaker argument than in the earlier papers. The manuscript presents a strictly modeling exercise, and as such lays out a good hypothesis, but it is presented as a one-sided debate, where the authors do not really challenge their hypothesis so much as advocate it.

Response to Comment 10: As we note in our response to Comment 2, the previous papers referred to by Reviewer 1 essentially demonstrated that shallow groundwater temperature can be very sensitive to climate change. The main objective of the present study is to equip

stream temperature modellers with equations that can be applied to overcome the limitations of ignoring shallow groundwater warming (see Objective 1). The results are illustrative and are primarily intended to demonstrate the utility of the solutions. Hence, Objective 2 has been amended to reflect this (P24). It is a bit difficult to challenge the hypothesis that shallow groundwater will warm in response to climate change. As we note in our introduction (e.g. P22, L27-30), this has been shown with field data as well as physically based models. Our intention is not so much to advocate this hypothesis as it is to demonstrate how known analytical solutions can be applied to consider groundwater warming in stream temperature models. Thus this is more of a 'methods' paper.

<u>Changes</u>: We have rewritten objective 2 to be clearer regarding the point of this contribution (P24). Our results are merely illustrative in nature and intended to demonstrate the utility of the solutions. The conclusions have also been amended to more clearly reflect that this is a methods paper.

Comment 11: On the net, the argument has a certain irony as well. The authors complain about lax assumptions of quite a few other works, but end up using a number of rough approximations themselves. They argue that these rough approximations are better than ignoring the problem (which may well be true), but we have to take their word for it.

Response to Comment 11: It is still very common to study subsurface thermal regimes using analytical solutions. For example, most recent papers in borehole paleoclimatology employ analytical solutions to the 1D conduction equation. Also, many studies in aquifer thermal energy storage or borehole heat exchangers employ analytical solutions to a similar governing equation as this study, albeit in radial coordinates. The continued use of these solutions is partially due to the fact that the variability in subsurface thermal diffusivity is generally constrained in comparison to aquifer hydraulic diffusivity. Also, conduction is usually more important in subsurface energy transfer than advection, and this tends to minimize uncertainties induced by temporal or spatial variation in groundwater advection. The equations are also derived from understood physical processes, and are not merely arbitrary functions based on some correlation between air and subsurface temperature (see Comment 1). Thus, using these solutions is better than the two common alternatives for considering groundwater temperature response to climate change in stream temperature models: (1) groundwater temperature is completely resilient to climate change or (2) changes in groundwater temperature equal changes in air temperature without consideration of surface temperature, damping, or lagging. As we note in our response to the last comment below, the recent paper by Menberg et al. (2014) illustrates these points using measured decadal trends in groundwater temperature.

<u>Changes</u>: Three sentences/paragraphs have been altered to be less critical of how groundwater temperature changes have been considered in previous studies (see P22, L6-

16, P25, L5-8, and P44, L25 (including 'potential'), P245, L6-8 (deleted), L8-10 (added). We are amenable to altering other critical statements, but these must be clearly identified to us.

Comment 12: Section 2.2 (specifically equations 4 & 5) and Section 3.1: Stallman (1965) attributes equation (5) to Suzuki (1960), which makes quite a bit of the language in these sections a bit awkward. Equations 6 and 7 are irrelevant to this paper, and are solutions to the inverse problem of finding downwelling infiltration rates. If one were going to attach a name to equation (5), Suzuki (1960) seems more appropriate, although I am unfamiliar enough with the literature to know whether there is an earlier solution. It would not be surprising, however. Equations 6 and 7 are most appropriately attributed to Stallman, but they are not used in this paper.

Response to Comment 12: We agree that Suzuki (1960) proposed the original form of Equation 5, but Stallman (1965) provided more accurate expressions for obtaining *d* and *L* (Eqs. 6 and 7). Hence, these equations (5-7) are often collectively referred to as 'Stallman's solution'. It is not true that Eqs. (6) and (7) are irrelevant to this paper and are only useful in the inverse solutions. Eqs. (6) and (7) can be applied in a direct manner to parameterize Eq. 5 (see *L* and *d*). Indeed this is the only way to obtain the solution presented in Eq. (5) using commonly available data. Hence. Eqs. (6) and (7) were used to generate Figures 5 and 6 and are integral to the results and discussion of this paper.

<u>Changes</u>: We have included a citation to Suzuki's (1960) paper before Eq. (5) (P27, L25). The caption for Figure 5 and the text (P37, L12 and 16) is amended to clearly indicate that Eqs. (6) and (7) were used.

Comment 13: 12602 Lines 3-4: criticize the use of time series of two decades length on the basis that groundwater could take a century to respond, but at the same time on 12577, lines 2-7 the authors are critical of papers suggesting long lags in groundwater response. It gives the impression that they are arguing in the introduction that the lags are short enough that it should be considered a more important process, but then they discount long term sensitivity work for not considering a long enough lag. In a similar vein they criticize another paper that deals with a very similar topic (Meisner 1988) for not considering the lag at all, but nominally treating the groundwater increase as an eventuality as well. All of this comes across as inconsistent. Perhaps a different tone, recognizing that most of the previous work is built on approximations, and that the current work is yet another set of approximations extending the earlier approximations would create a text that does not look internally inconsistent.

Response to Comment 11: Our point is that one cannot assume (1) the lag = 0 years or (2) the lag = 100's of years. Rather the lag should be determined using a physically based approach, and we present and demonstrate such an approach. There is another distinction here as well. The paper by Chu et al. (2008) (originally referenced in the HESSD paper)

assumes centuries before any response, whereas we show that the response increases over time and may realize its 'full potential' after 100 years.

Furthermore, we would like to note that we were very transparent regarding the approximations of our approaches. For example, we devoted an entire subsection to the limitations of the governing equation (Section 4). Terms such as, 'approximation', and 'estimate' are ubiquitously employed throughout the paper.

<u>Changes:</u> In our response to Comment 11, we indicate that our tone has been altered in a couple of places.

Comment 14: Again it ties back to thinking in terms of degrees of error propagating from climate models through to ground surface temperatures, groundwater temperatures, and ultimately stream temperatures. This would involve the use of data to substantiate their hypothesis and demonstrate that it is a sizable effect. Based on my reading of the literature, I would guess that analysis of observed data would put their work in a very favorable light.

Response to Comment 14: Wee agree, and such a study was published in *HESS* in late November (Menberg et al., 2014). That study compared measured groundwater temperature warming over several decades to results obtained with an analytical solution to the same governing equation that is employed in this study. The analytical solution performed very favourably for the wells with the most data (see Figure 4, Hardtwald 1 and 2, Menberg et al. 2014). The inter-annual variability in the groundwater temperature stemmed from a seasonal bias (warming on hose leading from well). There was no surface temperature warming data available for the other two wells, and this likely resulted in the underestimation of the Sinthern warming (Fig. 4).

Also, the recent study by Snyder et al. (2015) examines how assumptions regarding the sensitivity of groundwater temperature to climate change may alter the projections for future stream water temperature.

<u>Changes:</u> We have included a statement and citation in the limitations section indicating that these methods have been shown to generally match measured subsurface warming trends (P49, L28-30)and a statement indicating the need for more field-based studies (P51, L4-9).

Menberg K, Blum P, Kurylyk B, Bayer P. 2014. Observed groundwater temperature response to recent climate change. *Hydrol. Earth Syst. Sci.* 18, 4453–4466.

Snyder CD, Hitt NP, Young JA. 2015. Accounting for groundwater in stream fish thermal habitat responses to climate change. *Ecological Applications* Published online, DOI: 10.1890/14-1354.1.

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

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) because these solutions are driven with the land surface and not the air temperature. However, surface temperature trends cannot be assumed to follow air temperature if snowpack evolution occurs. Thus in these cases, surface temperature changes should be indirectly 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 and that any freeze-thaw process is cyclic rather than gradual (i.e., they should not be used in permafrost settings). In general, studies focused on stream and water temperature are not usually conducted in permafrost regimes as the water temperature in such settings does not usually exceed incipient thresholds for coldwater fish or other aquatic species.

Complex flow regimes in aquifers may potentially invalidate some of the equation assumptions.

<u>Changes</u>: We have included a paragraph on determining the surface boundary condition when snowpack evolution occurs (P46, L22-30). We have also included two sentences in the limitations that discuss the ideal depth range for which to apply these solutions (P49, L19-25). We have also included a statement regarding dealing with inhomogeneous thermal properties (P47, L25-29). Finally, we have included a statement regarding complex flow regimes (e.g., fractured rock) in the limitations (P48, L30-P49, L9).

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>: Table 3 has been added.

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. 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>: As noted previously, we have included the new table (Table 3) to briefly list alternatives for obtaining groundwater recharge and other important equation parameters and have cited recent sources devoted to this topic (e.g., Healy, 2010).

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 have proposed this in the revised version of this paper (P47, L25-31).

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 phrase has been removed in 17 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 have been 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 have removed the word 'expected' to clarify this sentence (P43, L22).

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 have changed this wording to 'seasonal' (P44, L8).

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 have modified this to 'groundwater warming at depths > 10 m may still be significant…'. (P44, L13).

Shallow groundwater thermal sensitivity to climate change and land cover disturbances: Derivation of analytical expressions and implications for stream temperature ~~projections~~modelling

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Abstract

Climate change is expected to increase stream temperatures, and the projected warming may alter the spatial extent of habitat for coldwater fish and other aquatic taxa. Recent studies have proposed that stream thermal sensitivities, derived from short term air temperature variations, can be employed to infer future stream warming due to long term climate change. However, this approach does not consider the potential for streambed heat fluxes to increase due to gradual warming of shallow groundwater. The temperature of shallow groundwater is particularly important for the thermal regimes of groundwater-dominated streams and rivers. Also, other recent stream temperature studies have investigated how land surface perturbations, such as wildfires or timber harvesting, can influence stream temperatures by changing surface heat fluxes, but these studies have typically not considered how these surface disturbances can also alter shallow groundwater temperatures and consequent streambed heat fluxes.

In this study, several analytical solutions to the one-dimensional unsteady advection-diffusion equation for subsurface heat transport are employed to investigate the timing and magnitude of groundwater warming due to seasonal and long term variability in land surface temperatures.

Novel groundwater thermal sensitivity formulae are proposed that accommodate different surface warming scenarios. The thermal sensitivity formulae demonstrate that shallow groundwater will warm in response to climate change and other surface perturbations, but the timing and magnitude of the warming depends on the rate of surface warming, subsurface thermal properties, bulk aquifer depth, and groundwater velocity. The results also emphasize the difference between the thermal sensitivity of shallow groundwater to short term (e.g., seasonal) and long term (e.g., multi-decadal) land surface temperature variability, and thus demonstrate the limitations of using short term air and water temperature records to project future stream warming. Suggestions are provided for implementing these formulae in stream temperature models to accommodate groundwater warming.

Keywords: groundwater temperature, subsurface warming, analytical solutions, deforestation, urbanization, river thermal sensitivity, wildfires, groundwater dependent ecosystems

1. Introduction

The ambient water temperature of streams and rivers is an important determinant of aquatic ecosystem health due to its influence on physicochemical conditions and the fact that many freshwater fish species can only tolerate a certain temperature range (Caissie 2006; Elliott and Elliott 2010; Hannah and Garner, 2015; Webb et al., 2008). Also, river thermal diversity enhances ecosystem complexity by providing thermally suitable habitat in reaches that would ~~be~~ otherwise be uninhabitable for certain species (Cunjak et al. 2013, Ebersole et al. 2003; Kurylyk et al., 2015; Sutton et al., 2007). The thermal regimes of streams and rivers are controlled by energy fluxes across the water surface and the streambed (Fig. 1) as well as the internal structure of the stream or river network (Guenther et al., 2014; Hannah et al., 2004; Leach and Moore 2011; Poole and Berman, 2001). The total streambed heat flux is composed of conductive and advective heat fluxes, which both depend on subsurface temperatures (Caissie et al., 2014; Moore et al., 2005; St-Hilaire et al., 2000).

Large rivers tend to be dominated by surface heat fluxes, but streambed advective heat fluxes induced by groundwater-surface water interactions can influence the thermal regimes of certain streams or rivers (Caissie, 2006). The significance of streambed advective heat fluxes generally varies spatially and temporally within a channel and depends on, among other things, the groundwater discharge rate and the degree of shading (e.g., Brown and Hannah, 2008; Leach and Moore, 2011; Story et al., 2003). Due to the thermal inertia of the subsurface soil-water matrix, groundwater-dominated streams and rivers typically exhibit attenuated thermal responses to diel and seasonal variations in air temperature compared to surface runoff-dominated streams and rivers (Caissie et al., 2014; Constantz, 1998; Garner et al., 2014; O'Driscoll and DeWalle, 2006; Tague et al., 2007). Kelleher et al. (2012) defined the *thermal sensitivity* of a stream as the slope of the linear regression between air and water temperatures. These regressions are typically performed on temperature data collected for a period of at least one year and averaged on a daily, weekly, or monthly basis. The stream thermal sensitivity is thus a measure of the short term (e.g., seasonal) change in water temperature in response to a short term change in air temperature (Kelleher et al., 2012; Mayer 2012).

Many studies have addressed the ~~sensitivity~~ response of river and stream thermal regimes to climate change (e.g., Isaak et al., 2012; Luce et al., 2014; MacDonald et al., 2014; van Vliet et al., 2011), deforestation for land development and/or timber harvesting (e.g., Janisch et al., 2012; Moore et al., 2005; Studinski et al., 2012), and wildfires (e.g., Hitt, 2003; Isaak et al., 2010; Wagner et al., 2014). Several very recent studies have proposed that the empirical relationship (e.g., linear regression) between seasonal records of air and stream temperatures ~~stream thermal sensitivities obtained from short term water and air temperature changes~~ can be applied to estimate long term stream warming due to future climate change (e.g., Caldwell et al., 2014a; Gu et al., 2014; Hilderbrand et al., 2014; ~~Johnson et al., 2014;~~ Trumbo et al., 2014).

Because groundwater temperature exhibits less seasonal variability than surface water temperature, it is not surprising that extrapolated stream thermal sensitivities obtained from short term temperature data will typically indicate that the temperature of groundwater-dominated streams will be relatively insensitive to climate change. As noted by Johnson (2003), care should be taken when using air temperature correlations to explain stream temperature dynamics, as air temperature is not the dominant controlling factor in stream temperature dynamics. Rather, the high correlation between stream and air temperature arises because both variables are influenced by incoming solar radiation, the primary driver of stream ~~and river~~ temperatures (Allan and Castillo, 2007). ~~Thus, t~~The approach of using short term stream thermal sensitivities to estimate multi-decadal stream warming essentially employs future air temperature as a surrogate for future stream surface heat fluxes (Gu et al., 2014; Johnson et al., 2014; Mohseni and Stefan 1999), but it ignores changes to streambed heat fluxes due to groundwater warming. Thus, the short term relationship between air and water temperatures is not necessarily representative of the concomitant warming of the lower atmosphere and surface water bodies on inter-annual or multi-decadal time scales (Arismendi et al., 2014; Bal et al., 2014; Luce et al., 2014).

There is a persistent notion in recent studies that springs or groundwater-dominated streams will generally warm less than surface runoff-dominated streams if exposed to the same long term climate warming scenario. For example, Kløve et al. (2014) proposed that since 'the thermal regime of groundwater systems is less dependent on air temperature patterns than that of surface water, the effects of altered air temperatures [climate change] are likely to be less pronounced in springs and other [groundwater-dependent ecosystems]'. Statements regarding the relative thermal resilience of aquifers and groundwater-dominated streams to climate change are often implicitly or explicitly predicated on the assumptions that groundwater temperature responds the same to long term climate changes as it does to seasonal weather changes or that the lag in future groundwater warming in response to climate change will be decades or even centuries (e.g., Chu et al., 2008).

Furthermore, many studies have addressed investigated the short term (i.e., within five years) response of stream thermal regimes to land surface perturbations, such as wildfires and deforestations, for the first few years following the disturbance. However, very few studies have considered how these perturbations could increase the temperature of groundwater discharge to these streams and thereby produce enhanced or sustained stream warming. In general, the common approach of ignoring future increases in groundwater temperature and streambed heat fluxes in stream temperature models may result in water temperature projections that are overly conservative and consequently underestimate future stream warming and associated future environmental impacts (e.g., habitat loss for coldwater fish, Snyder et al., 2015).

There is increasing evidence that the thermal regimes of shallow aquifers are sensitive to climate change, permanent deforestation, and wildfires. Observed shallow groundwater temperature warming has already been statistically related to recent trends in air temperature (an indicator of climate change) in Taiwan (Chen et al., 2011), Switzerland (Figura et al., 2011; 2014) and Germany (Menberg et al., 2014). Empirical and process-based models of energy transport in shallow aquifers have been used to demonstrate that future climate change will continue to warm shallow groundwater bodies (e.g., Gunawardhana and Kazama, 2011; Kurylyk et al., 2013, 2014a; Taylor and Stefan, 2009) as reviewed in detail by Kurylyk et al. (2014b). Previous studies have also noted groundwater warming in response to deforestation due to the removal of the ~~cooling influence of the~~ forest canopy (e.g., Alexander, 2006; Guenther et al., 2014; Henriksen and Kirkhusmo, 2000; Steeves, 2004; Taniguchi et al., 1998). Others have observed subsurface warming following wildfires. ~~For example,~~ Burn (1998) found that the mean annual surface temperature at a burned site in southern Yukon, Canada was 0.6°C warmer than the surrounding surface thermal regime, and this surface thermal perturbation rapidly warmed shallow subsurface temperatures.

In all cases (i.e., climate change, deforestation, and wildfires), the surface disturbance warms shallow aquifers by increasing the downward heat flux from the warming land surface. For example, climate change can influence surface thermal regimes and subsurface heat fluxes by increasing convective energy fluxes from the lower atmosphere and causing increased net radiation at the ground surface (Jungqvist et al., 2014; Kurylyk et al., 2013; Mellander et al., 2007). The influence of wildfires or forest harvesting on surface thermal regimes can be complex. ~~For example, the~~ The removal of the forest canopy can decrease transpiration and thus increase the energy available to warm the land surface (Rouse, 1976). Lewis and Wang (1998) demonstrated that the majority of surface and subsurface warming caused by wildfires at sites in British Columbia and Yukon, Canada could be attributed to decreased transpiration. Decreased surface albedo and consequent increased net radiation at the land surface can also arise due to wildfires (Yoshikawa et al., 2003). The increase in surface temperature as a result of a land cover disturbance will depend on the original vegetative state, climate, ground ice conditions, and potential for vegetative regrowth (Liljedahl et al., 2007). In the case of a wildfire or in post-harvest tree planting, the vegetation may eventually regenerate, and the surface energy balance and temperature return to the pre-fire conditions (Burn, 1998). ~~Although the surface and subsurface thermal influences of climate change and wildfires are addressed separately in this study, future climate change is expected to cause more severe and frequent wildfires (Flannigan et al., 2005).~~

Kurylyk et al. (2013, 2014a) demonstrated that shallow groundwater warming may eventually exceed the magnitude of surface water warming and thus stream temperature models that do not consider this phenomenon may be overly conservative. The empirical method proposed by Kurylyk et al. (2013) for estimating the magnitude of groundwater warming requires measured surface and depth-dependent groundwater temperature for model calibration, but there is often a paucity of such temperature data available at the catchment scale. Also, the numerical modeling described by Kurylyk et al. (2014a) is time intensive and requires considerable data for model parameterization. These previous approaches for quantifying groundwater warming are site specific, and thus the results are not generally transferable to existing stream temperature models that are used to investigate ~~consider~~stream thermal regimes.

The intent of this contribution is to provide alternative, parsimonious approaches for investigatinge ~~the~~ factors that influence the timing and magnitude of groundwater temperature changes in response to climate change or land cover disturbances. The specific objectives of this paper are twofold:

1. Derive easy-to-use formulae to estimate the thermal sensitivity of groundwater to different surface temperature changes (e.g., seasonal cycle or multi-decadal increases).
2. ~~Employ these~~Demonstrate how these formulae can be utilised to investigate how the groundwater thermal sensitivity for idealized environments is influenced by the depth, groundwater recharge rate, and subsurface thermal properties.

~~The information from (1) and (2)~~The illustrative examples (Objective 2) will also be used to demonstrate the difference in the subsurface thermal response to short term (seasonal) and long term (multi-decadal) surface temperature trends. Consequently, the results will be employed to ~~discuss~~ highlight the limitations of employing ~~regression-based~~empirical -stream temperature models with constant coefficients obtained from short-term temperature records to project future stream warming ~~and to~~. The results will also be used to describe how stream temperature models can be improved to accommodate groundwater warming using these simple approaches.

2. Methods

There are several approaches for estimating future groundwater temperature warming in response to changes in land cover or climate. ~~For example, it~~It is well known that mean annual ground surface temperature and shallow groundwater temperature are approximately equal to mean annual air temperature plus some thermal offset (e.g., 1-4°C) due to the insulating effect of snow (Zhang, 2005). Meisner (1988) employed this knowledge to estimate future groundwater temperatures by adding a thermal offset to projections of future mean annual air temperature. ~~This approach also ignores the fact that rising air temperatures can reduce the average thickness and duration of winter snowpack in boreal regions and thus decrease the thermal offset between mean annual air and surface temperatures (Jungqvist et al., 2014; Kurylyk et al., 2013; Mellander et al., 2007).~~ The approach employed by Meisner (1988) ~~utilizes~~ utilized mean annual surface temperature as a proxy for groundwater temperature and thus implicitly ~~assumes~~ assumed that the aquifer and surface are always in thermal equilibrium. The equilibrium assumption was also invoked in the empirical function employed by Kurylyk et al. (2013). ~~Hence it~~Such an approach does not consider the lag that occurs between an increase in surface temperature and its subsequent realization at some depth within the subsurface (Lesperance et al., 2010) and thus is only valid for very shallow groundwater (e.g., <5 m) or for long time scales. ~~This approach also ignores the fact that rising air temperatures can reduce the average thickness and duration of winter snowpack in boreal regions and thus decrease the thermal offset between mean annual air and surface temperatures (Jungqvist et al., 2014; Kurylyk et al., 2013; Mellander et al., 2007).~~

Analytical solutions to subsurface heat transfer differential equations can also be applied to investigate the influence of future climate change on groundwater temperature (Gunawardhana and Kazama, 2011; Kurylyk and MacQuarrie, 2014; Menberg et al., 2014), although these approaches have most often been applied for deeper aquifers. Finally, numerical models of groundwater flow and coupled heat transport can be applied to investigate the thermal evolution of aquifers due to warming surface temperatures (e.g., ~~Bense et al., 2009;~~ Gunawardhana and Kazama, 2012; Kurylyk et al., 2014a). These numerical models are more flexible and can accommodate multi-dimensional groundwater flow and heat transport and inhomogeneities in subsurface thermal properties (Kurylyk et al., 2014b), but they require extensive subsurface field data for model parameterization.

Herein, we employ analytical solutions to a one-dimensional, unsteady heat transport equation to investigate subsurface temperature evolution due to climate change, permanent land cover changes, and wildfires. These solutions are physically based and account for the lag in the thermal response of groundwater to surface temperature changes. Also, unlike the solution employed by Taylor and Stefan (2009), these solutions accommodate the subsurface thermal effects of vertically moving groundwater. The solutions provide an indication of expected groundwater warming due to climate or land cover changes, and the results can be incorporated into stream temperature models in the absence of site-specific hydrogeological modeling. Analytical solutions are particularly useful for performing parsimonious analyses when there is a paucity of subsurface data (e.g., hydraulic conductivity distribution) for parameterizing groundwater flow and energy transport models. Also, analytical solutions limit the degrees of freedom for a particular analysis and thus facilitate a comprehensive evaluation of possible interactions between model inputs and resultant solutions. As we demonstrate, the forms of these solutions can also be utilized to derive mathematical expressions for groundwater thermal sensitivity to surface temperature perturbations.

2.1 Advection-diffusion heat transport equation

Shallow subsurface heat transfer occurs primarily due to heat conduction and heat advection (Domenico and Schwartz, 1990), although the latent heat released or absorbed during pore water freeze-thaw can also be important in cold regions (Kurylyk et al., 2014b). The one-dimensional, transient conduction-advection equation for subsurface heat transport is (Stallman, 1963):

$$\lambda \frac{\partial^2 T}{\partial z^2} - q c_w \rho_w \frac{\partial T}{\partial z} = c\rho \frac{\partial T}{\partial t} \quad (1)$$

where λ is the bulk thermal conductivity of the soil-water matrix (W m^{-1} °C^{-1}), T is the temperature at any point in space or time (°C), z is the depth below the surface (m, down is positive and the land surface occurs at z = 0), q is the vertical Darcy flux (m s^{-1}, down is positive), $c_w \rho_w$ is the volumetric heat capacity of pure water (4.18×10^6 J m^{-3} °C^{-1}; Bonan, 2008), t is time (s), and $c\rho$ is the bulk volumetric heat capacity of the soil-water matrix (J m^{-3} °C^{-1}). The first term on the left of Eq. (1) represents the divergence of the conductive flux, the second term on the left represents the divergence of the advective flux, and the term on the right represents the rate of change of thermal storage. Subsurface heat transport phenomena and the physical meaning of the terms in Eq. (1) are reviewed in more detail by Rau et al. (2014) and Kurylyk et al. (2014b).

Equation (1) is often rewritten in the form ~~of the classic heat diffusion-advection equation~~ (Carslaw and Jaeger, 1959~~; Kurylyk et al., 2014c~~):

$$D\frac{\partial^2 T}{\partial z^2} - U\frac{\partial T}{\partial z} = \frac{\partial T}{\partial t} \qquad (2)$$

where D is the bulk thermal diffusivity (thermal conductivity divided by heat capacity) of the soil-water matrix (m^2 s^{-1}), and U is the velocity of a thermal plume due only to heat advection (m s^{-1}). Even in the absence of conduction, the thermal plume will not migrate at the same rate as the Darcy velocity due to differences in the heat capacities of water and the medium (Markle and Schincariol, 2007; Luce et al., 2013). An expression for U can be obtained via a comparison of Eqs. (1) and (2):

$$U = q\frac{c_w \rho_w}{c\rho} \qquad (3)$$

Often an effective thermal diffusivity term, which accounts for the combined thermal homogenizing effects of heat diffusion and heat dispersion, is utilized in place of the bulk thermal diffusivity term D in Eq. (2). However, it is still common to ignore the subsurface thermal effects of dispersion, which are often minimal in comparison to heat conduction (Kurylyk et al., 2014b; Rau et al., 2014). Equation (2) represents vertical subsurface heat transport processes and accounts for the thermal effects of heat conduction induced by a thermal gradient and heat advection induced by groundwater flow. The limitations of this equation will be discussed later. Analytical solutions to this equation can be developed and applied to investigate inter-relationships between groundwater flow, surface temperature changes, and subsurface thermal regimes. We consider four analytical solutions to Eq. (2) (Table 1) that vary based on the nature of the surface boundary condition. These are discussed in subsequent sections.

2.2 Analytical solution 1: Harmonic surface temperature changes

The diel or seasonal land surface temperature cycle can be approximated with a harmonic function. ~~Stallman~~ Suzuki (1960)~~(1965)~~ derived an analytical solution to Eq. (2) subject to a sinusoidal surface temperature boundary condition ~~to account for the subsurface thermal influence of seasonal or diel surface temperature variability~~:

$$\text{Boundary condition: } T(z=0,t)=T_m + A\sin\left(\frac{2\pi t}{p}-\phi\right) \qquad (4)$$

$$\text{Solution: } T(z,t)=T_m + A\exp(-dz)\sin\left(\frac{2\pi t}{p}-\phi - Lz\right) \qquad (5)$$

where A is the amplitude of the harmonic surface temperature cycle (°C), T_m is the mean surface temperature (°C), p is the period of the surface temperature cycle (s), ϕ is a phase shift to align the timing of the surface temperature signal with the sinusoid (rad), d is a thermal damping term (m^{-1}), and L is a lag term (m^{-1}). Eq. (5) thus states that the harmonic temperature signal at the surface retains its period within the subsurface but is exponentially damped and linearly lagged with depth. Stallman (1965) demonstrated that ~~The~~the exact expressions for d and L are:

$$d=\left[\left\{\left(\frac{\pi}{Dp}\right)^2+0.25\left(\frac{U}{2D}\right)^4\right\}^{0.5}+0.5\left(\frac{U}{2D}\right)^2\right]^{0.5}-\frac{U}{2D} \qquad (6)$$

$$L=\left[\left\{\left(\frac{\pi}{Dp}\right)^2+0.25\left(\frac{U}{2D}\right)^4\right\}^{0.5}-0.5\left(\frac{U}{2D}\right)^2\right]^{0.5} \qquad (7)$$

Equations (5) to (7) are generally collectively referred to as Stallman's equation. No initial conditions are presented for Stallman's (1965) solution as it assumes that the boundary condition has been repeating the harmonic cycle indefinitely. This solution also depends on a lower boundary condition ($T = T_m$) at infinite depth. Various forms of this solution have been applied/inverted to infer rates of groundwater flow due to subsurface temperature-time series arising from daily or seasonal harmonic variations in surface temperature (e.g., Anderson, 2005; Hatch et al., 2006; Rau et al., 2014). Here, we employ Stallman's (1965) solution in a forward manner to demonstrate why seasonal changes in air and surface temperature are not manifested in subsurface thermal regimes below certain depths, and thus why groundwater dominated streams and rivers exhibit low thermal sensitivity to seasonal weather variability. In particular, we consider the ratio of the amplitude of the seasonal groundwater temperature cycle at any arbitrary depth to the amplitude of the surface temperature boundary condition. This dimensionless parameter, herein referred to as the exponential damping factor *Ω*, can be obtained from Eqs. (4) and (5):

$$\Omega = \frac{\text{Amplitude at depth} = z}{\text{Amplitude at depth} = 0} = \frac{A\exp(-dz)}{A} = \exp(-dz) \tag{8}$$

2.3 Analytical solution 2: Step change(s) in surface temperature due to land cover disturbances

Taniguchi et al. (1999a) demonstrated how an analytical solution presented by Carslaw and Jaeger (1959) could be modified to ~~simulate~~ calculate the groundwater temperature warming arising from a sudden and permanent increase in surface temperature. This increase in surface temperature could arise ~~, for example,~~ due to rapid and large scale timber harvesting or changes in land use. Menberg et al. (2014) proposed that superposition principles could be employed to modify the solution by Taniguchi et al. (1999a) by considering a series of shifts in the surface temperature boundary condition. Herein we employ the technique by Menberg et al. (2014) and consider up to two sequential shifts in the boundary condition. The first shift, which warms the surface temperature, occurs at $t = 0$, and after a period of time ($t = t_1$), the surface temperature returns to its value prior to the initial warming (T_0). Such a boundary condition could approximate the sudden temporary increase in mean annual surface temperature due to a wildfire and the subsequent return to pre-fire surface temperatures due to vegetation regrowth (Burn, 1998). Alternatively, this boundary condition could represent the effect of clearcutting followed by industrial tree planting. The subsequent surface cooling due to gradual vegetative regrowth could also be represented with a series of shorter less intense cooling phases, but for the illustrative examples in the present study we assume one warming shift followed by one cooling shift of equal magnitude:

$$\text{Initial conditions: } T(z, t = 0) = T_0 \tag{9}$$

$$\text{Boundary condition: } T(z = 0, t) = \begin{cases} T_0 + \Delta T & \text{for } 0 < t < t_1 \\ T_0 & \text{for } t \geq t_1 \end{cases} \tag{10}$$

$$\text{Solution: } T(z,t) = \begin{bmatrix} T_0 + \frac{\Delta T}{2}\left\{\operatorname{erfc}\left(\frac{z-Ut}{2\sqrt{Dt}}\right) + \exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+Ut}{2\sqrt{Dt}}\right)\right\} \quad \text{for } 0 \le t < t_1 \\ \\ T_0 + \frac{\Delta T}{2}\left\{\operatorname{erfc}\left(\frac{z-Ut}{2\sqrt{Dt}}\right) + \exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+Ut}{2\sqrt{Dt}}\right)\right\} \quad \text{for } t \ge t_1 \\ -\frac{\Delta T}{2}\left\{\operatorname{erfc}\left(\frac{z-U(t-t_1)}{2\sqrt{D(t-t_1)}}\right) + \exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+U(t-t_1)}{2\sqrt{D(t-t_1)}}\right)\right\} \end{bmatrix} \quad (11)$$

where T_0 is the uniform initial temperature (°C), ΔT is the magnitude of the surface temperature shift (°C), erfc is the complementary error function, and t_1 is the duration of the period characterized by warmer surface temperatures (s).

This solution and the remaining three solutions presented below also require a lower boundary condition at infinite depth ($T=T_0$). ~~It should be noted that Eq.~~Equation (11) can be employed to consider the subsurface warming due to a permanent step change in surface temperature (i.e., no subsequent cooling due to vegetative regrowth) by setting t_1 to infinity. In this case, only the first line on the right hand side of Eq. (11) is retained. Even when t_1 is set to infinity, Eq. (11) differs slightly from the solution presented by Taniguchi et al. (1999a) because uniform initial temperatures are assumed in the present study (Eq. 9). These initial conditions ignore the influence of the geothermal gradient and imply that the recent climate has been relatively stable. We employ these simplifying assumptions given that we are primarily interested in shallower depths (e.g., < 25 m) where the influence of the geothermal gradient is not significant. Also, the boundary conditions for this solution and the solutions below do not accommodate seasonally varying surface temperatures, thus these solutions are valid ~~below the depth that the seasonal temperature wave penetrates (see Eq. 8) or more generally~~ for predicting the evolution of mean annual groundwater temperature.

2.4 Analytical solution 3: Linear increase in surface temperature due to climate change

Carslaw and Jaeger (1959) also presented an analytical solution to Eq. (2) subject to linearly increasing surface temperature. This solution was later adapted by Taniguchi et al. (1999b) and applied to study groundwater temperature evolution due to climate change. Herein, the analytical solution is presented in a slightly simpler form as thermally uniform initial conditions are assumed (i.e., initial conditions are given by Eq. 9):

$$\text{Boundary condition: } T(z=0,t)=T_0+\beta t \tag{12}$$

$$\text{Solution: } T(z,t)=T_0+\frac{\beta}{2U}\left[(Ut-z)\times \operatorname{erfc}\left(\frac{z-Ut}{2\sqrt{Dt}}\right)+(Ut+z)\exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+Ut}{2\sqrt{Dt}}\right)\right] \tag{13}$$

where β is the rate of the increase in surface temperature (°C s^{-1}).

Equation (13) has been applied in an inverse manner to investigate the complex relationships between past surface temperature changes, groundwater flow, and measured subsurface temperature-depth profiles (e.g., Miyakoshi et al., 2003; Taniguchi et al., 1999b; Uchida and Hayashi, 2005). It has also been applied to forward model future groundwater temperature evolution due to projected climate change (Gunawardhana and Kazama, 2011). Herein, the surface boundary condition (Eq. 12) is fitted to mean annual air temperature trends produced by climate models. Because it is surface temperature, rather than air temperature, that drives shallow subsurface thermal regimes, this approach tacitly assumes that mean annual surface and air temperature trends are coupled. Thus, air temperature is being used as a proxy for surface temperature in this approach. As previously indicated, snowpack evolution may invalidate this assumption (Kurylyk et al., 2013; Mellander et al., 2007), and thus this approachit is best employed where snowpack effects are minimal. Snowpack evolution would typically retard the rate of groundwater warming (Kurylyk et al., 2013).

2.5 Analytical solution 4: Exponential increase in surface temperature due to climate change

It may be inappropriate to assume a linear surface temperature rise as in Eq. (13), because many climate scenarios suggest that the rate of climate warming will increase over time. For example, Fig.ure 2 presents the globally-averaged IPCC (2007) multi-model air temperature projections

~~from the Fourth Assessment Report~~ for two different emission scenarios. ~~The Fifth Assessment Report employs representative concentration pathways rather than emissions scenarios (van Vuuren et al., 2011), but at this time, the multi-model results are not yet publicly available in tabulated format.~~ The global air temperature series projected for the conservative emission scenario B1 is much better represented by a linear function than the air temperature series for the aggressive A2 emission scenario, which exhibits significant concavity.

~~Kurylyk and MacQuarrie (2014) proposed that in~~ In such cases the boundary condition would be better represented as an exponential function (Kurylyk and MacQuarrie, 2014). The solution presented here is simpler than the original form given that the initial conditions are assumed to be thermally uniform (initial conditions = Eq. 9):

$$\text{Boundary condition: } T(z=0,t)=T_1+b\exp(ct) \tag{14}$$

Solution:

$$T(z,t)=T_0+\frac{(T_1-T_0)}{2}\left\{\begin{aligned}&\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}-\frac{U}{2}\sqrt{\frac{t}{D}}\right)\\&+\exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}+\frac{U}{2}\sqrt{\frac{t}{D}}\right)\end{aligned}\right\}+$$
$$\frac{b}{2}\exp\left(\frac{Uz}{2D}+ct\right)\left\{\begin{aligned}&\exp\left(-z\sqrt{U^2/4D^2+c/D}\right)\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}-\sqrt{\left(\frac{U^2}{4D}+c\right)t}\right)+\\&\exp\left(z\sqrt{U^2/4D^2+c/D}\right)\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}+\sqrt{\left(\frac{U^2}{4D}+c\right)t}\right)\end{aligned}\right\} \tag{15}$$

where T_1 (°C), b (°C), and c (s^{-1}) are parameters for the surface temperature boundary condition which can be fit to climate model projections. Note that $T_1 + b$ must equal T_0 for the boundary and initial conditions to converge at $t = 0$, $z = 0$. The original initial condition function proposed by Kurylyk and MacQuarrie (2014) superimposed linear and exponential functions, and thus the more complex form of the solution can also be applied to forward model future climate change impacts on deeper subsurface temperature profiles. These temperature profiles can deviate from the geothermal gradient due to groundwater flow or recent surface temperature changes (Ferguson and Woodbury, 2005; Reiter, 2005). The alternate forms of the boundary conditions presented in Eqs. (10), (12), and (14) are illustrated in Figure 3. Each of the listed analytical solutions to the one-dimensional, transient diffusion-advection equation (Eq. 2) is provided in Table 1 with details to highlight their differences.

2.6 Effective aquifer depth

The one-dimensional analytical solutions discussed above can be utilized to estimate the influence of surface warming at any desired depth. However, groundwater discharge to streams is sourced from different depths within the aquifer depending on the recharge location and the subsurface flow paths (Fig. 4a). For example, Bbecause the groundwater table slope in unconfined aquifers is typically subdued in comparison to the land surface slope (Domenico and Schwartz, 1990), soil water that recharges the aquifer further upslope typically has a longer residence time and reaches greater depths relative to the land surface than soil water recharging the aquifer close to the discharge point. Groundwater flow in aquifers is often conceptualized as occurring in different 'flow channels' or 'flow tubes' (Domenico and Schwartz, 1990), and groundwater discharge is a thermal and hydraulic mixture of different groundwater flow channels coming from different depths and converging at the discharge point (Hoehn and Cirpka, 2006 and Fig. 4). Thus, when investigating employing one-dimensional solutions to investigate the thermal evolution of groundwater discharge to streams and rivers, an effective depth z_{eff} (m) must be considered that represents the bulk aquifer depth (i.e., accounting for all discharging groundwater flow channels) as a single point within the subsurface (Fig. 4). As a first estimate, this depth may be taken as the average unsaturated zone thickness. Figure 4b shows the conceptual model employed in this study. Above the effective depth, heat transport and water flow is assumed to be predominantly vertical as is often the case within the unsaturated zone, in overlying aquitards, or even in the upper portion of the aquifer (e.g., Kurylyk et al., 2014b). Within the aquifer (located at the effective depth), groundwater discharges horizontally towards a stream, and horizontal heat transport is assumed to be negligible due to the relatively low horizontal thermal gradients in this zone. Heat advection and associated thermal dispersion near the discharge point is assumed to dominate vertical heat transfer and thus create a thermally uniform zone. . Thus, the aquifer is treated as a thin, horizontally well-mixed thermal reservoir discharging to a surface water body (Fig. 4b). This approach is somewhat analogous to how contaminant hydrogeology studies have considered aquifers to be well-mixed reservoirs with respect to solute concentrations (e.g., Gelhar and Wilson, 1974). Vertical heat transfer continues below the aquifer (Fig. 4b). Limitations of this approach are briefly discussed later.

2.7 Groundwater thermal sensitivity to long term surface temperature perturbations

Groundwater thermal sensitivity is herein defined as the change in groundwater temperature at some depth and time divided by the driving change in surface (z = 0) temperature at the same time. For example, if the surface temperature increases by 2°C and the groundwater temperature has only increased by 1.4°C at that same time, then the groundwater thermal sensitivity is 0.7 (1.4°C/2°C). The temperature changes at the surface and in the aquifer are measured with respect to the initial temperatures at those locations. This definition for groundwater thermal sensitivity S (°C °C^{-1}) can be mathematically expressed in the following manner:

$$S(z,t) = \frac{\Delta \text{Subsurface Temp.}}{\Delta \text{Surface Temp.}} = \frac{T(z,t) - T(z,t=0)}{T(z=0,t) - T(z=0,t=0)} \quad (16)$$

This groundwater thermal sensitivity is the groundwater analogue of to the stream thermal sensitivity defined by Kelleher et al. (2012), although the temperature changes are measured on a longer timescale for groundwater (e.g., multi-decadal vs. seasonal). Equation (16) represents the thermal sensitivity at any arbitrary depth within the aquifer. The bulk (i.e., the entire portion of the aquifer discharging to the stream or river) groundwater thermal sensitivity in Eq. (16) can be found by replacing z with z_{eff}.

2.7.1 Groundwater thermal sensitivity to a step increase in surface temperature (land cover disturbance)

The groundwater thermal sensitivity S_s (subscript denotes nature of boundary condition) to a step increase in surface temperature occurring at t = 0 followed by subsequent surface cooling at $t = t_1$ can be found by inserting Eqs. (9), (10), and (11) into Eq. (16):

$$S_s(z,t) = \begin{bmatrix} \frac{1}{2}\left\{\operatorname{erfc}\left(\frac{z-Ut}{2\sqrt{Dt}}\right) + \exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+Ut}{2\sqrt{Dt}}\right)\right\} \quad \text{for } 0 \le t < t_1 \\ \\ \frac{1}{2}\left\{\operatorname{erfc}\left(\frac{z-Ut}{2\sqrt{Dt}}\right) + \exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+Ut}{2\sqrt{Dt}}\right)\right\} \quad \text{for } t \ge t_1 \\ -\frac{1}{2}\left\{\operatorname{erfc}\left(\frac{z-U(t-t_1)}{2\sqrt{D(t-t_1)}}\right) + \exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+U(t-t_1)}{2\sqrt{D(t-t_1)}}\right)\right\} \end{bmatrix} \tag{17}$$

Interestingly, the groundwater thermal sensitivity is not dependent on the magnitude of the step change in surface temperature ΔT or the initial temperature T_0, provided that the initial temperature is uniform. Eq. (17) ~~is~~ has the same form as the ~~classic~~ well-known solute transport analytical solution proposed by Ogata and Banks (1961) to calculate normalized solute concentrations.

As in the case of Eq. (11), Eq. (17) can be simplified to represent the influence of a permanent step increase (i.e., no subsequent cooling) in surface temperature by setting t_1 to infinity and only considering the first line on the right hand side of the equation. It should be noted that there is a subtle difference in the groundwater thermal sensitivity value presented in Eq. (17) compared to those presented in Eqs. (18) and (19) below. The change in the surface temperature after $t = t_1$ is 0°C, as indicated in the boundary condition (Eq. 10), and this would produce an infinite groundwater thermal sensitivity via Eq. (16). Thus, the change in surface temperature used for Eq. (17) was assumed to be temporally constant and equal to ΔT. Thus, Eq. (17) can be considered the groundwater thermal sensitivity in response to the maximum surface temperature change.

2.7.2 Groundwater thermal sensitivity to gradual increases in surface temperature (climate change)

Equation (16) can also be applied to obtain an expression for the groundwater thermal sensitivity S_L (°C °C^{-1}) due to a linear increase in the surface temperature boundary condition by inserting Eqs. (9), (12), and (13) into Eq. (16) and simplifying:

$$S_L(z,t)=\frac{1}{2Ut}\left[(Ut-z)\times\operatorname{erfc}\left(\frac{z-Ut}{2\sqrt{Dt}}\right)+(Ut+z)\exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z+Ut}{2\sqrt{Dt}}\right)\right] \quad (18)$$

Thus, S_L is independent of the initial temperature T_0 and the rate of surface warming β.

The groundwater thermal sensitivity S_E (°C °C^{-1}) to an exponentially increasing surface temperature can be obtained by inserting Eqs. (9), (14), and (15) into Eq. (16). The resultant solution can be further simplified by canceling terms and by remembering that T_0 is the sum of T_1 and b:

$$S_E(z,t)=\frac{(T_1-T_0)}{2b\{\exp(ct)-1\}}\left\{\begin{aligned}&\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}-\frac{U}{2}\sqrt{\frac{t}{D}}\right)\\&+\exp\left(\frac{Uz}{D}\right)\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}+\frac{U}{2}\sqrt{\frac{t}{D}}\right)\end{aligned}\right\}+$$
$$\frac{1}{2\exp(ct)-2}\exp\left(\frac{Uz}{2D}+ct\right)\left\{\begin{aligned}&\exp\left(-z\sqrt{U^2/4D^2+c/D}\right)\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}-\sqrt{\left(\frac{U^2}{4D}+c\right)t}\right)+\\&\exp\left(z\sqrt{U^2/4D^2+c/D}\right)\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}+\sqrt{\left(\frac{U^2}{4D}+c\right)t}\right)\end{aligned}\right\} \quad (19)$$

A spreadsheet is included in the electronic supplement that facilitates the calculation of the results for each of the analytical solutions and groundwater thermal sensitivity equations. The user may vary input parameters such as depth, thermal properties, groundwater velocity, time, initial temperature and the surface temperature boundary conditions.

2.8 Subsurface thermal properties

These analytical solutions invoke the assumption that subsurface thermal properties are homogeneous, but in reality the bulk thermal properties of unconsolidated soils depend on many factors, including the mineral constituents, porosity, total moisture saturation, and the pore water phase (Farouki, 1981; Kurylyk et al., 2014b). ~~For example, water~~ Water has a much higher thermal conductivity than air, thus the saturated zone typically is characterized by a higher bulk thermal conductivity than the unsaturated zone (Oke, 1988). Despite the existence of subsurface thermal property heterogeneities, natural variability in soil thermal properties is orders of magnitude less than the natural variability in hydraulic properties (Domenico and Schwartz, 1990), and thus homogeneous assumptions are better justified for subsurface heat transport than for subsurface water flow. Table 2 lists the bulk thermal properties for unfrozen sand, clay, and peat at three water saturations (volume of soil water/pore volume). These values are used to represent the typical ranges of thermal conductivities experienced in common unconsolidated soils. The bulk thermal diffusivities of these soils do not vary significantly at pore water saturations above 0.5.

3. Results and Discussion

3.1 Seasonal surface temperature influences on groundwater temperature

Stallman's (1965) equation (Eqs. 5-7) can be utilised to investigate how idealized subsurface environments respond to seasonal surface temperature changes. For example, Fig.ure 5 shows temperature-depth profiles for each month and temperature-time series for different depths in a soil column driven by a harmonic boundary condition at the surface (Eq. 4). The results were obtained from Eqs. (5) to (7) for sandy soil (thermal properties, Table 2) and for a downwards Darcy velocity (i.e., recharge) of 0.2 m yr^{-1}. This recharge value was chosen as a representative basin groundwater recharge (Döll and Fiedler, 2008; Healy, 2010). Stallman's equation generally matches seasonal groundwater temperature data reasonably well in shallow subsurface thermal environments, except in locations where snowpack can make the surface temperature non-sinusoidal and the subsurface thermal envelope (Fig. 5a) somewhat asymmetrical (Lapham, 1989). Regardless, Eq. (5) and Fig. 5 both demonstrate that the seasonal subsurface temperature variability is exponentially attenuated with depth and is barely discernible beyond a certain depth (e.g., 10-14 m).

The exponential damping factor Ω is the ratio of the amplitude of the seasonal temperature cycle at an arbitrary depth z to the amplitude of the seasonal surface temperature cycle (Eq. 8). It is thus a measure of how the subsurface thermal regime responds to seasonal temperature variations, and it can be considered the seasonal counterpart to the groundwater thermal sensitivities derived from the analytical solutions experiencing long term surface temperature variability (e.g., Eq. 17). ~~Clearly,~~Figure 6 illustrates that the exponential damping factor (or seasonal thermal sensitivity) Ω for a given depth decreases for the discharge scenario (black series, Fig. 6) in comparison to the recharge scenario (dashed blue series). In a discharge scenario, the upward advective flux is impeding the downward propagation of the surface temperature signal, and thus the surface signal is more quickly attenuated.

~~A comparison of Figs~~Figures~~.~~ 6a, 6b, and 6c also indicate~~s~~ that the soil thermal properties greatly influence the subsurface thermal response to seasonal temperature variability. In particular, due to the significantly lower thermal diffusivity of partially saturated peat (Table 2), the surface temperature signal (Fig. 6c) is more quickly damped in the peat soil in comparison to the results obtained for sand (Fig. 6a) and clay (Fig. 6b). However, in all of the nine scenarios presented in Fig. 6, the Ω parameter is less than 0.2 (amplitude reduced by at least 80%) when the depth is greater than 5 m, which indicates that groundwater discharge does not have to be sourced from a very deep aquifer to decrease the stream thermal sensitivity to seasonal air temperature changes.

3.2 Impacts of land cover disturbances on groundwater temperatures

Beyond the depth of seasonal temperature fluctuations (Fig. 5), groundwater temperature will still be influenced by long term surface temperatures perturbations. For instance, Figure 7a (solid lines) shows the groundwater warming produced with Eq. (11) at different depths and for different soils ~~by~~ due to a sudden and permanent ($t_1 = \infty$, Eq. 10) mean annual surface temperature increase of 2°C. This is approximately the long term mean annual surface temperature increase observed by Lewis (1998) in response to deforestation. This is at the lower end of the range (1.6 to 5.1°C) in the mean annual surface temperature increases noted by Taniguchi et al. (1998) following forest removal in Western Australia. The groundwater *warming*, rather than the *temperature*, is obtained by setting the initial temperature to zero (T_0, Eqs. 10 and 11).

Results are presented for sandy soil and peat soil as these two soils respectively exhibit the highest and lowest thermal diffusivities given in Table 2. Due to the nature of the surface thermal boundary condition, these groundwater warming series exhibit a convex upward curvature. The results for the two depths (5 and 20 m) indicate that the lag between the surface and subsurface warming increases with increasing depth. ~~For example, for~~ For the sandy soil, the temperature at a depth of 20 m increases by 1.77°C after 100 years, whereas at 5 m depth, this magnitude of warming was realized after only 14 years. Thus, for initially uniform conditions, deeper aquifers will generally remain colder longer than shallow aquifers, as it takes longer for the warming signal to be advected or conducted downwards. Furthermore, Fig. 7a also indicates that soils with a higher thermal diffusivity (i.e., sand) will initially transport the surficial warming signal through the subsurface more rapidly than soils with lower thermal diffusivity (i.e., peat). However, because the subsurface is slowly equilibrating with the new constant surface temperature, the solid series representing the results for the different depths and soils begin to converge as time increases.

In the case of vegetation regrowth, the surface temperature warming due to the land cover disturbance would be temporary. As an illustrative example, Fig. 7a (dashed lines) shows the groundwater warming produced by Eq. (11) at two depths (5 and 20 m) and for two soils due to a sudden 2°C increase in surface temperature that persists for only 25 years (t_1, Eq. 10). If desired, the equation could be further enhanced to accommodate a gradual cooling phase, rather than the instant cooling employed in the present study, using the more general formula described by Menberg et al. (2014). In Fig. 7a, the dashed and solid lines overlap prior to the cooling phase occurring at 25 years. The dashed temperature curves after 25 years represent the thermal recovery period. The groundwater warming curve for a depth of 5 m and the more diffusive soil (sand) is sharp, whereas the groundwater warming curve for a depth of 20 m and the less diffusive soil (peat) is more diffused and lagged. For example, the maximum groundwater warming (0.88°C) for the peat soil at a depth of 20 m occurs at 33 years, which is 8 years after the surface warming has ceased. Thus, temporary deforestation thermal impacts to coldwater streams may persist several years after vegetation regrowth has occurred, particularly if groundwater discharge to the stream is sourced from a deeper aquifer. However, these effects would likely not be significant as the warming signal would be strongly damped.

Figure 7b shows the aquifer thermal sensitivities in response to a sudden permanent (solid lines) or temporary (dashed lines) step increase in surface temperature, which correspond to the same warming scenarios as shown in Fig. 7a. As indicated in Eq. (17), these thermal sensitivity curves are similar to the groundwater warming curves (Eq. 11 and Fig. 7a), but scaled ~~down~~ by a factor of ΔT. Hence, the thermal sensitivity curves due to a step increase in surface temperature are normalized with respect to the boundary temperature increase and are thus independent of the ΔT value. The results presented in Fig. 7 clearly demonstrate that shallow groundwater will initially warm rapidly in response to permanent deforestation and then the rate of temperature increase will decrease with time. This arises due to the initially high thermal gradient and heat conduction arising from the abrupt surface step change in temperature. The resultant impacts of groundwater warming on streambed conductive and advective heat fluxes should be considered in models that simulate stream temperature warming due to deforestation—at least for streams where groundwater discharge has been shown to influence stream temperature. Small headwater streams, which are often groundwater dominated, can warm more rapidly than larger streams in response to deforestation because, for natural vegetative conditions, smaller streams typically experience more shading than larger rivers (e.g., Caissie, 2006).

The results shown in Fig. 7 are presented for a recharge scenario (q = 0.2 m yr^{-1}). This approach is conservative ~~as~~ because recharge environments will typically warm more rapidly in response to rising surface temperatures than discharge environments, as conduction and advection are acting in parallel in the former case. The analytical solutions ~~listed~~ provided in this ~~contribution~~ study for simulating subsurface warming due to long term surface temperature trends (Eqs. 11, 13, and 15) are better suited for recharge environments than discharge environments as groundwater discharge can bring up warm groundwater from deeper within the aquifer in accordance with the geothermal gradient. This phenomenon is not accounted for in the uniform initial conditions (Eq. 9). These solutions can be modified to allow for linearly increasing temperature with depth to account for the geothermal gradient (Kurylyk and MacQuarrie, 2014; Taniguchi et al. 1999a, 1999b), but this adds complexity to the resultant sensitivity formulae. Also as previously noted, this study is primarily concerned with shallow aquifers where heat fluxes due to surface temperature changes can dominate the influence of the geothermal gradient.

3.3 Impacts of climate change on groundwater temperatures

Equations (13) and (15) can be employed to investigate the sensitivity of groundwater temperatures to long term gradual surface temperature changes such as those experienced during climate change. The IPCC (2007) multi-model results (Fig. 2) are globally averaged results, and these data will be used to form the surface boundary conditions for the illustrative examples presented herein as they are representative of typical local-scale air temperature projections for this century.

3.3.1 Exponential and linear boundary conditions

The IPCC air temperature anomalies (i.e., increases) for this century produced by the conservative emission scenario B1 were fit to a linear surface temperature function (Fig. 2). The best fit between the linear function and the projected B1 air temperature warming (root-mean-square-error = 0.05°C) was obtained with a slope β of 5.41×10^{-10} °C s^{-1} (1.7 °C per century, see Eq. 12). Also, the exponential function was employed to represent the IPCC multi-model results obtained using the more aggressive, non-linear A2 emission scenario (Fig. 2). The optimal exponential fit (root-mean-square-error = 0.04°C) was obtained with fitting parameters *b* and *c* of 1.59°C and 3.67×10^{-10} s^{-1}, respectively (Eq. 14). The RMSE values for the exponential and linear fits are presented in Fig. 2. The fitting parameter T_1 ($T_0 - b$) can be adjusted to obtain the desired initial temperature, and herein we consider the subsurface warming (rather than the temperature *per se*) by setting initial temperatures to 0°C (i.e., $T_1 = -b$).

3.3.2 Groundwater warming due to climate change

Eq. (13) was employed to demonstrate how an idealised, shallow aquifer would respond to a slow linear surface temperature rise (Fig. 3c). Figure 8a shows the groundwater warming results at different depths and for different soils calculated with Eq. (13) by applying a 0.017 °C yr^{-1} linear surface warming as the boundary condition (B1, Fig. 2). The starting date is the year 2000. Similar to the results presented above for land cover disturbances, the surface warming is more rapidly propagated to shallower depths (i.e., 5 m vs. 20 m) and for more thermally diffusive soils (sand vs. peat). For example, afterAfter 100 years, the 1.7°C surface warming produced a 1.6°C increase in groundwater temperature for the sandy soil at a depth of 5 m (solid red series), but only a 0.94°C increase for the peat soil at a depth of 20 m (dashed black series, Fig. 8a).

Solution results were also obtained for recharge rates of 0.4 m yr^{-1} and 0.001 m yr^{-1} to investigate the influence of vertical groundwater velocity on the timing and magnitude of groundwater temperature evolution. These recharge values are representative of the typical range in natural groundwater recharge (e.g., Healy, 2010). The same soil thermal properties (sand) and linear surface warming rate used for Fig. 8a were utilized to parameterize the solution to investigate the role of groundwater recharge in accelerating and/or intensifying groundwater temperature warming. The results (not shown) demonstrated that higher groundwater recharge produces more rapid subsurface warming than lower recharge rates due to higher advective heat transport in the former case. For instance, after 100 years, the resultant groundwater warming was only 1.08°C for the sandy soil at a depth of 20 m and subject to a negligible recharge rate (pure conduction) compared to 1.34°C for the same soil and depth but with a recharge rate of 0.4 m yr^{-1}. In the case of high groundwater recharge (0.4 m yr^{-1}), the groundwater temperature at 20 m increased by 1.08°C in only 84 years, which is 16 years earlier than the timing of the same magnitude of warming to be realized in the case of negligible recharge. Thus, shallow aquifers exposed to higher recharge rates may be more vulnerable to climate change from a thermal perspective.

Figure 8b shows the groundwater warming results produced with the analytical solution that accommodates exponential increases in surface temperature (Eq. 15). The boundary condition (Eq. 14) was parameterized by fitting the exponential function to the IPCC multi-model A2 climate projections (Fig. 2). The soil thermal properties and recharge rates are identical for the results shown in Figs. 8a and 8b, and thus the only difference between the two figure panels is the surface temperature boundary condition. Predictably, the groundwater warming curves presented for the exponential A2 warming scenario in Fig. 8b exhibit more concavity than those for the linear B1 warming scenario (Fig. 8a). The results shown in Figs. 8a and 8b for a given soil type and depth (i.e., same colour and line type) begin to significantly diverge after approximately 30 years because the IPCC A2 multi-model projections exhibit more extreme warming than the B1 projections after 2030 (Fig. 2). In general, due to the different boundary conditions employed, the groundwater warming scenarios shown in Fig. 8b are approximately twice as strong as those shown in Fig 8a after 100 years (note difference of vertical scale). For example, Fig. 8b indicates that an exponential surface temperature increase of 3.5°C over the next 100 years (green series) would result in a groundwater temperature increase of 2.3°C for the sandy soil at a depth of 20 m (black, solid series), whereas a linear surface temperature increase of 1.7C over the next 100 years would increase groundwater temperature by only 1.2°C for the same soil type and depth (grey, solid series, Fig. 8a).

3.3.3 Groundwater thermal sensitivity due to climate change

Figures 8c and 8d show the groundwater thermal sensitivity (Eqs. 18 and 19) results due to the linear surface warming and the exponential surface warming shown in Figs. 8a and 8b, respectively. Although the surface warming scenario shown in Fig. 8b is much more pronounced than that shown in Fig. 8a, it is interesting to note that the groundwater thermal sensitivity results for these warming scenarios are very similar (Figs. 8c and 8d) ~~as~~ because the thermal sensitivity is essentially the thermal effect divided by the driving cause. Figs 8c and 8d illustrate that the thermal sensitivities are generally higher at shallower depths and for more thermally diffusive soils as groundwater temperature warming would be manifested more quickly in these cases. ~~Thus, streams sourced from deeper aquifers with less thermally diffusive overlying soil (e.g., the unsaturated zone, Fig. 4) would not experience as much increase in streambed advective heat fluxes as streams sourced from shallower aquifers with more thermally diffusive overlying soil.~~

Due to the lag between the surface warming and the subsurface thermal response, the subsurface thermal regime will never reach equilibrium with the surface thermal regime when the boundary condition represents continuous surface temperature increases. Hence, the groundwater thermal sensitivities will never attain unity unless a stable surface temperature regime is eventually established. However, Figs. 8c and 8d indicate that the groundwater thermal sensitivity increases with time as the magnitudes of both the surface and subsurface temperature warming increase, and thus the relative impact of the lag decreases. For example, after 100 years, the thermal sensitivity of the sandy soil at a depth of 5 m is about 0.90 for both the B1 linear warming scenario (Fig. 8c) and the A2 exponential warming scenario (Fig. 8d). Thus, shallow groundwater at this depth and for ~~this soil~~these conditions would ~~most likely~~ warm ~~change~~ by approximately 90% of the ~~expected~~ surface temperature increase within 100 years.

3.4 Implications for groundwater-dominated streams and rivers

The consideration of groundwater temperature in stream temperature modeling is especially relevant in small streams where surface heat fluxes ~~no longer~~do not dominate the total energy budget. In fact, small streams are generally very dependent on groundwater inputs and temperatures, and their low thermal capacity (shallow depth and volume) makes them very vulnerable to any surface or subsurface energy flux modifications (e.g., Matheswaran et al., 2014). ~~For example, this~~ This has been shown in many timber harvesting studies, where the smallest streams have experienced the greatest increase in stream temperature following forest removal (e.g., Brown and Krygier, 1970). Thus, quantifying future changes in shallow groundwater flow and temperatures is essential for a better understanding of the future thermal regimes of groundwater-dominated rivers and associated impacts to aquatic organisms (Kanno et al., 2014).

The results presented in Fig. 8 ~~have important implications for stream and river thermal regimes influenced by groundwater discharge. In particular, these results~~ demonstrate the limitations inherent in inferring future stream warming from stream thermal sensitivities obtained from ~~sub-annual~~seasonal ~~-~~stream and air temperature data. For instance, the seasonal groundwater thermal sensitivity (Ω) values presented in Fig. 6 indicate that groundwater temperature beyond 10 m depth generally exhibits minimal sensitivity to seasonal variations in weather. Thus, groundwater-dominated stream thermal sensitivities obtained from seasonal air and stream temperature data are typically low (Kelleher et al., 2012). However, as Figs. 8c and 8d illustrate, ~~groundwater thermal sensitivities~~groundwater warming at depths ~~>~~ greater than 10 m may still be significant in response to long term surface temperature changes, such as would be experienced under climate change. ~~For a given surface warming scenario, the magnitude of the groundwater thermal sensitivity depends on the time, depth, subsurface thermal properties, and vertical groundwater flow.~~ Due to the interrelationships between the thermal regimes of stream and aquifers and the differences between the thermal sensitivities of shallow aquifers to short term (Fig. 6) and long term (e.g., Figs. 7b and 8) surface temperature changes, it is not generally valid to extrapolate thermal sensitivities for groundwater-dominated streams obtained from sub-annual data to project long term stream warming. ~~Long term surface temperature warming due to climate change and/or land cover disturbances will increase the temperature of shallow groundwater and influence streambed heat fluxes, and these processes should be accounted for in stream temperature models.~~

These results ~~also~~ demonstrate the potential limitations of using relatively short records of inter-annual air and water temperature data to obtain estimations of future stream warming. ~~For example,~~ Luce et al. (2014) obtained stream and air temperature data for 256 temperature stations in streams of the Pacific Northwest of the United States to determine a range of stream thermal sensitivities. These stations collected data for time spans ranging from 7 to 23 years. Their results suggested that cold streams (including groundwater-dominated streams) exhibited lower thermal sensitivities than warmer streams on inter-annual time scales. However, results for the present study (Figs. 8c and 8d) indicate that even at a time scale of 23 years, the thermal sensitivities of relatively shallow (e.g., 10 m) groundwater reservoirs may be very low compared to the thermal sensitivities that could be attained after 100 years of surface warming. For example, Fig. 8c indicates that the thermal sensitivity for peat soil at a depth of 10 m (dashed blue series) is 0.38 at 23 years but increases to 0.69 after 100 years. Furthermore, the aquifer thermal sensitivities would continue to increase, albeit at a slower rate, if the time were extended for another 100 years. Hence, We acknowledge, however, that extrapolating employing thermal sensitivities derived from inter-annual temperature data to project future stream warming is preferable to considering thermal sensitivities from seasonal obtained for relatively short inter-annual time scalestemperature data (Luce et al., 2014) to predict future stream warming for many decades into the future may not always be appropriate. The appropriateness of these methods depend on the depth to the aquifer, the degree of groundwater contribution to the stream/river, the subsurface thermal properties, and the timescale of interest.

These results suggest that what is interpreted as a damped groundwater-dominated stream thermal sensitivity to inter-annual air temperature variability may actually be a delayed thermal sensitivity due to the lag in the warming of groundwater and associated streambed heat fluxes. These results may also help to partly explain why Arismendi et al. (2014) found that regression-based models of stream temperature performed poorly when they are were applied to reproduce observed long term trends in stream temperature.

long term will not truly represent the relationship between which are expected to be most sententivethat air and surface temperatures are perfectly coupled, which the present study shows is not the case for long term studies

We acknowledge that projecting future stream warming from short inter-annual datasets may be more valid for stream and river thermal regimes that are not significantly influenced by streambed advective heat fluxes. However, this approach ignores the potential for future changes in other parameters (e.g., precipitation and streamflow), which may also exert control on future stream thermal sensitivity (Ficklin et al., 2014; van Vliet et al., 2011). Also, in some streams or rivers where current streambed heat inputs are less important, climate change may produce significant increases in the magnitude of groundwater discharge (Bense et al., 2009; Kurylyk et al., 2014a) and thus cause advective streambed heat fluxes to become more important.

3.5. Addressing groundwater warming in stream temperature models

The present study demonstrates the importance of surface temperature forcing on groundwater temperature, particularly for shallow aquifers. The potential influence of shallow groundwater warming on stream temperatures is not generally considered in existing empirical stream temperature models. Regression-based models may thus produce stream temperature warming scenarios that are overly conservative. Similarly, deterministic stream temperature models that neglect potential changes in groundwater temperature and streambed heat fluxes may underestimate future stream warming in response to changes in land cover or climate. The equations proposed in this study can be used to develop an approach to approximate the timing and magnitude of groundwater temperature warming in response to long term surface temperature changes. As described below, this information may be integrated within existing stream temperature models that consider streambed heat fluxes.

The upper boundary condition for the equations presented in this study is the ground surface temperature. Thus, Prior to utilising these equations, the projected trends in catchment land surface temperature due to future climate change or land cover disturbances must be obtained prior to utilising these equations. A detailed discussion on appropriate techniques for simulating these relationships can be found, for example, in Mellander et al. (2007), Kurylyk et al. (2013), and Jungqvist et al. (2014). In the case of climate change without concomitant related snowpack changes, mean annual surface temperature trends are often assumed to follow mean annual air temperature trends (see Mann and Schmidt, 2003). This simplification facilitates the boundary condition generation because air temperature trends can be readily obtained from the output of climate models. However, in the case of land cover changes (e.g. urbanisation) or snowpack evolution, mean annual air temperature trends may be decoupled from mean annual surface temperature trends (Mann and Schmidt, 2003; Mellander et al., 2007). In this situation, a simple surface heat flux balance model can be applied to calculate the surface temperature changes due to changes in the climate and/or land cover. A detailed discussion on appropriate techniques for simulating these relationships can be found in Mellander et al. (2007), Kurylyk et al. (2013), and Jungqvist et al. (2014).

Once the~~The~~ surface temperature trends are obtained, they can then be fit to the appropriate boundary condition function ~~presented in this study as shown in(~~ Fig. 3). The ~~appropriate~~ associated analytical solution (Table 1) and groundwater thermal sensitivity formula ~~associated with the chosen boundary condition~~ can be utilized to perform simulations of future subsurface warming and/or groundwater thermal sensitivity due to the surface temperature change. It should be noted that these solutions only calculate increases in mean annual groundwater temperature and do not account for ~~, but its~~seasonality. It is generally reasonable to assume that the amplitude and timing of the seasonal groundwater cycle will not be greatly influenced by climate change (Taylor and Stefan, 2009), provided snowpack conditions or the seasonality of soil moisture will not change significantly (Kurylyk et al., 2013).

In addition to the surface temperature boundary condition terms, the~~se~~ analytical solutions must be parameterized with subsurface thermal properties, vertical groundwater flow ~~conditions~~information, and effective aquifer depth. Subsurface thermal properties can be obtained from information regarding the soil type and typical water saturation of the sediment overlying the aquifer (Table 2). Vertical groundwater flow rates can be obtained from field measurements (e.g., using heat as a hydrologic tracer, Gordon et al., 2012; Lautz, 2010; Rau et al., 2014) or from regional or local groundwater recharge and discharge maps. Potential changes in groundwater recharge (Crosbie et al., 2011, Kurylyk and MacQuarrie, 2013; Hayashi and Farrow, 2014) and groundwater discharge (Kurylyk et al., 2014a; Levison et al., 2014) due to changes in climate or land cover could also be considered. The aquifer effective depth can be crudely ~~and conservatively~~ estimated as the average unsaturated zone or aquitard thickness overlying the aquifer (e.g., Figure 4). Such information may be available from well data, geophysical surveys, or regional maps of the groundwater table depth (Fan et al., 2013; Snyder, 2008). Further research is required to assess approaches for more accurately determining the effective aquifer depth~~.~~ A reasonable range of the input variables to these equations should be considered to generate an envelope of predicted groundwater warming (see Fig. 4 of Menberg et al., 2014). Such a range could incorporate uncertainties arising from, for example, heterogeneities in soil thermal properties and inter-annual variability in groundwater recharge (Hayashi and Farrow, 2014). Table 3 lists alternative options for parameterizing the equations presented in this study. The parameter values used in the present study are representative of conditions often observed.

To determine the influence of warming groundwater on stream temperatures, the future groundwater thermal sensitivity can be applied to estimate the resultant changes to streambed heat fluxes. There are different approaches available for estimating streambed heat fluxes from subsurface temperatures depending on whether the total streambed energy flux or the apparent sensible flux is being considered (e.g., Caissie et al., 2014, Moore et al., 2005), but in either case, the streambed fluxes depend on subsurface temperature, particularly the temperature immediately below the stream. These changes in streambed heat fluxes can then be combined with simulated changes in stream surface heat fluxes, and the resultant change in stream temperature can be obtained in a deterministic stream temperature model. Such an approach to estimate long term evolution of stream temperatures would be more realistic than considering a stream temperature model driven by air temperature only, as both surface and streambed heat fluxes are important in stream temperature dynamics.

~~However,~~. ~~this approach ignores the potential for future changes in other parameters (e.g., precipitation and streamflow), which may also exert control on future stream thermal sensitivity (Ficklin et al., 2014; van Vliet et al., 2011). Also, in some streams or rivers where current streambed heat inputs are less important, climate change may produce significant increases in the magnitude of groundwater discharge (Bense et al., 2009; Kurylyk et al., 2014a) and thus cause advective streambed heat fluxes to become more important.~~

4. Limitations

The unsteady heat diffusion-advection equation utilized in this study (Eq. 2) assumes one-dimensional groundwater flow and heat transport, spatiotemporally invariant groundwater flow, isothermal conditions between the soil grains and water at every point, and homogeneous thermal properties. Flashy groundwater flow regimes with very short residence times (e.g., aquifers with large fractures) may invalidate the assumption of thermal equilibrium between the subsurface environment and the mobile water. In such settings, recharge seasonality may exert strong control on the temperature of groundwater discharge (Luhmann et al., 2011). Horizontal groundwater flow can perturb subsurface thermal regimes, at least in regions with significant horizontal thermal gradients (Ferguson and Bense, 2011; Reiter, 2001), and there may be a vertical discontinuity in vertical water flow across aquifers due to horizontal discharge to surface water bodies (e.g., Fig. 2). Aquifers that exhibit considerable lateral hydraulic heterogeneities may be characterized by flow regimes that are not well represented by the conceptual model (Fig. 2).

Herein, we propose that the average depth to the groundwater table may be a reasonable approximation for the effective depth (z_{eff}). This approach assumes that the groundwater temperature at the bottom of the vertical flow tubes is fully mixed and that there is no modification of the temperature signal as the groundwater flows horizontally towards the discharge location (Fig. 4). This assumption may be violated in very shallow aquifers with slow groundwater flow (i.e., low horizontal advection and dispersion) due to vertical conductive heat fluxes from the surface in the vicinity of the discharge location.

In very shallow aquifers, groundwater velocity varies seasonally and is driven by the seasonality of precipitation, but subsurface hydraulic storage properties tend to damp the seasonality of groundwater flow in comparison to precipitation. Eq. (2) also assumes that no soil thawing occurs as a result of the surface temperature change, but latent heat absorbed during soil thaw can significantly retard subsurface warming (Kurylyk et al., 2014b). Ignoring soil thaw is reasonable, except in permafrost regions, because in ephemerally freezing regions the dynamic freeze-thaw process only influences the seasonality of groundwater temperature, and does not significantly influence the change in mean annual groundwater temperature in response to long term climate change (Kurylyk et al., 2014a).

At very shallow depths (e.g., < 3m), the subsurface thermal regime can be considered to be in equilibrium with the mean annual surface temperature. Because the lag between surface and subsurface warming is negligible in this case, the solutions presented in this study are not overly useful at very shallow depths. Also, at greater depths (e.g., 25 m), the influence of the geothermal gradient should be explicitly considered. In such cases, the equations proposed in this study can be modified to incorporate a geothermal gradient (Kurylyk and MacQuarrie, 2014; Taniguchi et al., 1999a; 1999b). Despite these limitations, these analytical solutions presented here can be employed to obtain reasonable estimates of the evolution of mean annual groundwater temperature due to climate change and land cover disturbances for a broad range of aquifer depths. For example, Menberg et al. (2014) applied these approaches to calculate groundwater warming trends that generally concurred with measured 1970-2010 groundwater warming trends recorded at forested and agricultural sites in Germany. The parsimonious

~~approach proposed in this study is preferred to merely ignoring groundwater temperature evolution and the associated impacts to streambed heat fluxes in groundwater-dominated streams.~~ We anticipate that other studies may also benefit from these approaches.

5. Summary and conclusions

Stream temperature models often ignore the potential for future groundwater warming ~~to influence stream temperatures~~. This simplifying assumption is employed because mean annual groundwater temperature is relatively constant (or thermally insensitive) on the intra-annual or short inter-annual time scales that it is typically measured. We have demonstrated in this study that although seasonal surface temperature changes are damped in the shallow subsurface, long term changes in surface temperatures can be propagated to much greater depths. This phenomenon has been known for some time in the field of thermal geophysics, but it is generally overlooked in stream temperature modeling. Due to the difference in the subsurface thermal response to seasonal and multi-decadal surface temperature changes, it may be inappropriate to infer multi-decadal warming of groundwater-dominated streams based on linear regressions of short term air and water temperature data.

Previous studies have identified the potential importance of considering shallow groundwater temperature warming when projecting future stream temperature (Kurylyk et al., 2013; 2014a). These studies have employed methods that either require extensive surface and subsurface temperature data collection or detailed numerical modeling. In many cases, these methods may be prohibitive. Several analytical solutions and associated groundwater thermal sensitivity equations are herein presented as alternative approaches for estimating a range for the potential timing and magnitude of future groundwater warming in response to climate change or land cover disturbances. ~~The groundwater thermal sensitivity formulae developed in this study can be applied in stream temperature models to consider the interrelationships between climate change, groundwater warming, and surface water warming.~~ These are most applicable to idealized environments, but the methods can be employed to obtain first-order approximations of future groundwater warming in natural environments (see Menberg et al., 2014). The subsurface warming scenarios can be considered within existing stream temperature models to investigate whether groundwater warming is an important consideration for the future thermal regime of a particular stream- (Snyder et al., 2015).

The present study has highlighted the importance of shallow groundwater sensitivity to surface warming. Although groundwater warming has been inferred from subsurface temperature-depth profiles at many sites, few long term datasets of directly measured groundwater temperature exist to corroborate the methods proposed herein (Menberg et al, 2014). The initiation of long-term shallow groundwater temperature monitoring sites would provide a better understanding of the processes linking atmospheric and subsurface warming (e.g., Caldwell et al., 2014b).

~~The resultant aquifer warming could increase net streambed heat fluxes and consequently warm groundwater-dominated streams. Thus, models that do not consider the potential for groundwater warming likely underestimate the thermal sensitivity of such streams to future climate change. Consequently, the predicted loss of thermally suitable habitat for coldwater fish species presented in many studies may be overly conservative.~~

~~The generally accepted assumption that groundwater-dominated streams will warm less in response to climate change than surface runoff-generated streams is not universally true. In fact, the warming may eventually be greater in groundwater-dominated streams, which have temperatures that are significantly influenced by subsurface heat fluxes and which do not experience the same evaporative cooling effect observed in warmer streams (Mohseni and Stefan, 1999). The groundwater discharge to these streams, which reduces their thermal sensitivity to variations in weather, will not necessarily also damp their thermal sensitivity to climate change or deforestation, at least not after several decades of time has passed. The groundwater thermal sensitivity formulae developed in this study can be applied in stream temperature models to consider the interrelationships between climate change, groundwater warming, and surface water warming.~~

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Figure 1: Heat fluxes at the water surface and streambed for the cross-section of a gaining stream or river (modified from Caissie, 2006).

Figure 2: IPCC Multi-model globally averaged air temperature anomaly projections for the 21st century relative to the air temperature data for 1980-1999 for emission scenarios B1 and A2 (data from, IPCC, 2007)**.** Details concerning the exponential and linear fits to the IPCC projections are given in Section 3.3.1. Modified from Kurylyk and MacQuarrie (2014).

Figure 3: (a-b) The boundary conditions for ground surface temperature (GST) disturbances due to land cover changes. Both (a) and (b) represent the boundary condition given in Eq. (10). The difference between these is the duration of the period of warm surface temperatures ($t_1 = \infty$ in (a)). (c-d) The boundary conditions for GST due to long term climate change for conservative (linear, Eq. 12) and aggressive (exponential, Eq. 14) climate scenarios.

Figure 4: (a) Groundwater flow and heat transport in a two-dimensional cross-section of an aquifer-stream system. (b) Conceptual model of the physical processes shown in (a). Dashed arrows indicate heat transport, and solid arrows indicate water flow.

Figure 5: (a) Temperature-depth profiles for each month obtained from Stallman's equation (Eqs. 5-7) for homogeneous soil subject to harmonic seasonal surface temperature variation. (b) Temperature-time series generated with Stallman's equation for depths of 0, 1, 5, and 10 m. In (a) and (b) the thermal properties for sand at 50% saturation (Table 2) were employed, and a recharge Darcy velocity of 0.2 m yr^{-1} was assumed. The boundary condition parameters T_m, A, ϕ, and p were assigned values of 10°C, 15°C, -4.355 radians, and 31,536,000 s (1 yr), respectively to represent typical surface temperature conditions for a forested site in New Brunswick, Canada (e.g., Kurylyk et al., 2013).

Figure 6: Exponential damping factor (seasonal temperature sensitivity) Ω (Eq. 8) vs. depth for (a) sandy soil, (b) clay soil, and (c) peat soil. The thermal properties were taken from Table 2 assuming a volumetric water saturation of 50%. Results are presented for Darcy velocities of 0.2 m yr^{-1} (recharge, downwards flow), 0 (conduction-dominated thermal regime), and -2 m yr^{-1} (discharge, upwards flow) and a period of 1 year. A higher discharge value was used in comparison to the recharge value given that discharge is typically concentrated over a smaller area than recharge.

Figure 7: (a) Groundwater temperature warming due to a permanent (solid lines) or temporary (dashed lines) step increase in surface temperature vs. the time since the surface warming began. (b) Groundwater thermal sensitivity vs. time for each of the eight scenarios presented in (a). The results shown in (a) were obtained with Eq. (11) driven with the step boundary condition (Eq. 10), with $\Delta T = 2$°C and t_1 = infinity (~~or at least > 100 yr,~~ solid lines) or 25 years (dashed lines). The subsurface thermal properties were taken from the 50% saturated sand and peat values in Table 2, and the recharge rate was 20 cm yr^{-1}. The results shown in (b) were calculated with Eq. (17) using the same parameters as (a).

Figure 8: Groundwater temperature warming due to a linear trend (a) and an exponential trend (b) in surface temperature vs. the time since the surface warming began ~~(vertical axes to different scales)~~. (c) and (d) Groundwater thermal sensitivity vs. time for each of the six scenarios presented in (a) and (b), respectively. The results shown in (a) were obtained with Eq. (13) ~~driven with the linear boundary condition (Eq. 12),~~ with $\beta = 5.41\times10^{-10}$ °C s^{-1} based on ~~matching~~ the IPCC ~~multi-model~~ B1 projections and setting T_0 = 0°C. The results shown in (b) were obtained with Eq. (15) ~~driven with the exponential boundary condition (Eq. 14) fitted to the IPCC A2 projections:~~ with T_1, b, and c = -1.59°C, 1.59°C, and 3.68×10^{-10} s^{-1}, respectively (to match the IPCC A2 projections). The subsurface thermal properties were ~~taken from the~~for 50% saturated ~~sand and peat values in~~soil (Table 2), and the recharge rate was 20 cm yr^{-1}. The aquifer thermal sensitivities shown in (c) and (d) were calculated with Eqs. (18) and (19) respectively~~,~~ ~~using the same parameters as in (a) and (b)~~.

Table 1: Details regarding the four analytical solutions employed in this study[1]

Solution ID	Equation number	Time scale	Surface temperature[1]	Solution reference
1	(5)	Seasonal or diel	Sinusoidal	(Stallman, 1965)
2	(11)	Multi-decadal	Step change(s)	(Menberg et al., 2014)
3	(13)	Multi-decadal	Linear increase	(Taniguchi et al., 1999a)
4	(15)	Multi-decadal	Exponential increase	(Kurylyk and MacQuarrie, 2014)

[1]For boundary conditions, see Eq. (4), (10), (12), and (14) respectively.

Table 2: Bulk thermal properties of some common soils and their dependence on saturation[1]

Saturation (vol/vol)	Thermal conductivity λ (W m^{-1} °C^{-1})	Heat capacity $c\rho$ (10^6 J m^{-3} °C^{-1})	Thermal diffusivity D (10^{-6} m^2 s^{-1})
	Sandy soil (porosity = 0.4)		
0	0.30	1.28	0.24
0.5	1.80	2.12	0.85
1.0	2.20	2.96	0.74
	Clay soil (porosity = 0.4)		
0	0.25	1.42	0.18
0.5	1.18	2.25	0.53
1.0	1.58	3.10	0.51
	Peat soil (porosity = 0.8)		
0	0.06	0.60	0.10
0.5	0.29	2.23	0.13
1.0	0.50	4.17	0.12

[1] Data obtained from Monteith and Unsworth (2007).

Table 3: Parameters for equations considered in this study

Symbol	**Physical meaning**	**Units**	**Determination method**	**Example Sources**
D	Thermal diffusivity	m^2 s^{-1}	Obtain from tabulated values (e.g. Table 2)	(Oke, 1978; Monteith and Unsworth, 2007)
z, z_{eff}	Depth, effective depth[1]	m	Geophysics, groundwater table maps, local wells	(Fan et al., 2013; Snyder, 2008)
U, q	Thermal plume velocity, groundwater recharge[2]	m s^{-1}	Thermal tracing, lysimeters, local recharge maps	(Healy, 2010; Scanlon et al., 2002)
T_0	Initial temperature	°C	Mean annual surface temperature[3]	(USEPA, 2013)
T_m, A, ΔT, T_1, β, b, and c,	Surface temperature fitting parameters	Various	Climate model output, surface energy balance models[4]	(Kurylyk et al., 2013; Mellander et al., 2007; Taniguchi, 1993)

[1]The effective depth represents the bulk depth of the portion of the aquifer discharging to the stream (Fig. 4).
[2]U represents the thermal plume velocity only due to advection. This can be easily obtained if the groundwater recharge rate is known (see Eq. 3).
[3] In the absence of persistent snowpack, the mean annual surface temperature can be approximated with the mean annual air temperature. Otherwise a thermal offset can be assumed from literature values (Zhang, 2005).
[4] See Section 3.5 for more information.