

# ***Interactive comment on “Detecting groundwater discharge dynamics from point to catchment scale in a lowland stream: combining hydraulic and tracer methods” by J. B. Poulsen et al.***

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Response to reviewers' comments to the manuscript: Detecting groundwater discharge dynamics from point to catchment scale in a lowland stream: combining hydraulic and tracer methods MS No.: hess-2014-369

by J. R. Poulsen, E. Sebok, C. Duque, D. Tetzlaff, P. K. Engesgaard

The authors wish to thank the two anonymous reviewers for their comments and helpful suggestions to changes and corrections in the manuscript. We have addressed all comments and find that the resulting changes in the manuscript have helped to clarify

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several passages and generally improved the manuscript.

Note that references of pages, lines and figures with corrected parts of the manuscript refer to the manuscript version submitted in relation to this response to reviewers' comments.

Response to referee #1

Response to general remarks on the VTP's

Referee comment #1: Page 13108, Line 3: As far as I saw do you use all the measurements at 0, 0.025, 0.05, 0.075, 0.1, 0.15, 0.2, 0.3, 0.4 and 0.5m below the streambed and the groundwater temperature at 5 m depth to solve the analytical equation. Both Schmidt et al. (2007) and Anibas et al. (2011) recommend that for the steady state analysis only temperature measurements below the zone of diurnal temperature oscillations should be used for the analysis. Usually this is the zone between 0.1 and 0.2 m below the streambed. Otherwise the diurnal influences determine the final result. You use all of them-so it would be interesting to see how much your results would change if only the measurements of 0.15, 0.2, 0.3, 0.4 and 0.5m would be used for analysis! The new flux rates might be lower than the presented ones but would be more reliable and realistic.

Response #1: In our study we used temperature measurements from all depths below the streambed, but we agree with the reviewer that these measurements and consequently also the calculated groundwater fluxes would generally be influenced by the diurnal temperature oscillations. The reason we have such a high density of temperature measurements close to the streambed is that based on our experience with this stream, streambed temperatures become constant at shallow depth, even by 0.5 m below streambed (see reply to next comment), thus these measurements are often necessary to capture the transition from streambed to groundwater temperature. As shown on Figure 4 in the manuscript, the observed diurnal temperature change at the streambed was at most 2.5-3°C for layout B, 1.5-2°C for layouts A and C and most likely

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even lower below the streambed. Thus due to the small diurnal oscillations, we do not think that the streambed temperatures recorded by the upper sensors are considerably influenced.

Based on the comment of the reviewer we recalculated the fluxes only using temperature measurements at 0.15 cm and below the streambed surface. Using only these temperature measurements resulted in minor changes in the calculated fluxes (Figure R1). A significant difference in fluxes was only discovered on four occasions (see red circles on Figure R1), where the fluxes were quite high and temperatures close to groundwater temperature were observed close to the streambed (Figure R2). Even on these profiles it is possible to see that removing the upper temperature observations does not change the general shape of the temperature profile calculated by the analytical solution, thus we kept the original flux estimates in the manuscript.

Action #1: No action

Referee comment #2: P 13115, L 15-28 and P 13115-13116, L 29-5: I could imagine that the spatial trend and distribution of fluxes determined with fewer sensors would fit better with the results of the other methods. Regarding the range of the estimated results; I detected another methodological problem with: You measured the VTP beginning of June, hence in spring, a time when transient seasonal influences on the streambed temperatures are still strong (especially given the location in Northern Europe). Anibas et al. (2009) show that the results of a steady state analysis are sensitive to these seasonal transients. So you have to be aware that your presented results most probably overestimate the real fluxes. The methodology itself does not allow quantifying this effect; however you should discuss or recognize this in your manuscript. To conclude, I think that it is not impossible to do the steady-state analysis with your profiles, but it should be clearly stated that it is difficult to get a reliable quantitative estimate with them. Trends and distribution however should be OK.

Response #2: We agree with the reviewer that in general it is possible to detect sea-

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sonal influences in streambed temperatures in June. In the meanwhile we think that in this study due to the high upward fluxes the seasonal temperature differences can be almost entirely neglected. In Denmark groundwater temperature equals the annual average air temperature of around 8-8.5°C. In the majority of temperature profiles this streambed temperature range was reached by 0.5 m depth below the streambed and the highest streambed temperature detected at this depth was 9.42°C (Figure R3).

Anibas et al., 2009 measured annual streambed temperature changes from 7 to 18°C at 0.5 m depth below the streambed (Figure 6 in Anibas et al., 2009), thus in their study streambed temperatures at 0.5 m depth below the streambed show an annual variation of at least 11°C. In this study area the annual variation in streambed temperatures is much less (Jensen and Engesgaard, 2011; Karan et al., 2013). Independent temperature data (collected by thermocouples of an accuracy of 0.2°C) measured at Station 2 (Figure R4), 0.5 m below the streambed shows that the annual temperature variability is much lower in Holtum stream. Considering that the DTS measurements did not identify potential groundwater discharge at the area of Station 2 (Figure 4 in the manuscript), thus the VTP measurements presented in the manuscript are carried out at locations with higher groundwater discharge than shown on Figure R4, we expect the seasonal temperature variations at the VTP locations to be even lower and thus not influencing our flux estimates. A similar annual temperature range was also observed at Station 4 over the hydrological year of 2008 (Figure R5), where a low discharge location (T1) and a high discharge location (T2) show an annual temperature variability of 2°C and less than 0.5°C at 0.5 m depth below the streambed.

Action #2: A sentence about the steady-state assumption was added to the text of the manuscript: 'As previous studies (Jensen and Engesgaard, 2011; Karan et al., 2013) in the same area only detected moderate seasonal changes in streambed temperatures, the steady-state conditions were assumed to be valid for the study period in June.' (p. 7. lines 19-21)

Referee comment #3: P 13115, L 24: You state that no downward fluxes were de-

ted. That is good, while anything else would have surprised me! The presented methodology only allows for the quantification of upward fluxes (see Schmidt et al., 2007 and Anibas et al., 2011). The model can be easily inverted but a stable surface water temperature combined with a varying groundwater temperature does not exist, so in practice only upward fluxes can be calculated. With some experience one can visually analyze the measured temperature profiles, relative straight gradients or discontinuous temperature distributions in depth can indicate losing locations; such profiles often lead to a bad model fit. Such results should be treated with caution since the error margin can be very big (several 100% or even a different direction in flow). In any case can the steady state analysis be misleading in river sections which are partly gaining and losing since it will always only result in gaining estimates. Please state and handle this in your manuscript accordingly.

Response #3: By this sentence we meant that the streambed temperatures in the profiles were quickly decreasing below the streambed and in at least half of the profiles a stable streambed temperature was reached at around 0.3 m depth below streambed surface, thus indicating upward fluxes. Slowly decreasing temperature from the streambed to the groundwater was not observed in any of the VTPs.

Action #3: A sentence about the losing reach was added to the manuscript: ‘The VTP measurements were carried out at potential discharge sites, correspondingly even in the losing reach the streambed temperature profiles visually indicate upward fluxes by streambed temperatures quickly decreasing below the streambed.’ (p. 12 lines 31-34).

Response to specific comments

Referee comment #4: P 13107, L11: Here you could refer to Figure 2; there all the events are indicated.

Action #4: Reference to Figure 2 in the manuscript added to text.

Referee comment #5: P 13123, L 22: Please add a reference for the EU water frame-

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work directive like: European Commission: Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy, Official Journal of the European Community, L327, 1–72, 2000.

Action #5: Reference has been added both in the text and the full reference in the reference list.

Referee comment #6: P 13124, L 7: Must be ‘Verhoeven, R.’

Action #6: Has been changed in the manuscript.

Response to general remarks on the Figures

Referee comment #7: Figure 1: I would extend the caption for ‘Map of the study area in Jutland, Denmark showing the Skjern River catchment and sampling sites’. In the legend above (c) I see a graphical problem with the words ‘layout’. Please indicate in the figure, caption and or the text the direction of flow within the Skjern River catchment.

Action #7: Caption extended, graphical problem solved and direction of flow noted in the figure caption of Figure 1 in the manuscript.

Referee comment #8: Figure 2: The difference between ‘event sampling’ and ‘campaign’ is not properly explained. Please indicate this in the caption and also in the text of the manuscript. Why did you choose these times for the event sampling and campaign?

Response #8: The distinction between “event” and “campaign” sampling is described under the “Methods” section (p. 6 lines 13 – 25). However, to clarify this for the reader, additional explanations are added (see below). In order to conduct a successful hydrograph separation, especially in lowland groundwater influenced streams, it is necessary to monitor events, with the largest possible difference between pre-event and event conditions. This is due to the fact that the larger difference between the isotope concentrations in event and pre-event water, the more certain the hydrograph separation will be. Since the event sampling requires a high sampling frequency, it was

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not possible to have the ISCO sampler continuously running. Therefore, decisions of which rain events to sample for the hydrograph separations were based on weather forecasts, and the three selected events are therefore the best choices we could obtain, given the general uncertainty in weather forecasts as well as the desire to have relatively low flow antecedent conditions. As far as the campaign sampling goes, it was again chosen based on weather forecasts. For estimating the groundwater discharge, it is desirable to have close to base flow conditions, so that differences in streamflow are most likely to be caused by only groundwater discharge and not by contributions from drains or overland flow. For the choice of the campaign there was also a practical issue, since 5 people and one week of field work were needed to conduct the campaign, which required a few days' notice, delaying the possibility of day-to-day action based on the weather forecast. That is why it was not possible to conduct the campaign sampling during a complete low flow period, as seen in Figure 2 in the manuscript.

Action #8: Further explanation to issues of campaign and event sampling has been added to the text: 'The lowflow period was chosen to minimize the risk of surface discharge to the stream.' (p. 6 lines 15-16) and 'The decision of monitoring the three selected rain events were based on weather forecasts of upcoming large rain events, combined with antecedent medium to low stream flow conditions.' (p. 6 lines 18-20). Figure caption has been changed, Figure 2 in the manuscript.

Referee comment #9: Figure 3: What do the different colors mean for the contour lines?

Response #9: The color of the contour lines is also showing the changes in head values to make the changes more visual supplementing the contour line labels.

Action #9: No action.

Referee comment #10: Figure 4: As indicated in Fig.1(c) the river section runs almost in east-west direction, starting with 'layout A' on the right hand side. In Fig. 4 however 'Layout A' starts on the left side of the figure and layouts B and C follow towards the

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right side. For me it would be more logic if Fig. 4 would follow Fig.1(c). Thus Fig. 4 could be mirrored so that 'Layout A' is right and 'Layout C' is left. The same is valid for Fig. 6.

Response #10: Based on the comment of the reviewer to help the readers' understanding, the orientation of Figures 4, 6 and 8 were changed in the manuscript.

Action #10: The orientation of Figure 4 in the manuscript was changed.

Referee comment #11: Figure 5: Also here I have a graphical problem with the words 'Layout'. The caption on the vertical axes must be 'Strength':

Action #11: The captions and the graphical problem in Figure 5 were changed in the manuscript.

Referee comment #12: Figure 6: As in Fig. 4 here I also suggest that the figure is mirrored so that 'station 1' is on the right side and 'station 4' on the left. In (b) 'Station 3 (tributary)' I have a graphical problem.

Action #12: The orientation of Figure 6 in the manuscript was changed and the graphical problem solved.

Figure captions

Figure R1: Fluxes calculated based on all streambed temperature measurements (x axis) and only considering temperature measurements at and below 0.15 m below the streambed (y axis). The straight black line shows the 1:1 correspondence. Profiles with a large deviation from the line are marked with red circles.

Figure R2: Observed temperature profiles (Observed\_all) and fitted temperature profiles using all the temperature observations (Model\_all) and only temperature data below 0.15 m (Model\_deep)

Figure R3: Histogram of observed streambed temperatures at 0.5 m depth below the streambed.



Figure R4: Streambed temperatures recorded at 0.5 m depth below the streambed in the area of Station 2.

Figure R5: Streambed temperatures recorded at two locations in the area of Station 4

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 11, 13101, 2014.

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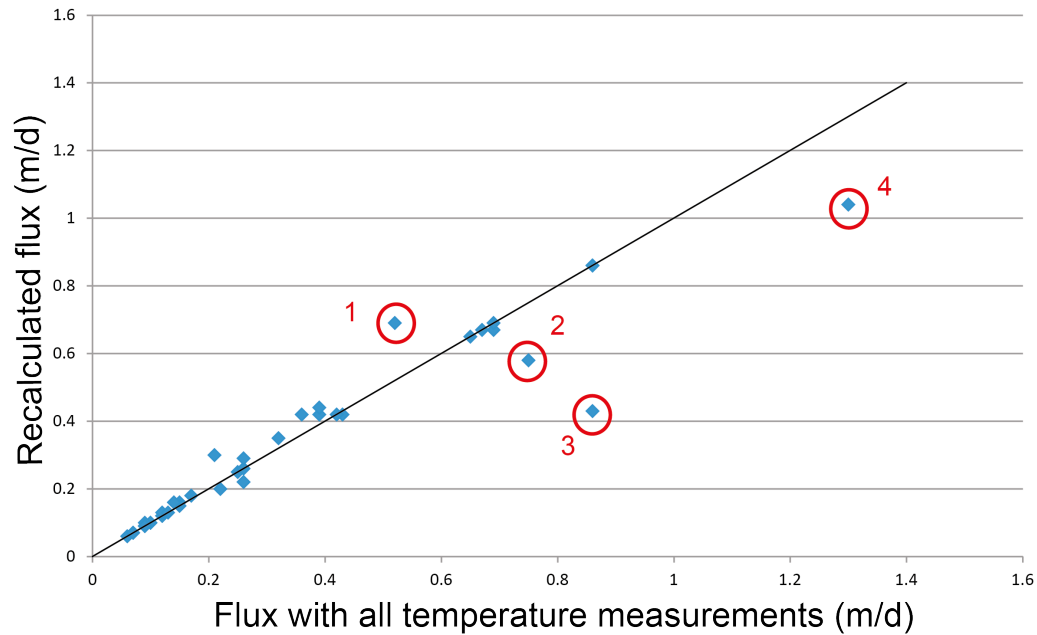


Fig. 1.

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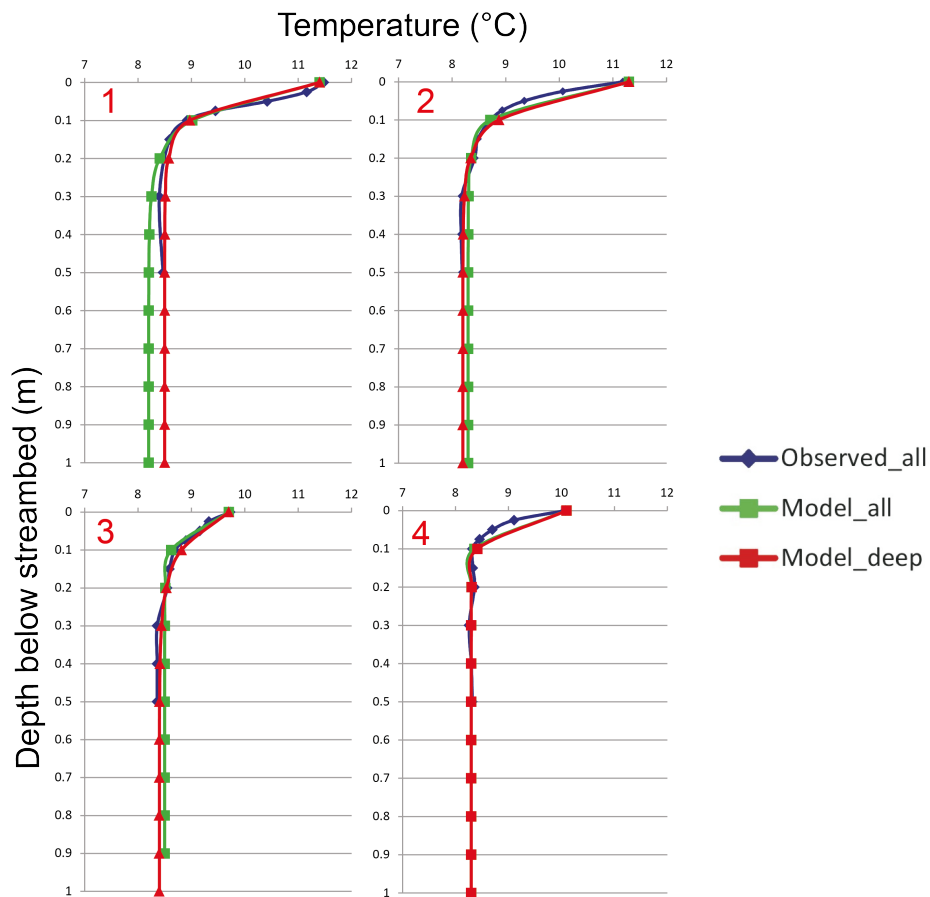
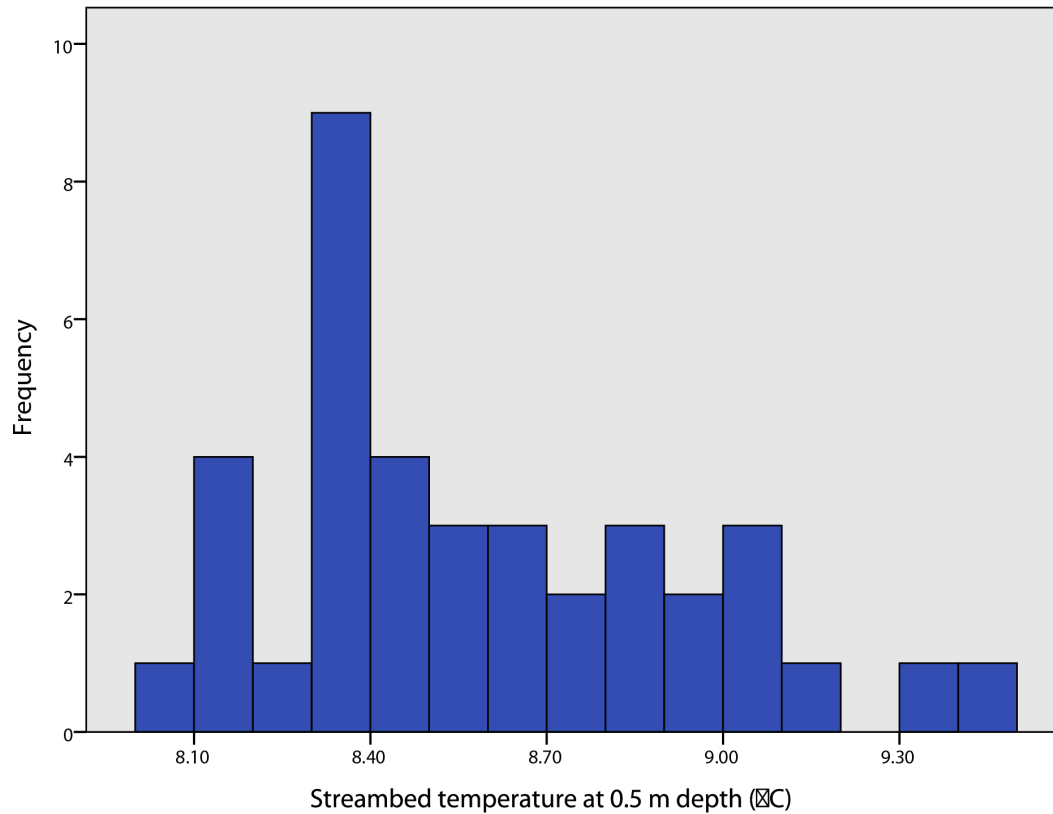


Fig. 2.

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**Fig. 3.**

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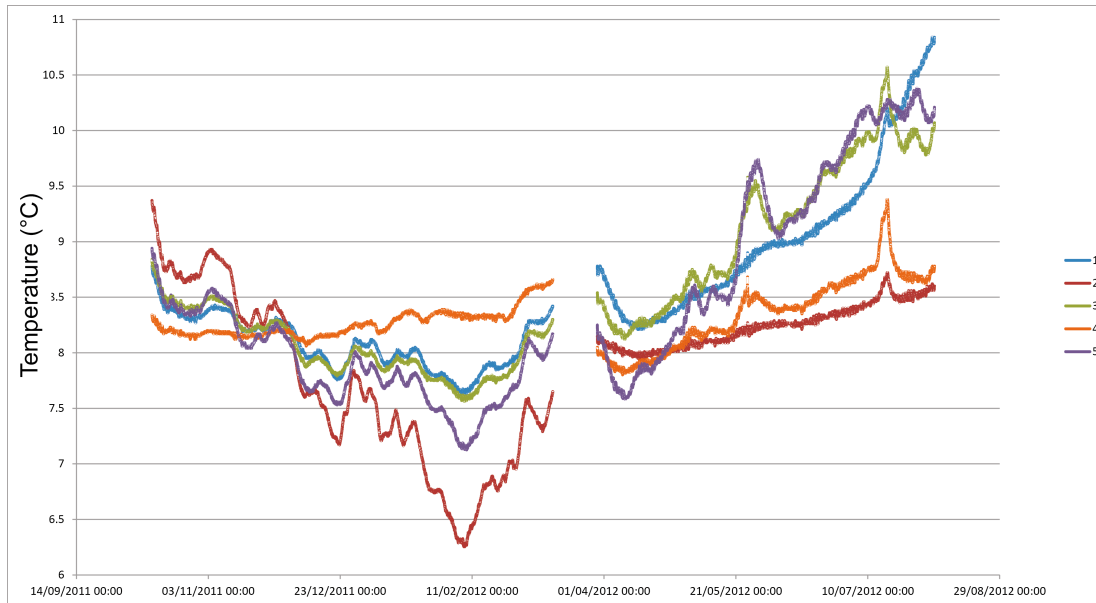


Fig. 4.

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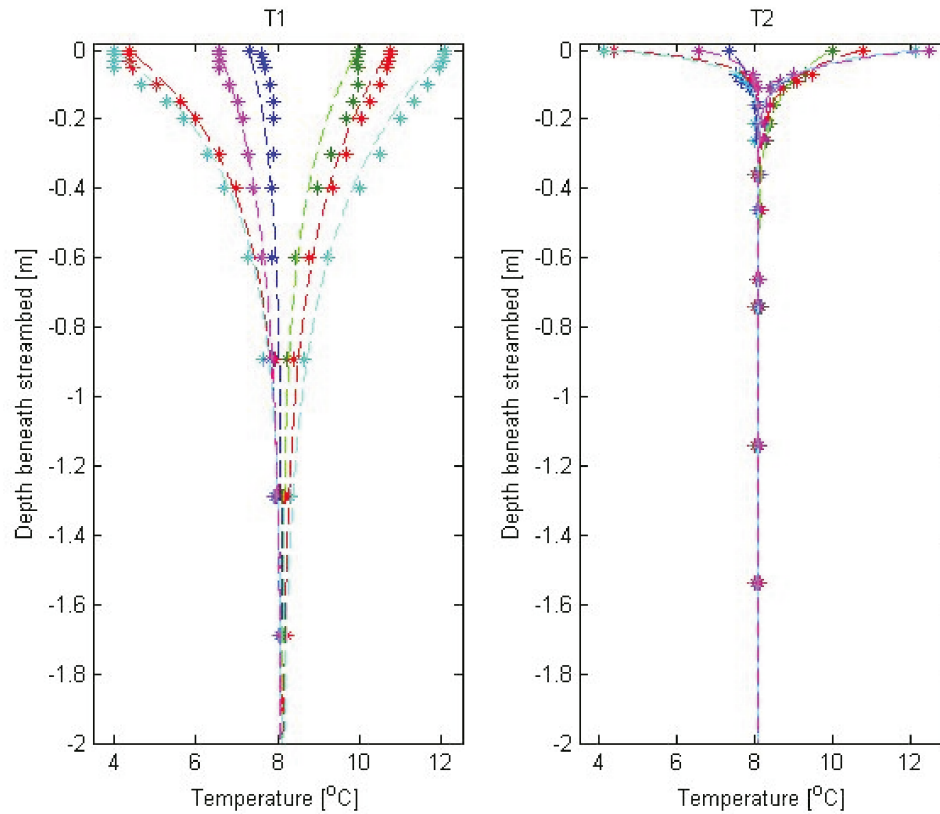


Fig. 5.