Byer i Vandbalance notat 9

Stormwater infiltration in Beder

Byer i Vandbalance

Indhold

Forord

Dette notat er udarbejdet i regi af innovationskonsortiet Byer i Vandbalances aktiviteter fra 2011 til 2014 og omhandler nedsivning af regnvandsafstrømning fra Beder by hvor grundvandsspejlets respons moniteres og den underjordiske magasinering af regnvand og udsivning over tid til Giber Å beskrives med en vandbalancemodel.

I forbindelse med innovationskonsortiet Byer i Vandbalance er der udgivet følgende notater:

Notat 1: Transport af vand på veje
Notat 2: Dobbeltporøst filter i København og Århus – anlæg og instrumentering
Notat 3: Anlæg af vejbede –erfaringer fra vejbede i Brøndby og København
Notat 4: Geologisk variation og LAR
Notat 5: Vurdering af regnafstrømningens kvalitet før og efter rensning
Notat 6: Renseeffektivitet af filterjord – danske erfaringer
Notat 7: Rensning af regnafstrømning med dobbeltporøs filtrering
Notat 8: Beplantning og drift af vejbede
Notat 9: Stormwater infiltration in Beder
Notat 10: Erfaringsopsamling på LAR-projekter udviklet under Byer i Vandbalance 2011-2014

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Maj 2015

Summary

The effect of stormwater infiltration into the secondary aquifer in Beder is investigated. The main focus of the project was to model the effect of stormwater infiltration on the water balance in Beder, to assess if infiltration poses a risk of polluting the primary aquifer, and to evaluate if infiltration can help providing flow to Hovedgrøften in periods of low stream flow. Results show that 25-27% of the infiltrated stormwater reaches the stream and 67-73% reaches the primary aquifer. The infiltrated stormwater poses a risk to the primary aquifer. Stormwater infiltration can contribute up to 11% of the Hovedgrøften stream flow during a low stream flow period.

Introduction

The overall aim of this Byer i Vandbalance project is to investigate if stormwater infiltration can increase the baseflow flow to Giber Å. In this report we model the impact of implementing stormwater infiltration in Beder and particularly we focus on three questions:

- What is the impact of stormwater infiltration on the water balance in Beder?
- Does stormwater infiltration pose a risk of polluting the primary aquifer?
- Can stormwater infiltration enhance streamflow in low streamflow periods?

We assume the infiltration of roof and street stormwater runoff from Beder into the secondary sandy aquifer along Hovedgøften.

Stormwater infiltration in Beder through injection wells and infiltration trenches was previously analyzed by DTU (''Injection wells for stormwater infiltration at Beder'') and Orbicon (''infiltration af regnevand ved Hovedgrøften, beder''). These studies focused on dimensioning infiltration facilities and analyzing the impact of stormwater infiltration on Høvedgroften's water balance without explicit modeling of hydrogeological processes. These studies concluded that stormwater runoff infiltration from a 6.8 ha area (area that was suggested from Aarhus Vand) with 25% imperviousness can contribute to Høvedgroften with an annual average flow of maximum 0.37 l/s.

The groundwater-surface water model

The integrated groundwater-surface water model was implemented using the integrated tool Mike She/Mike 11. The model area is a part of the Giber Å catchment and focuses particularly on Beder and Hovedgrøften (Figure 1).

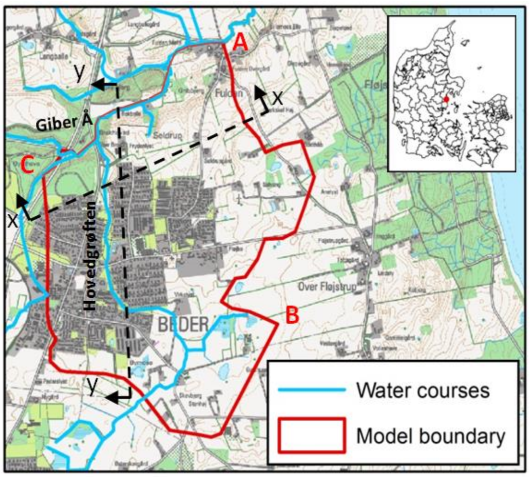


Figure 1. The model area.

1.1. The geological model

The geological model for the area is a GeoScene model originally developed by Rambøll and refined with new geophysical, spear mapping and borehole data collected by GEUS and KU as part of the field campaign carried out in 2012-2014 supported by Byer I Vandbalance. The new geological model has a better representation of the geology In Beder and especially for the top layers close to Hovedgrøften.

The model includes 4 different geological layers from top to bottom: clay till, sandy layer (secondary aquifer), tertiary clay, sandy layer (primary aquifer). Cross sections of the geological model are shown in Figure 2 and Figure 3. The model grid was set to be 10x10 m.

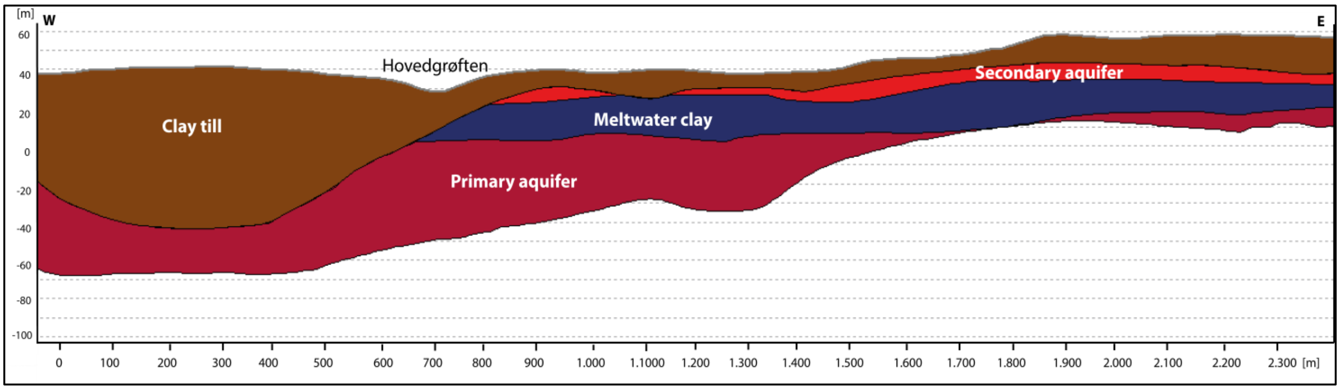


Figure 2. Geological cross section x-x shown in Figure 1.

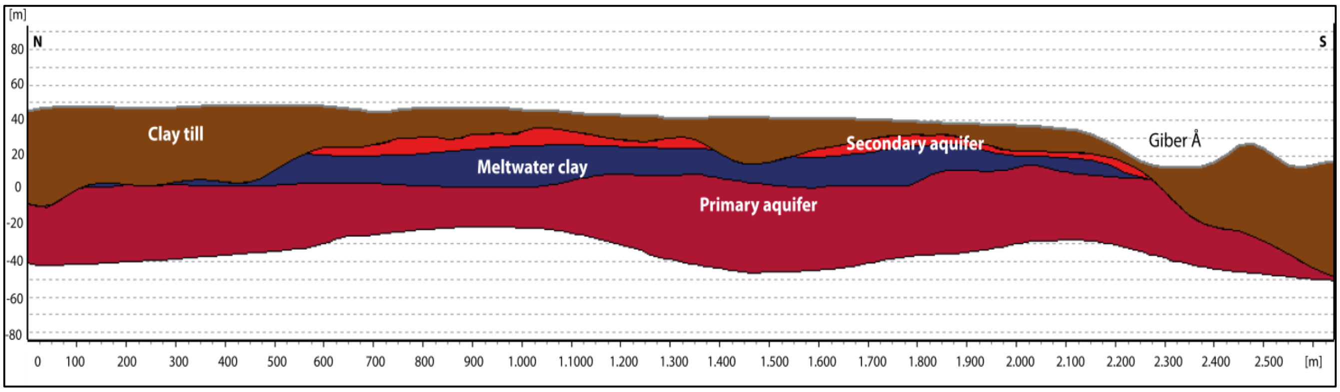


Figure 3. Geological cross section y-y shown in Figure 1.

The hydrogeological model boundaries

The hydrogeological model boundaries were shown in Figure 1. Three different boundaries are selected:

- A-B boundary (Figure 1). It is based on the topography of the bottom of the secondary aquifer and the boundary of the primary aquifer, i.e. the boundary line partly represents the topographical divide between the model area and other watersheds and partly the secondary aquifer boundary.
- B-C boundary (Figure 1). It follows the hydraulic barrier along the primary aquifer on the western side of Beder (see Figure 4). The figure shows that the thickness of primary aquifer is significantly reduced. This is due to the presence of a buried valley filled with tertiary clay on top of the primary aquifer (see also Figure 2).
- C-A boundary (Figure 1). It follows Giber Å up to the point A where a flow measuring station is located.

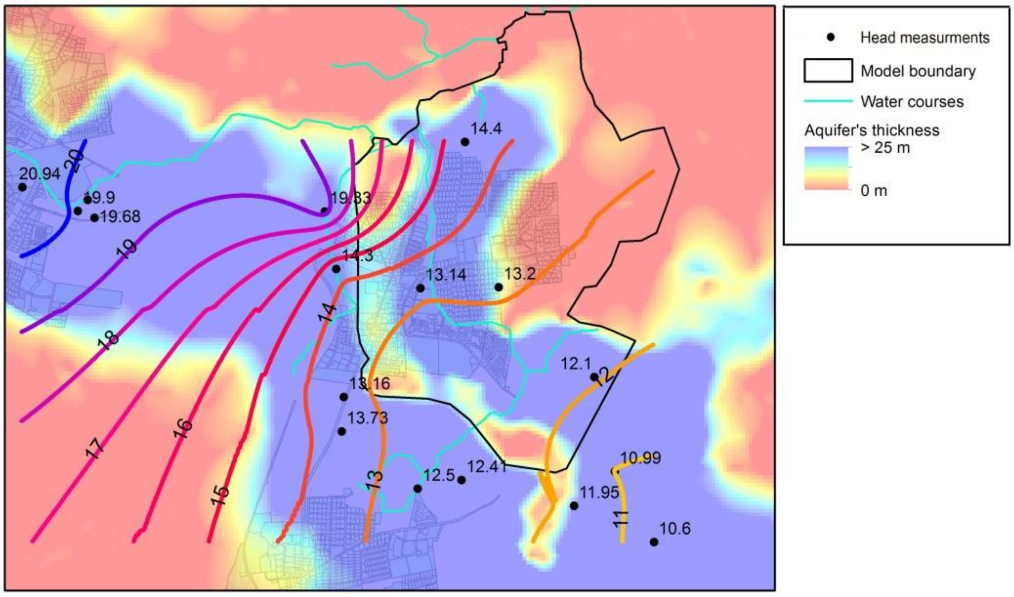


Figure 4. Thickness of the primary aquifer and equipotential groundwater lines based on groundwater measurements in the period May2003-Oct2003.

The model boundaries are defined for each geological/computational layer and are summarized in table 1. A no-flow boundary condition is applied to the clay layers with exception of the Head dependent boundary in Layer 1 which was chosen due to the direct connection to the stream. A no-flow boundary condition for the clay layers is based on the assumption that the flow in the clay is mainly vertical since the hydraulic conductivity of clay is approximately 2 orders of magnitude smaller than the sand. A no-flow boundary condition for Layer 2 (secondary aquifer) is selected because of both the physical boundary of the secondary aquifer (see Figure 11 in Appendix I), and the catchment divide of the flow measuring station derived from bottom topography of the secondary aquifer. A specified head boundary for the primary aquifer is chosen because of the head gradients across the selected model boundary which suggests that there is water flowing through the boundary (see Figure 3).

Tabel 1. Model boundary conditions.

	A-B	B-C	C-A
Layer 1. Clay till	No-flow	No-flow	Head dependent
Layer 2. Secondary aq.	No-flow	No-flow	No-flow
Layer 3. Tertiary clay	No-flow	No-flow	No-flow
Layer 4. Primary aq.	No-flow	Specified head	No-flow

The river model boundaries

Hovedgrøften discharges into Giber Å in the northern part of Beder and Giber Å flows eastward towards Aahus Bugt as shown in Figure 4.

The catchment area of Giber Å was modeled based on topographic analysis using the terrain model (DHM/Terræn 1,6 m grid); and the results areshown in Figure 4. Giber Å has a catchment area of approx. 51 km^2. The sub-catchment of Hovedgøften covers an area of approx. 6.6 km km^2. The measuring station 27.09 on Giber Å has a catchment area of 40.7 km^2 so Hovedgrøften is assumed to contribute 16.2% to the flow measured at the station.

The river network was implemented in MIKE 11 within the 'Model boundary' shown in Figure 4.

The downstream point where the gauging station is located is modeled as an open boundary. All the other points in the river network which intersect the model boundary are given a specified inflow rate. The inflow rate was calculated for every boundary point of the network and the rate is assumed to be a fraction of the flow measured at the 27.09 station. The fraction was calculated as the ratio between the upstream area of the inflow point and the catchment area of the measuring station.

The choice of this boundaries implies that the model area should contribute with 10% of the flow measured the station.

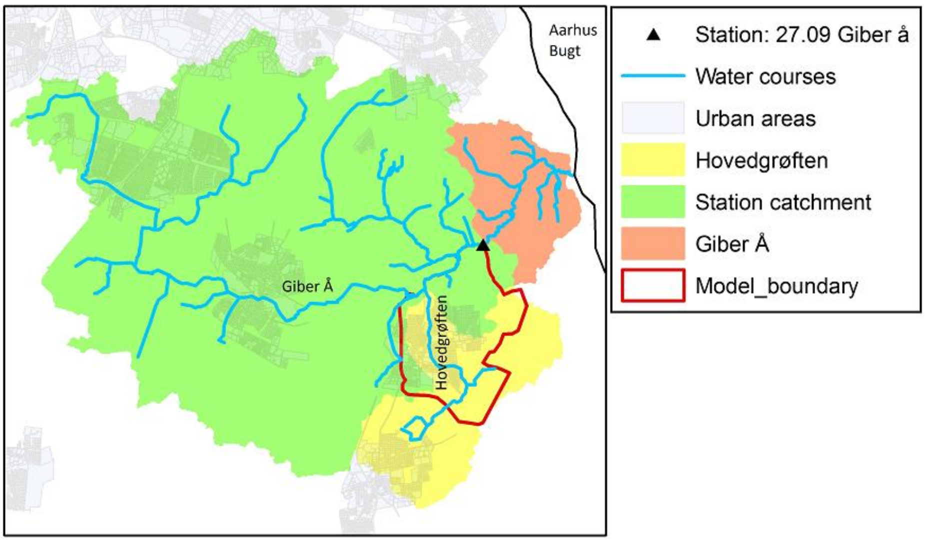


Figure 5. Giber Å catchment and sub-catchments. Obtained from terrain analysis.

The hydrological and hydrogeological data

The rainfall input to the model is taken from the 10x10 km Danish national grid. The mean annual rainfall in the area is approximately 723 mm per year (1989-2010). The potential evapotranspiration data are taken from the 20x20 km Danish national grid.

There are several observation and abstraction wells in the area and they are shown in Figure 6. The timeseries of observed head in the boreholes is shown in Figure 7. The figure shows that the head in the secondary aquifer is 10-15 m higher than in the primary aquifer suggesting that the water flows downwards from the secondary to the primary aquifer. The total abstraction from the model area is in the order of magnitude of 10^6 m^3/y.

The runoff coefficient for the urban area was assumed to be 0.25.

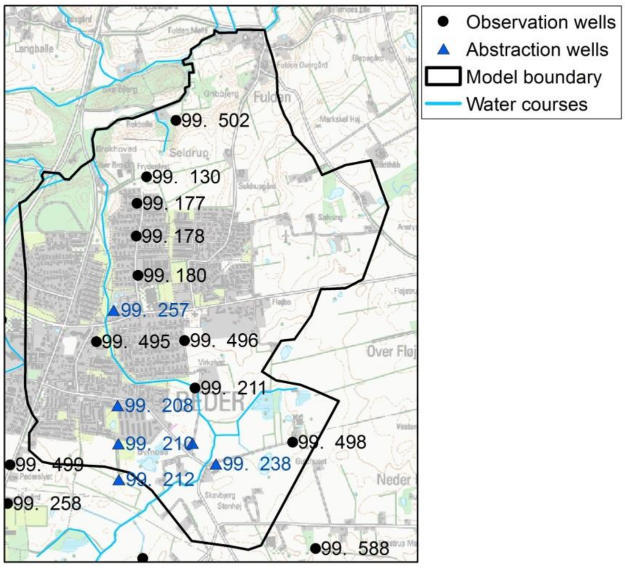


Figure 6. Observation and abstraction wells on the area.

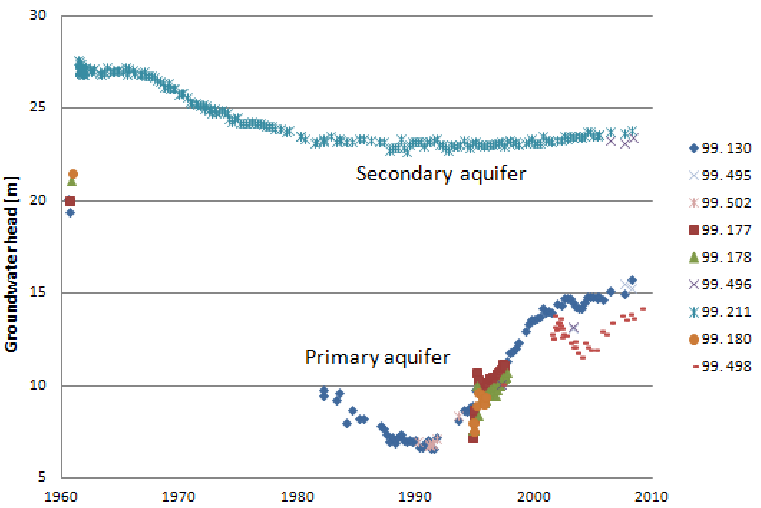


Figure 7. Observed head on the model area.

2.5 Calibration and validation

The model was calibrated for 2.5 years (nov-2003 and apr-2005) and validated for 2008. The calibration parameters were the horizontal hydraulic conductivity of the 4 geological layers (the vertical hydraulic conductivity was fixed to the horizontal one assuming an anisotropy value of 10), the leakage coefficient (river–aquifer leakage coefficient) and the drain time constant. The model warm-up period was 2 years.

The objective function to be minimized was the sum of the squared error for the observed head in the boreholes and the observed flow rates in Giber Å. Equal weight was given to each measurement.

The calibrated parameters are reported in Table 2. These values are in the same order of magnitude of the values reported by DHI (2005). Table 3 gives the mean error and the root mean squared error for the calibration and validation period.

Table 2. Calibrated parameters

		Units	Calibrated values
Layer 1. Clay till	K_{h1}	m/s	$8.1\ 10^{-5}$
Layer 2. Secondary aquifer	K_{h2}	m/s	$2.1\ 10^{-4}$
Layer 3. Tertiary clay	K_{h3}	m/s	$4.0\ 10^{-7}$
Layer 4. Secondary aquifer	K_{h4}	m/s	$3.4\ 10^{-4}$
Leakage coefficient	L	s^{-1}	$1.2\ 10^{-5}$
Drain time constant	D	m/s	$2.3\ 10^{-7}$

Table 3. Calibration and validation errors.

		calibration	validation
Head observations [m]	Mean Error (ME)	0.72	1.5
	Root Mean Square Error (RMSE)	1.3	2.4
Stream-flow observations [l/s]	Mean Error (ME)	7	9
	Root Mean Square Error (RMSE)	9	12

Method

Three different scenarios are modeled:

a) Baseline scenario
b) Realistic infiltration scenario
c) Potential infiltration scenario

The baseline scenario is modeled in order to understand the water balance in the area and the catchment area of abstraction wells.

The realistic infiltration scenario assumes that stormwater runoff from the northern part of Beder is infiltrated into the secondary aquifer. The kommune of Aarhus suggested to infiltrate stormwater runoff from an area of 6.8 hectars having 25% imperviousness. The infiltration area is shown in Figure 8. The results of the infiltration scenario focus on the water balance differences with the baseline scenario and also on the path of infiltrated particles dissolved in water. Particle tracking of the infiltrated stromwater particles helps understanding where the infiltrated stormwater flows.

The potential infiltration scenario assumes that stormwater runoff from the whole urban area in the model is infiltrated into the secondary aquifer. Stormwater runoff from a 1.5 km^2 area with 25% imperviousness is infiltrated into the secondary aquifer close to Hovedgrøften (see Figure 7). The results of the potential infiltration scenario focus on the water balance differences with the baseline scenario.

Figure 8. Proposed stormwater infiltration area in Beder.

Results

Baseline scenario

Particle tracking

The results of backward particle tracking simulation from drinking water wells are shown in Figure 9. The figure shows (red shaded area) the catchment area of the abstraction wells. This means that particles falling within this area likely reach the drinking water wells. Stormwater infiltration in this area would require an assessment of water quality.

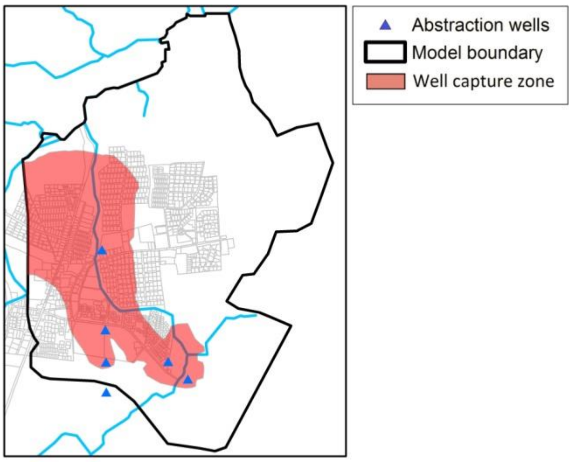


Figure 9. Catchment zones of the abstraction wells

Water Balance

The water balance for the baseline scenario was calculated over 5 years (2004-2009) and is shown in Figure 10. Some observations can be derived from the figure:

- Hovedgrøften is a gaining stream. However, the amount of water received by the stream from the model area is uncertain since it is highly sensitive to the choice of the network boundary conditions. The network boundaries assumed in the model imply that the model area contributes with approximately 10% of the flow measured at the station 27.09 along Giber Å.
  Figure 11 shows the simulated depth of the phreatic aquifer below ground level. The picture shows that the phreatic aquifer is more than 8 meter below ground for most of the model area; and that the downstream part of Hovedgrøften and the whole segment of Giber Å have phreatic aquifer above terrain meaning that in these areas (red area in Figure 11) the stream receives seepage flow and saturated overland flow.
  Temperature measurements were also carried out in order to locate groundwater discharge areas into Hovedgrøften, however there was no evidence discharge areas; the measurements are reported in APPENDIX II.
- There is a consistent groundwater flow in the primary aquifer. As shown in Figure 4 there is an overall groundwater flow south-east ward.

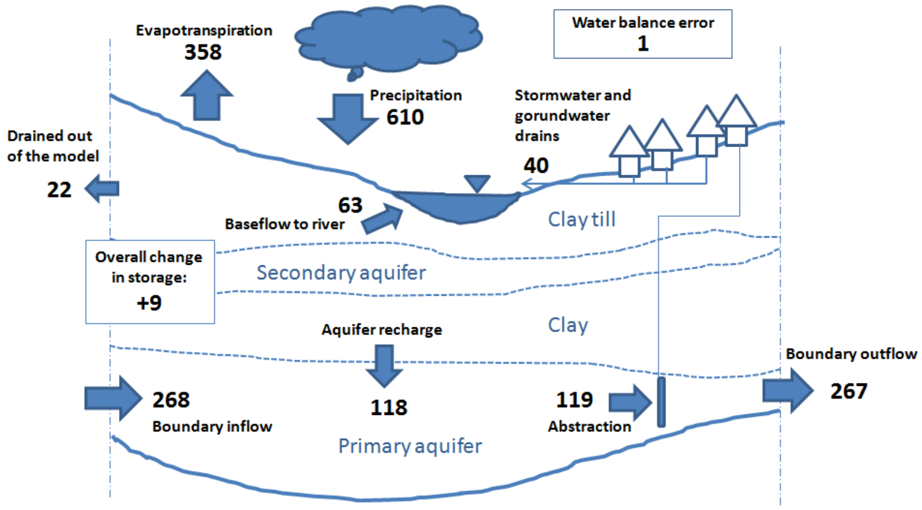


Figure 10. Annual water balance for the period nov2002-oct2003 showing the fluxes in mm/y.

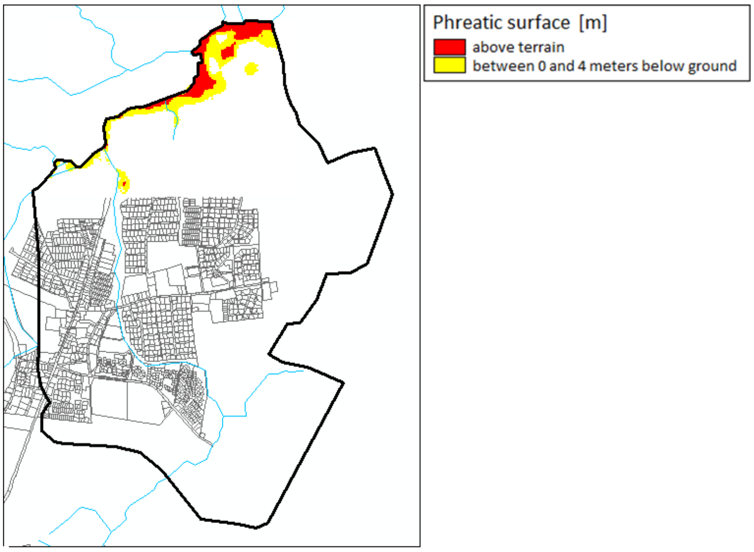


Figure 11. Groundwater discharge areas in the model.

Realistic infiltration scenario

Particle tracking

The results of particle tracking simulation are shown in Figure 11. The figure shows the path-line of particles initially placed at the infiltration area. The results show that infiltrated water partly reach Hovedgrøften and partly flows to the primary aquifer and out to the south-eastern boundary flowing through the abstraction wells areas.

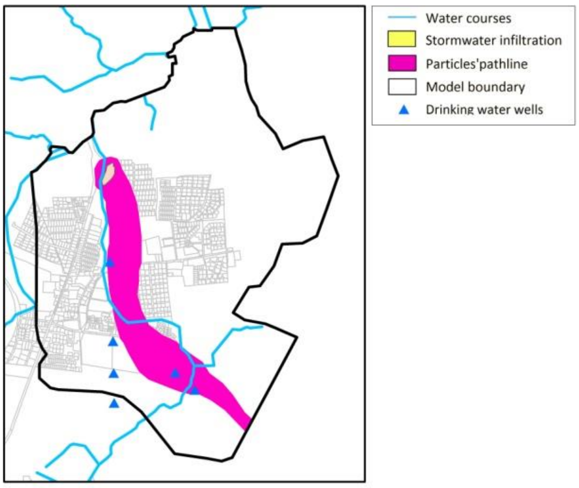


Figure 12. Particles'streamlines.

Water Balance and baseflow

The water balance for the infiltration scenario is shown in Figure 13. The figure highlights the effect of stormwater infiltration to the different components of the water balance. The following observations are derived from the figure:

- 8% of the infiltrated stormwater contributes to baseflow to the stream.
- 19% of the infiltrated stormwater contributes to groundwater drainage to the stream.
- 73% of the infiltrated stormwater reaches the primary aquifer.
- 27% of the infiltreated stormwater reached the stream.

This means that the infiltrated stormwater contributes to stream flow with an annual average 0.1 l/s. Hovedgrøften is assumed to have an annual average stream flow of 59 l/s in (16.2% of the measured flow in Giber Å); this means that stormwater infiltration contributes with 0.2% to the annual stream flow of Hvedgrøften.

Stormwater runoff from most of Beder is currently drained into Hovedgrøften by stormwater drains. By changing from stormwater runoff drainage into the stream to stormwater infiltration would actually reduce mean annual stream flow rates since not all the infiltrated stormwater would reach the stream. The annual average stream flow for the realistic infiltration scenario would actually decrease by 0.4%.

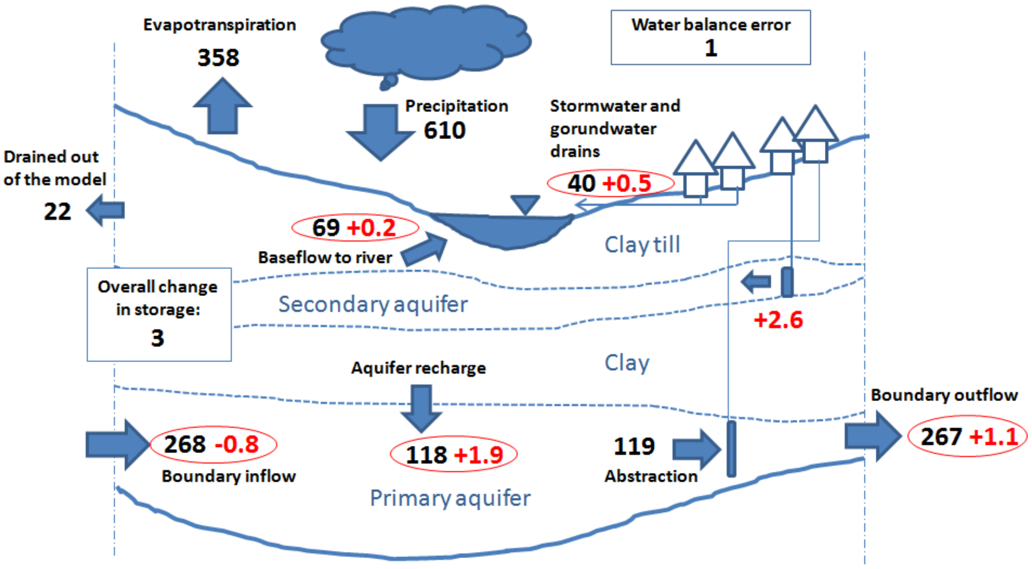


Figure 13. 5 years average water balance for the realistic stormwater infiltration scenario.

The modeled hydrograph at the downstream point of Hovedgrøften does not show a significant difference since the amount of water that contributes to hovedgrøften is very small compared to its stream flow . During periods of low stream flow like the summer 2003 (with a summer average flow of ≈ 11 l/s), the infiltration scenario contributes with approximately 0.01 l/s corresponding to 0.1% of the stream flow.

The realistic infiltration scenario insignificantly contributes to low stream flow periods of Hovedgrøten.

4.3 POTENTIAL INFILTRATION SCENARIO

The water balance for the potential infiltration scenario is shown in Figure 14. The figure highlights the effect of stormwater infiltration to the different components of the water balance. The following observations are derived from the figure:

- 8% of the infiltrated stormwater contributes to baseflow to the stream.
- 17% of the infiltrated stormwater contributes to groundwater drainage to the stream.
- 66% of the infiltrated stormwater reaches the primary aquifer.
- 25% of the infiltreated stormwater reached the stream.
- 3% of the infiltrated stormwater contributes an increase in storage.

This means that the infiltrated stormwater contributes to stream flow with an annual average 1.8 l/s. Hovedgrøften is assumed to have an annual average stream flow of 59 l/s in (16.2% of the measured flow in Giber Å); this means that stormwater infiltration contributes with 3 % to the annual stream flow of Hvedgrøften.

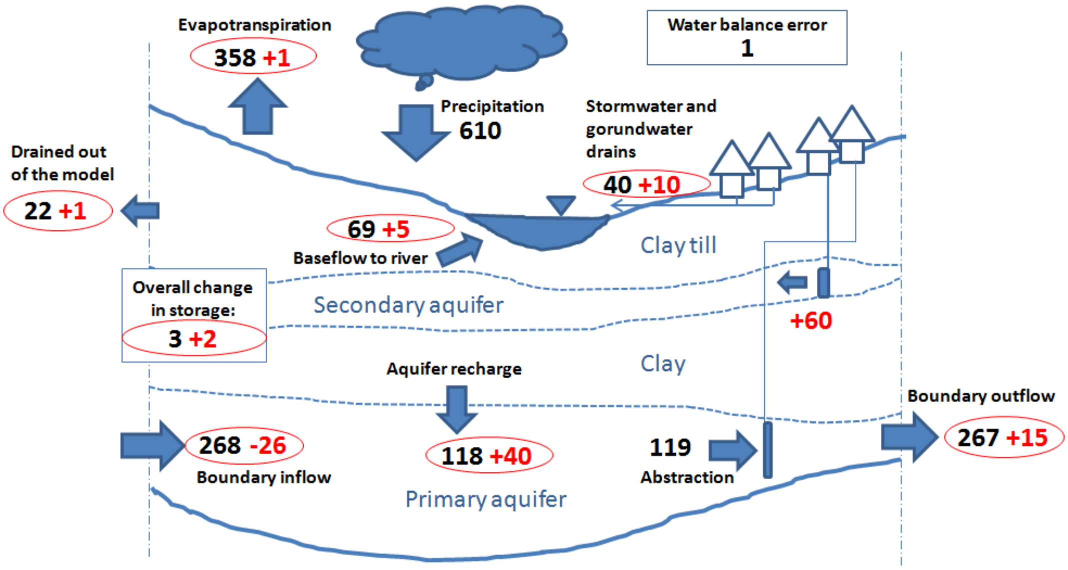


Figure 14. 5 years average water balance for the potential stormwater infiltration scenario.

Stormwater runoff from most of Beder is currently drained into Hovedgrøften by stormwater drains. By changing from stormwater runoff drainage into the stream to stormwater infiltration would actually reduce mean annual stream flow rates since not all the infiltrated stormwater would reach the stream. The annual average stream flow for the realistic infiltration scenario would actually decrease by 9%.

The modeled hydrograph at the downstream point of Hovedgrøften is shown on Figure 15. The figure shows that the potential infiltration scenario increases the flow rate during low flow periods. It was chosen to analyze the impact of the infiltration scenario for the driest summer in the time series which was the summer 2003. The baseline scenario has a summer average flow of 11.2 l/s whereas the potential infiltration scenario 12.4 l/s. The potential infiltration scenario increases of 11% the streamflow during low-flow periods

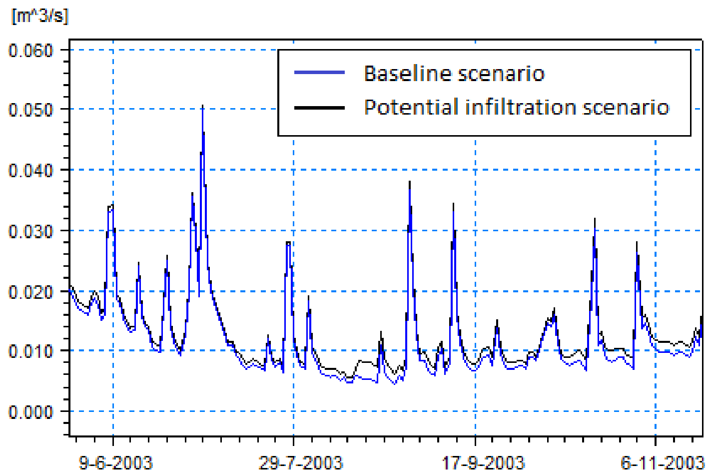


Figure 15. Streamflow at the downstream point of Hovedgrøften.

The potential infiltration scenario is shown to affect both the water balance of the area and the low stream flow periods of Hovedgrøften.

Conclusion

Stormwater infiltration in Beder poses a risk to the drinking water wells in the area. 66-73% of the infiltrated stormwater runoff would reach the primary aquifer.

The model shows that 25-27% of the infiltrated stormwater reaches the stream.

Changing from the actual stormwater drainage into the stream to stormwater infiltration would reduce the mean annual stream flow by 0.4-9% since only 25-27% infiltrated volume would reach the stream. Stormwater infiltration can contribute with 0.1-11% of the stream flow of Hovedgrøften during low stream flow periods.

The realistic infiltration scenario, which follows the suggestion of Aarhus Kommune of infiltrating stormwater runoff from a 6.8 ha area in Beder is shown to insignificantly impact the annual stream flow and the low stream flow periods of Hovedgrøften. The potential infiltration scenario where stormwater runoff from most of the Beder area is infiltrated would reduce mean annual stream flow of Hovedgrøften by 9% and increase up to 11% stream flow during dry periods.

More widespread stormwater infiltration in the Giber Å catchment will likely increase streamflow during dry periods. The contribution will strongly depend on the local hydro-geological conditions of the selected infiltration areas.

References

Schmidt, C., Conant, B., Bayer-Raich, M., and Schirmer, M., 2007, Evaluation and field-scale application of an analytical method to quantify groundwater discharge using mapped streambed temperatures: Journal of Hydrology, v. 347, p. 292-307.

DHI, 2005. Århus Syd Indsatsplanlægning; Udpegning af grundvandsdannende oplande.

APPENDIX I. Additional figures.

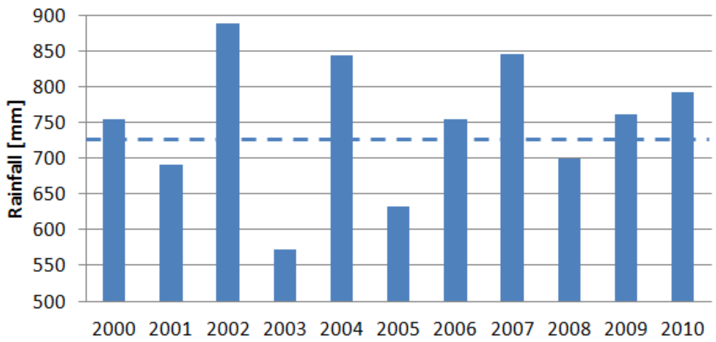


Figure 16. Average annual rainfall for the model area.

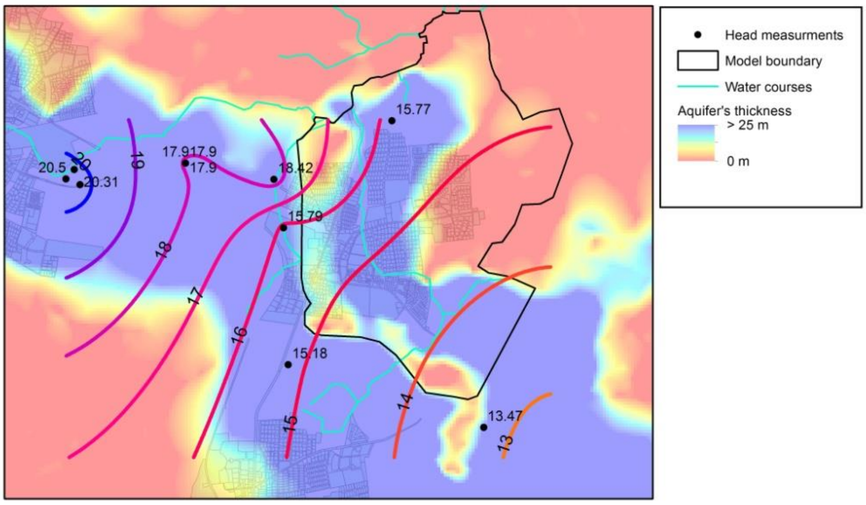


Figure 17. Measured equipotential groundwater lines.

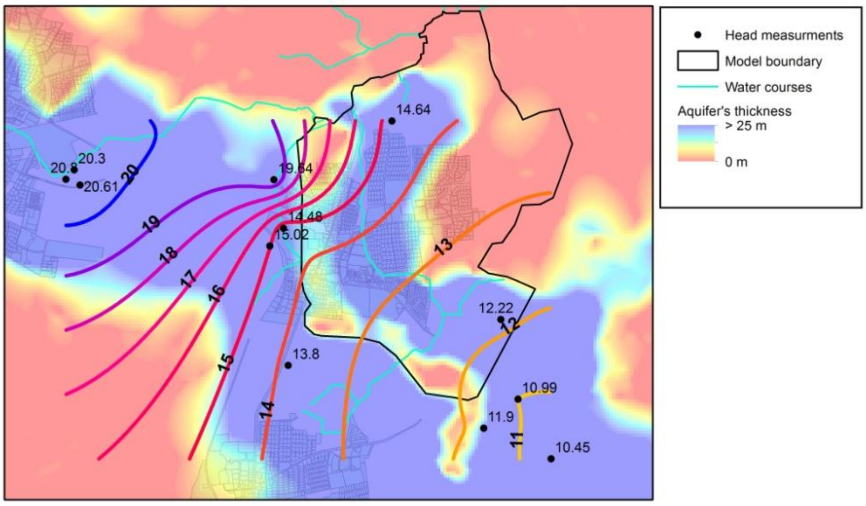


Figure 18. Measured equipotential groundwater lines. May2004-0ct2004.

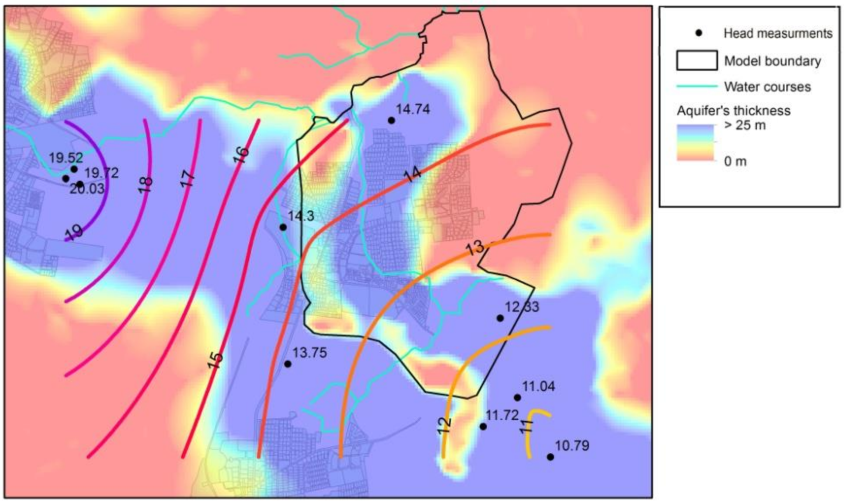


Figure 19. Measured equipotential groundwater lines. Nov2002-Apr2003.

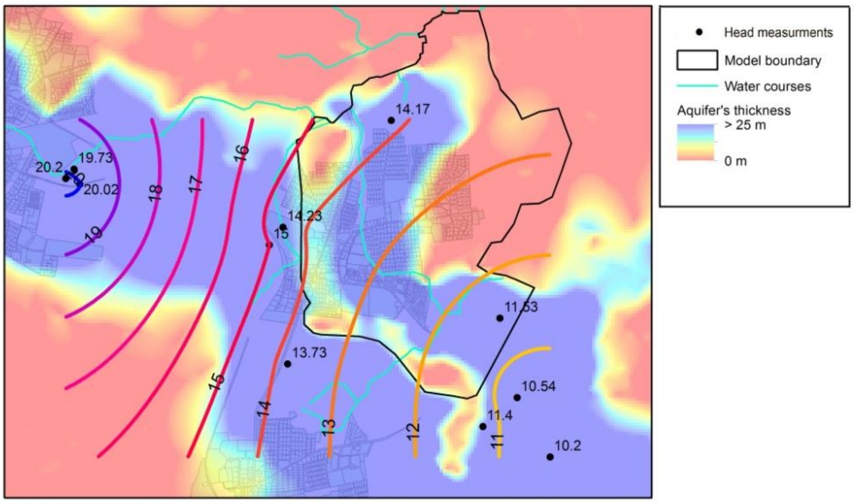


Figure 20. Measured equipotential groundwater lines. Nov2003-Apr2004.

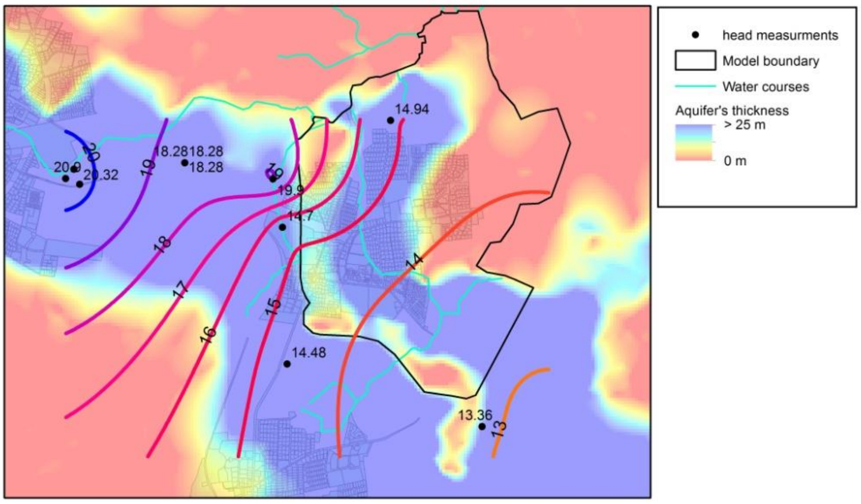


Figure 21. Measured equipotential groundwater lines. Nov07-Apr08.

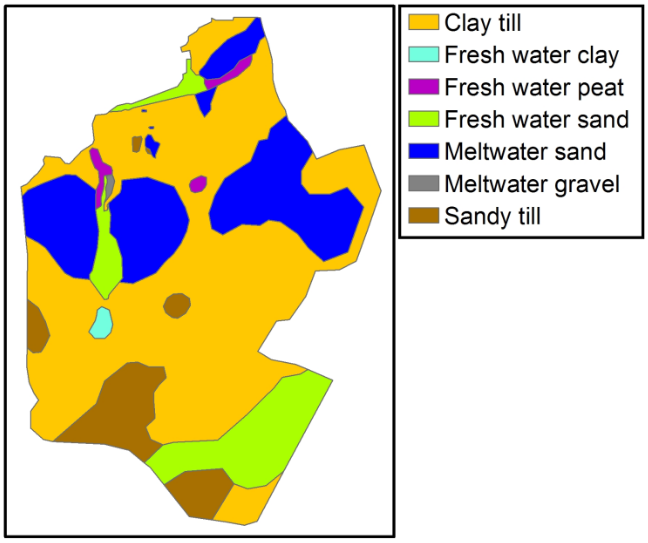


Figure 22. Surface geology in the model area

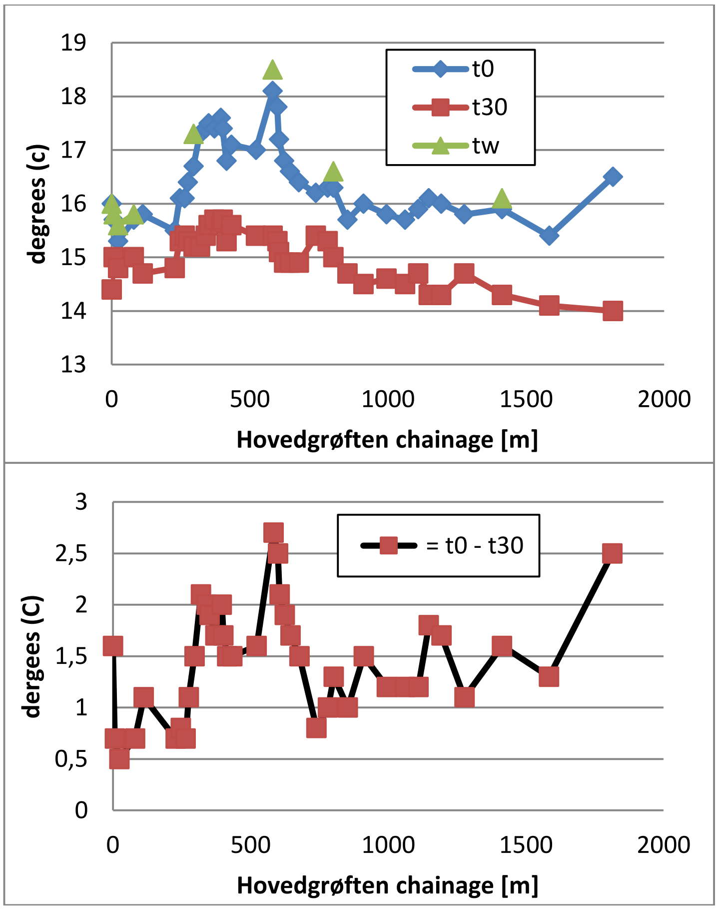
APPENDIX II. Temperature measurements

The aim of the temperature measurements was to spot the areas along Hovedgrøften where groundwater discharges into the stream. The measurements did not show any evidence of groundwater discharge zones into the stream.

Temperature measurements were carried out the 21/08/2013 by DTU (Luca Locatelli) and KU (Britta Bockhorn). The method applied was presented by (Schmidt et al., 2007).

Temperature measurements were taken 30 cm below stream bed (t_{30}), at the stream bed (t_0) and approximately in the middle depth of the stream (t_w).

Figure 25 shows the measurements. The measured temperature t_{30} is shown to be between 14 and 15 °C. These values suggest that there were not groundwater recharge zone in the measured points at the time of measurements. Groundwater in Denmark has an average temperature of 8-10°C; if there were a discharge zone we would expect t_{30} to be 11-13°C.



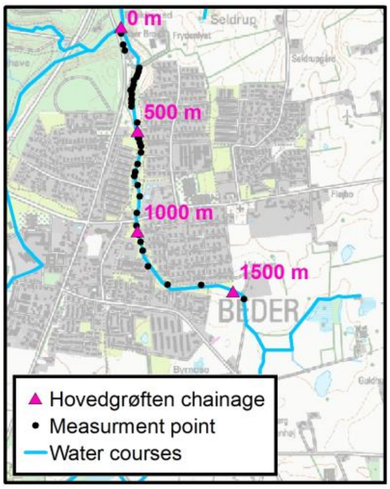


Figure 23. Temperature measurements

The computed Darcy flux is shown in Figure 26. The fluxes are so small that it is difficult to derive any conclusion.

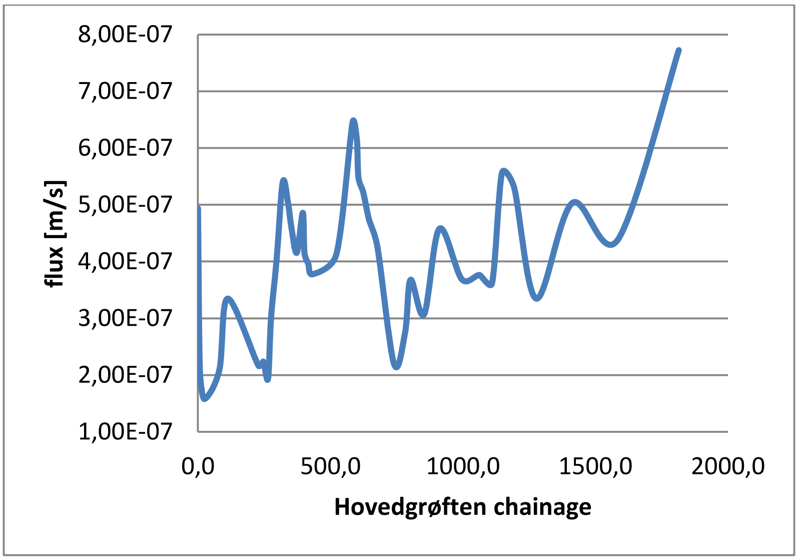


Figure 24. Darcy flux calculated from the temperature measurments