Temperature distributions as an indicator for groundwater seepage in lowland streams

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Cover photograph: Springendalse Beek, Twente.

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Abstract

Persevering clean water resources is not only important for the aquatic ecology but also for human health. However, many surface water bodies and groundwater resources do not have a good ecological or chemical status. The MARS project (Managing Aquatic ecosystems and water Resources under multiple Stress) is improving the knowledge on the effect of multiple stressors, such as climate change and different types of land use, on the aquatic ecosystem. This knowledge is necessary to find what measures are needed to improve the ecological and chemical status of the water resources.

Many lowland streams are influenced by groundwater- surface water interaction, which can both have a positive and negative influence on the aquatic ecosystem. In this research the effect of groundwater seepage on the stream temperature of two tributaries of the Dinkel river is examined. Distributed Temperature Sensing (DTS) was used to locate the groundwater seepages zones along the streams, while measurements of the water chemistry, seepage flux and vertical temperature profiles provided more detailed information about the groundwater-surface water interaction. The stream temperature of the Springendalse Beek was found to be highly affected by groundwater which resulted in a reduced temperature variation over time which is an advantage for the aquatic ecology. However, seepage also transported high levels of nutrients to the stream which is an important stressor. For the Elsbeek the effect of groundwater seepage on the stream temperature was found to be minimal, although additional measurements did indicate the presence of groundwater seepage. However, shading was found to have a major effect by significantly reducing both the mean and maximum stream temperature.

With global warming in mind, both shading and groundwater seepage were found to be beneficial to aquatic species which are sensitive to high temperature fluctuations as stable temperature habitats are created. However, shading would be an easier measure to reduce the stream temperature. From all measurements and findings it was concluded that the Springendalse Beek and the Elsbeek both have completely different systems and therefore need different measures to assure a healthy aquatic ecosystem.

Chapter 1

Introduction

1.1 Introduction

Preserving clean water resources is not only important for the aquatic ecology but also for human health. However, currently over 50% of the surface water bodies and 25% of the groundwater resources in Europe do not have a good ecological or chemical status (Kristensen et al., 2012). To understand how to improve the ecological and chemical status, knowledge of the numerous stressors influencing the water resources is required. Often the impact of a single stress on a catchment or water body can easily be studied and understood, but the influence of a combination of stressors is difficult. Therefore the European funded project MARS (Managing Aquatic ecosystems and water Resources under multiple Stress) is examining the impact of multiple stressors such as combinations of hydropower generation, climate change and urban and agricultural land use on the water quantity, ecosystem and ecological and chemical status of Europe's water resources (Hering et al., 2015). Research is done at three different spatial scales: water body, river basin and European scale.

Part of the project, at the river basin scale, researches the influence of groundwater surface water interaction and the effect of global warming on the aquatic ecosystems of the Regge and Dinkel catchments. On the one hand, high nutrient levels transported via the groundwater to the surface water can cause a high stresses on the aquatic ecosystem, while on the other hand the interaction between groundwater and surface water can provide a stable temperature habitat for aquatic species and reduce the effect of global warming on stream temperatures (Broadmeadow et al., 2011). To improve the overall quality of the Regge and Dinkel catchments it is therefore important to examine the effect of different processes playing a role in the groundwater-surface water interaction and whether they have a positive or negative influence on the aquatic ecosystem. For this, the first step is to locate the areas of groundwater-surface water interaction along streams. As differences in temperature between groundwater and surface water is recognized as a natural tracer for groundwater seepage, temperature measurements can be used to locate these zones (Anderson, 2005; Constantz, 2008).

1.2 Objectives

In the current study this first step of locating seepage zones is made for the Elsbeek and Springendalse Beek, which are two tributaries of the Dinkel river. Distributed Temperature Sensing (DTS) is used to locate seepage zones and to explain the temperature distribution along both tributaries. The main research question is: **How do groundwater seepage zones in tributaries of the Dinkel river influence stream temperature?** Additionally, the responds of the stream temperature to changes in air temperature, shade and to inlets of small seepage lakes and drainage pipes is examined. Five subquestions will be discussed, which will all contribute to the understanding of how seepage is influencing the stream temperature of the tributaries:

- 1. Where are the seepage zones located along the tributaries?
- 2. What is the best method to identify seepage zones from distributed temperature sensing data?
- 3. What other indicators of seepage can be found along the tributaries?
- 4. How does the effect of groundwater seepage compare to the effect of shade on the stream temperature?

These questions are answered by using different methods to gain information about the temperature dynamics of the studied tributaries. First laboratory experiments were performed to examine the accuracy and thermal response time of the fiber-optic cable used in the field. Once this was known, DTS measurements were done in the Elsbeek and Springendalse Beek. In addition to DTS, point measurements with independent temperature loggers were used to examine the temperature distribution along the tributaries. Furthermore, vertical temperature profiles were made to study vertical flow through the streambed to get more insight into the temperature distribution below the streams. Seepage flux measurements were performed to quantify the amount of seepage. Lastly, the responds of stream temperature to changes in air temperature and shade was examined and quantified.

In Chapter 2 relevant background information about stream temperature, groundwater-surface water interaction and distributed temperature sensing is given and previous research is discussed. In Chapter 3 a description of the research areas are given, including information about the geologic background, land use, climate and hydrology. Next, the methodology is given in Chapter 4 which includes a description of the temperature measurements performed during this study, how the temperature information can be used to identify seepage zones and how the seepage flux in the tributaries is determined. The results are shown in Chapter 5 and a discussion of the results, together with the limitations and recommendations of this thesis, is given in Chapter 6. Lastly, in Chapter 7 the conclusions are given.

Chapter 2

Background information: Stream temperature

Over the past decades much research has been done on thermal processes influencing the water temperature of streams and rivers due to its importance for the health of the aquatic ecosystem and water quality (Malcolm et al., 2004; Broadmeadow et al., 2011; Matheswaran et al., 2014). Caissie (2006) summarized the most important factors influencing the thermal regime of a river. He concluded that water temperature is the result of the energy balance of a stream which is influenced by multiple factors that can be grouped in four categories: atmospheric conditions, topographic conditions, streambed conditions and stream discharge conditions (Figure 2.1). These factors all contribute to the total energy flux of the stream. Atmospheric conditions, such as air temperature, solar radiation, long-wave radiation, evaporation and convection by wind, generally have the largest influence on the stream temperature since over 80% of the total energy is exchanged on the air-water interface (Caissie, 2006). Of all atmospheric factors, direct solar radiation is seen as the most important factor influencing the stream temperature due to its high energy exchange during daytime and minimal energy exchange during nighttime. This causes the main daily temperature fluctuations in the stream, which is also highly related to air temperature. On its way downstream, the stream temperature is constantly moving towards its equilibrium temperature which is linearly related to the daily average air temperature (Bogan et al., 2003; Gu et al., 1998). The incoming energy by atmospheric factors is reduced by topographic factors such as latitude, altitude, surrounding bedrock and riparian vegetation, by limiting the amount of solar radiation reaching the stream and by transmitting long-wave radiation which results in a damped and often delayed timing of the day-night fluctuations (Broadmeadow et al., 2011). Especially in small streams, riparian vegetation is recognized as a major factor influencing the stream temperature because it lowers both the incoming solar radiation and air temperature (Johnson, 2004; Matheswaran et al., 2014). Studies performed by Broadmeadow et al. (2011) and Verdonschot et al. (2014) examined whether creating more shade by placing additional riparian vegetation, is an option to reduce the effect of climate change on stream temperature and as such limit the impact of global warming on the aquatic ecosystem in streams. Broadmeadow et al. (2011) found that a canopy cover of at least 20% along a 500 meter reach of a stream is needed to lower maximum water temperatures during summer and therefore prevent



Figure 2.1: Main factors influencing the energy budget of a stream. Based on a figure by Caissie (2006))

the exceedance of lethal temperature limits for fish. However, with predicted climate warming an even higher percentage of canopy cover will be needed.

Besides atmospheric and topographic factors, stream temperature is also influenced by discharge characteristics and stream geometry. High volumes of water and high water levels limit the heating of the entire water column by short wave solar radiation (Neilson et al., 2010; Grabowski and Gurnell, 2016). Additionally, rapid stream velocities result in less warming over the same distance. In contrast, streams with a low discharge and a wide streambed can easily be warmed by solar radiation. Moreover, the streambed sediments are warmed during the day by solar radiation and release their heat by conduction during night (Caissie, 2006).

For gaining streams, an additional factor influencing the stream temperature is present since they are receiving their water from the groundwater. Due to the relatively stable groundwater temperature, which usually approximates the average annual air temperature (Brunke and Gonser, 1997), groundwater discharge has a lower temperature compared to the stream temperature during summer and a higher temperature during winter. The process of groundwater discharge therefore creates zones with relatively stable stream temperatures. At the source in gaining streams, the stream water temperature upstream is highly related to the groundwater temperature (Caissie, 2006). However, when moving farther from the source, the correlation with the groundwater temperature will decrease and the correlation with the atmospheric conditions will increase (Zwieniecki and Newton, 1999).

Chapter 3

Research area

3.1 Introduction to the research areas

This study focuses on two tributaries of the Dinkel river in Twente, the Netherlands, called the Elsbeek and the Springendalse Beek (Figure 3.1). Land use of the catchments of the tributaries is dominated by agricultural fields (>70%) and the remaining land is used as urbanized and forested area (Louw and Monincx, 2006). The mean annual precipitation and mean annual evaporation in this area are respectively 800-850 mm and 560-570 mm (KNMI Klimaatatlas 1981-2010). The Elsbeek is a second order tributary of the Dinkel. This stream springs in the ice-pushed ridge of Oldenzaal and directly mouths into the Dinkel south of Losser ($52^{\circ}14'27.40''N$ 7° 0'25.36''E). The upstream area of the Elsbeek consists of three smaller streams which confluence together and form the main stream. The stream has a total catchment area of 1320 hectares and a total length of 5.9 km (Verdonschot, 1999). Within this research 1.5 km of the downstream part of the Elsbeek is studied which has a surface elevation ranging from 36 meter above sealevel upstream and 33 meter above sealevel downstream.

The other studied tributary, the Springendalse Beek, is a third order stream which discharges into the Hollander Graven and eventually into the Dinkel close to the border with Germany (52°26'4.62"N 6°56'53.98"E). This stream has a more natural character compared to the Elsbeek since less humane interference took place in its catchment. However, some weirs for discharge monitoring and artifical dams have been placed. Moreover, sand has been added to counter the deep incision of the stream (Verdonschot et al., 2004). Just like the ElsBbeek, the Springendalse Beek springs from an ice-pushed ridge; the Ootmarsum ice-pushed ridge. The upstream part of the Springendalse Beek springs on the eastern flank of the ice-pushed ridge at a surface elevation of 56 meter above sealevel and consist of a northern branch and a southern branch which confluence after approximately 600 meter from the first spring (Verdonschot et al., 2004). In addition, outflow of multiple seepage lakes mouth into the stream. The Springendalse Beek has a total length of 5.4 km and a catchment area of 485 hectares. This study focuses on parts of the northern and southern branch and 1 km of the main stream.



Figure 3.1: Locations of the Elsbeek and the Springendalse Beek on a map of the Netherlands (Source: ESRI Nederland).

3.2 Geology

To explain some of the occurring hydrological phenomena in the research areas, knowledge of the local geology, which was mainly formed during the last 65 million years, is necessary. During the Early Tertiary the Noordzeebekken was a coastal area where marine deposits, now named as the Dongen Formation, where formed on the seabed. Nowadays, these deposits configure as the hydrological basis in Twente and consist of calcareous clay with an easily recognizable green colour due to the clay mineral glauconiet (Louw and Monincx, 2006). During the Pleistocene the sea level in the Noordzeebekken decreased causing large parts of the Netherlands to be dominated by rivers, which led to the deposition of a few meters of fluvial sands(Berendsen, 2004). Arctic ice covered the northern part of the Netherlands during the Saalien ice-age. This ice sheet moved in westerly direction, pushing up the Tertiary and Pleistocene sediments and forming ice-pushed ridges with a complex internal structure of alternating clay and coarse fluvial sediments (Van den Berg and Den Otter, 1982). Two ice-pushed ridges were formed in Twente during this period; the Enschede-Oldenzaal ice-pushed ridge and the Ootmarsum ice-pushed ridge. Outwash fans were created on the western side of the ridges and while the ice sheet was moving more south, the ridges were partly eroded due to overriding of the ice forming a basal till and drumlin shaped ice-pushed ridges (Van den Berg and Den Otter, 1982). The next change of landscape occurred in the periglacial environment during the Weichselian. Eolian sands were blown from the dry Noordzeebekken and accumulated as coversands at the foot of the ridges. The combining effect of the lack of vegetation, a thick layer of permafrost and an abundance of meltwater caused major erosion of the surface. This formed erosion valleys in the ridges, of which one is now known as the Springendal (Alberts, 1979; Van der Aa and Stuurman, 1999; Van den Berg and Den Otter, 1982). The local geology of the research areas has not changed significantly since the start of the Holocene.

3.3 Hydrology

Elsbeek

The Elsbeek is a low gradient stream (2.5 m/km) with a width varying between 1 to 1.5 meter and a fluctuating water depth of 0.1 to 1 meter. The average discharge is 0.106 m^3 /s and the main component of the discharge originates from precipitation and from drainage water from agricultural fields (Verdonschot, 1999). Due to canalization and drainage systems in the surrounding agricultural fields, precipitation is rapidly drained into the stream resulting in peak discharges at times of rainfall. On the other hand, the stream can also fall dry during dry summers (Figure 3.2a). This also means that groundwater discharge during these dry periods is minimal. The high nutrient levels in the Elsbeek can be explained by the agricultural origin of the water.

Springendalse Beek

The Springendalse Beek has a stream width varying between 0.5 to 2 meters and a fluctuating water depth of 0.1 to 0.5 meter. Unlike the Elsbeek, the Springendalse Beek has a minimum baseflow of 0.015 m³/s and an average discharge of 0.047 m³/s. As can be seen in Figure 3.2b, this baseflow occurs during most summers. The main component of the discharge originates from groundwater seepage within the stream and from the outflow of seepage lakes. The groundwater discharge in the area can be explained by the geology in the area. Due the presence of alternating clay and sand layers in the ice-pushed ridge of Ootmarsum, water is infiltrating through permeable sand layers until it reaches an impermeable clay layer. Because the stream is located in a major erosion valley, these clay layers outcrop the surface at multiple places, leading to the formation of groundwater springs (Van Dam et al., 1993). The seepage areas along the Springendalse Beek can be identified as helocrene springs, which are known for their large groundwater discharge areas and are permanently flowing. The origin of most of the seepage water around the Springendalse Beek are the agricultural fields on the western side of the stream, causing high nitrate concentrations in the stream (Van Dam et al., 1993). Historically, drainage systems in these agricultural fields caused peak discharges in wet periods and drought and acidification during dry periods. These large fluctuations in discharge together with the high nutrient loads from the agricultural fields had a harmful effect on the ecology of the stream and therefore the drainage systems were removed in 1998 (Horsthuis, 2007). To prevent further erosion a large sand supply was placed in the mid-section of the stream, causing the stream to redistribute the sand over its downstream area and limit the vertical erosion (Verdonschot et al., 2004). Additionally, flumes were placed at multiple location for the same purpose. These flumes are passable for fish and macrofauna and therefore do not limit the aquatic migration. The streambed gra-



Figure 3.2: (a) Discharge data of the Elsbeek and (b) discharge data of the Springendalse Beek (Source: Waterboard Vechtstromen).

dient along the Springendalse Beek decreases from 20 m/km upstream till 6 m/km completely downstream.

Chapter 4

Methods

This chapter describes the methods used during this study to find groundwater seepage zones and to explain the temperature distribution along the Elsbeek and Springendalse Beek. First different methods to measure the stream temperature are discussed, followed by multiple methods to locate seepage zones from this temperature data. At the end of this chapter additional measurements are described, such as measurements of the seepage flux, vertical temperature distribution and water chemistry.

4.1 Stream temperature: Distributed Temperature Sensing

Detailed temperature information about the stream temperature of the Elsbeek and the Springendalse Beek was obtained using fiber-optic distributed temperature sensing (FO-DTS). The streambed temperatures were measured using an Oryx DTS sensornet (USA) unit and a CTC LSZH fiber-optic cable (TKF Connectivity Solutions, Nederland). The Oryx unit has a temperature accuracy of $\pm 0.5^{\circ}$ and a default attenuation coefficient of 1.2 to 1.5 dB/km. The cable contains four optic fibers, surrounded by a hydrophobic gel filled PVC pipe and a layer of glass yarns for reinforcement (Figure 4.1). The outer shell is made of low smoke zero halogen (LSZH) material with a radius of 7 mm.

Over the last years, DTS has been used regularly as a method to monitor temperature on a small spatial resolution, down to meters or even millimeters, over distances up to a few kilometers (Briggs et al., 2012; Sebok et al., 2013; Selker et al., 2006b). The main advantage over traditional single-point temperature measurements is the high spatial resolution. The principle of DTS is based on the fact that the wavelength of photons is influenced by temperature. A DTS unit transmits a laser signal through an optic fiber and receives a backscattered signal from every location in the cable. Part of the backscattered signal has the same wavelength as the original laser pulse, while another part is influenced by temperature and has a different wavelength (Selker et al., 2006b). The photons with changed wavelength are called Raman scattering and can be divided in a Stokes (higher wavelength) and anti-Stokes (lower wavelength) signal. Since the anti-Stokes signal is more sensitive to temperature changes compared with the Stokes signal, the Stokes:anti-Stokes ratio can be used to calculate the the temperature along the cable (Van De Giesen et al., 2012). Figure 4.2 shows an example of a Stokes and anti-Stokes signal



Figure 4.1: Components of the CTC LSZH fiber-optic cable.



Figure 4.2: Example of a stokes and anti-stokes signal with its corresponding temperature.

with its corresponding temperature profile. The time between transmitting and receiving the laser signal in combination with the speed of light tells the position of the temperature measurement along the fiber-optic cable (Hare et al., 2015).

Adsorption and radiation along the fiber-optic cable will influence the light signal transmitted by the DTS unit, this is called attenuation. Attenuation increases with distance from the DTS (Hare et al., 2015) and is strengthened by splices, stresses, bending and heterogeneity of the cable (Van De Giesen et al., 2012). When not corrected for attenuation, these signals can be misinterpreted as temperature signals. There are multiple DTS-configurations described in literature to correct for attenuation. The simplest temperature sensing is done using a single-ended configuration (Figure 4.3a), where laser pulses are launched and monitored at one end of the fiber-optic cable. Although the measuring method for single-ended measurements is quite easy, the calibration to correct for attenuation is often more extensive, since multiple calibration baths with known temperature are necessary at the beginning and at the end of the fiber-optic cable (Hausner et al., 2011). Furthermore, this method assumes that attenuation is constant for the en-



Figure 4.3: (a) Single-ended DTS measurement configuration. (b) Double-ended DTS measurement configuration or duplexed single-ended measurement method with a double-ended configuration. Both Figures are modified from Hausner et al. (2011).

tire length of the cable. A different DTS configuration is the double-ended configuration (Figure 4.3b), where laser pulses are launched from both ends of the optic-fiber and are monitored at the other end. This usually happens in an alternating way. An advantage of the double-ended method is that the attenuation during the calibration is reduced since the error is minimized by averaging the measurements from both sides (Van De Giesen et al., 2012). Furthermore, only two calibration baths are needed and can be positioned near the DTS device since the optic fiber is duplexed. Due to this configuration, the temperature signal inside both water baths is measured in both the forward and reverse direction. Van De Giesen et al. (2012) reported that a disadvantage of double-ended measurements is that using multiple channels of the DTS unit lead to more algorithmic complexity and a noisier signal near the DTS unit.

4.1.1 Laboratory tests

Before applying the distributed temperature sensing method in the field, some laboratory experiments using the fiber-optic cable were performed to examine the reaction time of the cable to temperature changes and to determine the effect of the measurement time on the accuracy of the temperature data. The tests were performed using a duplexed single-ended configuration, meaning that the end of the 6 meter long optic fiber (CTC LSZH fiber-optic cable, TKF Connectivity Solutions Nederland) was spliced to another optic fiber within the same cable using a MicroCore DCM Fusion Splicer Type 39. A total of twelve meters of fiber-optic cable was therefore available for measurements. Besides the fiber-optic cable, the laboratory setup consisted of the Oryx DTS unit and two calibration baths, one kept at a constant temperature of 15°C and the temperature of the other bath was increased in steps by adding boiled water. Furthermore, a TP-100 temperature sensor provided with the Oryx unit was continuously measuring the temperature of the calibration baths. First the thermal response time, which is the time it takes for the cable to stabilize after a temperature change, was tested by placing four meter of fiber-optic cable in the constant temperature calibration bath. Boiled water was added to the second calibration bath and mixed. Next, the cable was moved to the second bath until the temperature of the cable had stabilized. Then the cable was placed back in the first bath and the process was repeated a few times.

Previous research found that a longer measurement time has a positive effect on the accuracy of the measured temperature (Selker et al., 2006b; Deltares, 2014; Sensornet, 2007). According to Deltares (2014) the accuracy of the temperature measurements is not only depending on the temporal resolution, but is a trade of between the length of the fiber-optic cable, temporal and spatial resolution. During the laboratory testing measurement times of 15 and 30 seconds were used and measurement a time of 300 seconds was used in the field.

4.1.2 Field measurements

The Oryx unit was installed in a barn in the downstream part of the Elsbeek approximately 300 meter before the Elsbeek mouths into the Dinkel. The fiber-optic cable had a length of 1.5 km and was placed on the streambed in the upstream direction (Figure 4.4a). This part of the Elsbeek was chosen such that the cable ran through two forested areas and two open/agricultural areas. Therefore the effect of shade on the stream temperature could be monitored. The fiberoptic cable was secured to the streambed using pegs with a length of 30 cm. At the Springendalse Beek another Oryx unit was placed 50 meter downstream from the intersection of the stream and the Blauweweg and the fiber-optic cable, with a length of 1 km, was secured to the streambed in the upstream direction. To see the effect of the confluence of the two upstream branches, the cable was placed partly in the southern branch and partly in the northern branch (Figure 4.4b). At places where the stream was overgrown by plant or cut off by fallen trees, weirs or bridges, the cable was placed on the stream bank. To increase the amount of measurements at specific location such as the location of independent temperature sensors, active drainage pipes or outflow from seepage lakes an extra few meters of the cable was coiled and placed at these locations. The exact location of the fiber-optic cables were determined by interpolating known locations along the cable, such as inlets of seepage lakes (Springendalse Beek) or fast flowing drainage pipes (Elsbeek).

For this study a duplexed single-ended measurement method with a double-ended configuration was chosen. This means that the signal was transmitted and received on one end of the duplexed fiber-optic cable and subsequently from the other side (Figure 4.3b). The advantage of this configuration is that the chance to lose data in case of a broken or damaged optic fiber is minimized since the temperature is measured from both ends and it is relatively easy to correct for attenuation. Two calibration baths were placed close to the Oryx unit at both tributaries. One calibration bath was filled with magic gel (isolation gel) and the other bath with polyurethane foam to damp the fluctuations in diurnal temperature. The automatic calibration method provided with the Oryx unit was continuously performed during the measurement period whereas the raw-data calibration was done after the measurements were finished. These calibration methods will be further discussed in Section 4.1.3. The stokes and anti-stokes data was collected with



Figure 4.4: (a) Location of the independent temperature sensors (dots) and the fiber-optic cable along the Elsbeek. Zones A and C: forested/shaded areas, Zones B and D: agricultural/open areas. (b) Location of the independent temperature sensors and the fiber-optic cable along the Springendalse Beek divided into 5 zones. Zone A: northern branch, Zone B: southern branch, Zone C: midstream high, Zone D: midstream low, Zone E: downstream. The squares represent the locations of the Oryx DTS units. Both tributaries flow from west to east. (Source map: ESRI Nederland)

a spatial resolution of 1 meter and a measurement time of 5 minutes with a repetition time of 30 minutes on two channels. This measurement time was chosen as it was short enough to see the effect of short rainfall events on the stream temperature and long enough to minimize noise in the measurements. In this study the temperature data set from 10 to 23 August 2016 is used for the Springendalse Beek and 16 to 29 August 2016 for the Elsbeek.

4.1.3 Calibration methods

The goal of calibration is to minimize the error between the real temperature in the calibration bath (measured by a TP-100 temperature sensor) and the temperature calculated from the fiber-optic cable. Two calibration baths with known temperatures were placed close to the Oryx unit at each stream, with 30 to 50 meter of fiber-optic cable coiled in both calibration baths. According to Tyler et al. (2009) the minimum length of the cable inside a calibration bath must be 10 times the spatial resolution so enough measurement points are present in the calibration bath to minimize the RMSE and noise. One calibration a correction for attenuation is done by comparing the temperature profile at both ends of the cable within the calibration baths, which should have the same temperature. If not, the slope can be calculated and the temperature can be corrected for this slope. Moreover, step losses can be identified from the temperature profiles as a sudden change in temperature which often occur at places of splices, damages and bends of the cable (Hausner and Kobs, 2016). When a step change occurs in a duplexed configuration, which is the case for this study, it can simply be corrected by assuming that the temperature on either side of the splice is equal and by correcting the second half of the cable for the temperature

difference. Although it is usually advised to correct the temperature for step losses, averaging the temperatures given by each measurement channel in the double-ended configuration already minimizes the temperature step.

The other calibration was performed using the stokes and anti-stokes data measured by the Oryx unit. Hausner et al. (2011) concluded that the raw-data calibration they describe is more accurate than the instrument-calibration data and therefore their calibration method for duplexed single-ended measurements was also tested in this study. The first step in this calibration was to identify the positions of the calibration baths along the cable. The noise was minimized and the accuracy improved by using the entire length of the fiber-optic cable inside the calibration bath as a reference section (z^*) instead of using a single reference point (z) inside the baths. The position of the reference section was defined as the average distance from the Oryx unit:

$$z^* = \frac{1}{n} \sum_{i=1}^n z_i \tag{4.1}$$

Where $z_i[m]$ is the distance from the Oryx unit from each measurement point along the reference section and n is the amount of measurement points. This was calculated for each calibration bath after which the ratio between the stokes and anti-stokes signal was calculated at these reference sections:

$$ln\frac{P_S}{P_{aS}}^* = \frac{1}{n}\sum_{i=1}^n ln\frac{P_S(z_i)}{P_{aS}(z_i)}$$
(4.2)

Where P_S [dB] is the power of the stokes signal and P_{aS} [dB] being the power of the anti-stokes signal. The attenuation was calculated for each time step by comparing the stokes anti-stokes ratio of the two reference sections with the same temperature on both ends of the cable and determining the slope between these two reference sections using:

$$\Delta \alpha = \frac{ln \frac{P_s(z_2)^*}{P_{as}(z_2)} - ln \frac{P_s(z_1)^*}{P_{as}(z_1)}}{z_2^* - z_1^*}$$
(4.3)

Where $\Delta \alpha$ [dB/m] is the total amount of attenuation over the length of the cable. Finally, two other calibration parameters were calculated: a dimensionless calibration parameter C which is a parameter that includes all properties of the Oryx unit and laser (Equation 4.4), and γ (K) which describes the shift in energy between the photon launched by the laser and the backscattered Raman photon (Hausner et al., 2011) (Equation 4.5). In this study it was assumed that γ and C are equal for the entire length of the cable and are constant over time, although C might slightly vary over time (Van De Giesen et al., 2012). These two parameters were calculated for each measurement and subsequently averaged.

$$C = \frac{T(z_2)ln\frac{P_s(z_2)}{P_{as}(z_2)}^* - T(z_1)ln\frac{P_s(z_1)}{P_{as}(z_1)}^* - T(z_2)\Delta\alpha z_2^* + T(z_1)\Delta\alpha z_1^*}{T(z_1) - T(z_2)}$$
(4.4)

$$\gamma = T(z_1) * \left(ln \frac{P_s(z_1)}{P_{as}(z_1)}^* + C - \Delta \alpha z_1^* \right)$$
(4.5)

In the end, the temperature (T $[^{\circ}C]$) can be calculated for each time step using the raw stokes and anti-stokes data and the calibration parameters:

$$T = \frac{\gamma}{\ln \frac{P_s(z_i)}{P_{as}(z_i)} + C - \Delta \alpha z_i}$$
(4.6)

4.2 Stream temperature: Independent temperature sensors

To validate data of the fiber-optic distributed temperature sensing and to have independent point measurements, a total of twelve temperature sensors were placed along both the Elsbeek and the Springendalse Beek. Eight temperature sensors were used to measure stream temperature and four sensors to measure air temperature (Table 4.1). For these measurements a combination of HOBO 12-bit temperature smart sensors with 6 meter cable (S-TMB-M006, Onset USA) in combination with HOBO Weather Station Data Loggers (H21-001, Onset USA). The sensors have an accuracy of 0.2° C and a resolution of 0.03° C over a range of $0 - 50^{\circ}$ C. Measurements were performed every 1 minute in the period from June 22^{nd} to November 15^{th} 2016. The HOBO weather stations were placed on the stream bank and the stainless steel temperature sensors were installed a few centimeter above the streambed to ensure the sensor is not affected by sedimentation or low water levels.

Three of the temperature sensors were positioned along the downstream part of the Elsbeek (Figure 4.4a). As the Elsbeek can be divided into two major shaded zones and two open zones along the stream, the locations of these loggers were chosen such that the effect of shade on the stream temperature could be examined. To capture the maximum effect of the shade or open part of the stream, the loggers were placed downstream of each zone. In addition to stream temperature, air temperature was logged at two locations in the Elsbeek catchment.

Along the upstream part of the Springendalse Beek five temperature sensors were placed to measure stream temperature. Besides for the validation the DTS measurements, these loggers were placed to examine the effect of the confluence of the northern and southern branch. Therefore, one logger was placed within each branch in the upstream part of the stream and one logger approximately 30 meter downstream of the point where the two branches confluence together to

Stream	Station	UTM	Northing	Easting	Stream temp.	Air temp.
Elsbeek	T2	32	5789597	363298	\checkmark	\checkmark
Elsbeek	Т3	32	5789645	362965	\checkmark	\checkmark
Elsbeek	T6	32	5789824	362674	\checkmark	×
Springendal	T4	32	5811213	356723	\checkmark	×
Springendal	T5	32	5811288	356355	\checkmark	\checkmark
Springendal	Τ7	32	5811261	356320	\checkmark	×
Springendal	T8	32	5811146	357004	\checkmark	\checkmark
Springendal	Т9	32	5811301	356348	\checkmark	×

Table 4.1: Locations of the HOBO independent temperature sensors. Locations were also showed in Figure 4.4.

see how the stream temperature responds to the mixing of the two branches (Figure 4.4b). Since the outflow of multiple seepage lakes streams into the Springendalse Beek, the effect of these lakes on the stream temperature was monitored by examining the difference between the stream temperatures measured upstream and downstream of the lakes.

4.3 Locating of groundwater seepage zones

Four different methods are described in literature to detect seepage zones from the DTS data. Selker et al. (2006a) used step changes in the longitudinal temperature profile at a specific time to identify these locations. This step in temperature (negative in summer and positive in winter) is only visible when the groundwater discharge has influence on the downstream temperature, which occurs when the groundwater discharge is a major input to the total stream discharge at that location. Another method is the standard deviation of diurnal temperatures as an indication of groundwater seepage zones (Lowry et al., 2007). Therefor the standard deviation of each location is calculated for the entire measurement period. Zones with low standard deviation show minimum temperature change through time and are therefore a good indication of seepage zones. A third method, the constant temperature method, was used by Briggs et al. (2012). By plotting 24-hour mean stream temperatures along the whole stream profile, locations with an average lower temperature compared with the surrounding stream can be found, which is an indication for seepage. The fourth method to identify groundwater seepage zones is comparing the daily minimum and maximum temperatures along the profile of the streams (Matheswaran et al., 2014). Locations with minor difference between the minimum daily temperature, which is reached at sunrise, and the maximum daily temperature, which is reached in the late afternoon (Caissie, 2006), are likely to be influenced by groundwater. Matheswaran et al. (2014) already concluded that the temperature difference between the maximum and minimum temperature and the standard deviation of the diurnal temperatures are the most useful methods to identify groundwater seepage zones in summer and spring, mainly due to the wide temperature range and low discharge rates, which is also the case in this study. In this study all four methods to detect seepage zones from the DTS data are used and their applicability in this study area is compared.

4.4 Seepage flux

Quantitative measurements on the amount of seepage in the streams is useful to get an idea of the amount of seepage occurring in the streams, but also for future research in modelling of the temperature distribution of the stream. From the temperature profiles made with the DTS data interesting locations with suspected seepage are identified to perform the flux measurements. PVC pipes with a radius of 12.5 cm were placed 30 cm in the streambed (Figure 4.5). Next, a Schlumberger CTD Diver was placed on the streambed inside the pipe and the water level in the pipe was lowered. The CTD diver measured time and water depth inside the pipe when seepage started to fill the pipe again. As the water level inside the pipe approached the water level of the stream, the increase in water level slowed down (Figure 4.6). The seepage velocity



Figure 4.5: Measurement setup for flux measurements. Several PVC pipes placed in the streambed in the Springendalse Beek.



Figure 4.6: Example of a time-water level graph for the determination of the seepage flux.

was determined at the time when the hydrostatic pressure was equal inside and outside of the pipe, which is when the water level inside the pipe equals the stream level. The water height was measured using a ruler and an uncertainty of 1 mm was used in the calculations. By fitting a line through the data, the slope of the line could be determined at the position where the water levels are equal which is the seepage velocity.

4.5 Vertical temperature distribution

Whereas spatial variation in streambed temperatures can be used as an indicator for seepage zones, a vertical temperature profile in the streambed gives more detailed information about the vertical water movement between groundwater and surface water (Constantz, 2008; Vandenbohede and Lebbe, 2010). The daily or annual temperature envelope in the subsurface indicates the stream is gaining or losing water and whether there is a high or low vertical velocity. In a losing stream the thermal diurnal oscillation surface can be found at greater depths with increasing infiltration rates and has a relatively short delay relative to the stream temperature due to the combi-



Figure 4.7: Simplified annually or daily maximum and minimum temperature envelopes below a streambed of a gaining or losing stream. Modified from Constantz (2008)

nation of heat advection and convection(Constantz, 2008). On the other hand, gaining streams experience upward water movement so that the thermal diurnal oscillation surface is found at shallower depths. In this case heat conduction from the surface is the dominant factor influ-

encing the diurnal temperature oscillation. However, with increasing seepage rates the upward advective heat transport will dominate the heat conduction from the surface which will lead to the movement of the thermal diurnal oscillation surface to a shallower depth (Figure 4.7), a greater lag in oscillation or even an absence of diurnal temperature variation in the streambed sediment (Constantz, 2008).

Vertical temperature profiles were made measuring the temperature and electrical conductivity every 10 cm in the streambed by using a TEC-probe (temperature-electrical conductivity probe, developed by Van Wirdum (1991)) at several location along the streams. At each location multiple measurements were done perpendicular to the stream, so the difference between the sides and the middle of the stream can be compared.

Besides giving insight into whether the stream is gaining or losing, multiple vertical temperature profile through the year can be used for quantitative calculations of the vertical water flux. Based on the ideas of Stallman (1963), multiple researches used the one-dimensional heat transport equation (Equation 4.7) to quantify vertical water flow between groundwater and surface water (Constantz, 2008; Vandenbohede and Lebbe, 2010; Briggs et al., 2012)

$$K_T \frac{\delta^2 T}{\delta z^2} - qC_w \frac{\delta T}{\delta z} = C_s \frac{\delta T}{\delta t}$$
(4.7)

Where K_T [W/m°C] is the thermal conductivity of the streambed sediments, T [°C] is the temperature, z [m] is the depth, q [m/s] is the water flux, C_w [J/m³ °C] is the volumetric heat capacity of water, C_s [J/m³ °C] the volumetric heat capacity of the bulk sediment and t [s] is time.

4.6 Other seepage indicators

In addition to temperature, other indicators for groundwater seepage were present including both visible and chemical indicators. In the following section a description is given of the visible seepage indicators and of the chemistry measurements performed with samples of surface water and groundwater.

4.6.1 Water chemistry

The chemistry of groundwater and surface water is different and as such changing chemistry of the surface water along a stream can be used as a tracer for groundwater seepage. Water samples of the surface water and groundwater were taken at multiple location along both the Elsbeek and the Springendalse Beek. Nitrate, iron 2+ and iron 3+ concentrations were measured using a HACH field spectrophotometer (Type DR-1900). The pH of the water samples was measured using a Hach multimeter (Type HQ40d) and the EC was measured using a portable conductivity meter (Type Cond3110, WTW). For future research samples were filtered over a 45 nm membrane, stored cool and measured for anions and cations on a Dionex ICS-3000.

An additional chemical groundwater indicator is Radon-222 which is an useful natural tracer for groundwater-surface water interaction. The presence of radon in the streams was measured to see whether the streams are affected by groundwater seepage. Radon is a decay product of Radium-226 within the radioactive decay chain of Uranium-238 (Wu et al., 2004). Due to the

constant decay of radium into radon within soils and bedrock, high concentrations of radon can be found in the surrounding groundwater. However, as soon as the groundwater reaches the surface the amount of radon quickly decreases due to the short decay half life time of 3.8 days and the volatile character of radon which causes degassing towards the air (Cartwright and Hofmann, 2016). This is why relatively large radon concentrations can be found in surface water close to seepage zones and concentrations quickly decrease with distance from it source (Wu et al., 2004). Although it is possible to use radon to quantify the groundwater discharge in rivers and streams, in this study radon was only used to get an idea whether the surface was was influenced by groundwater and to locate groundwater seepage zones.

To measure the amount of radon in the Elsbeek and Springendalse Beek, several water samples of 250 mL were taken from the streams before, within and after possible seepage zones determined from the DTS data. Moreover, groundwater samples were taken from multiple piezometers to see what radon concentration could be found in groundwater. The water samples were attached to the RAD7 in combination with the RAD H₂O (Durridge Company Inc.) (Figure 4.8). The RAD7 aerates the water sample for five minutes causing the radon concentration in the water and air to approach equilibrium (DURRIDGE, 2016). Using Henry's Law for radon and its distribution coefficient, the amount of radon in the water sample was calculated by the RAD7 and given in becquerels per cubic meter (Bq/m^3).

4.6.2 Visible seepage indicators

There are several seepage indicators found along the streams which are often directly correlated with the presence of seepage in an area. One of the most common visible indicators is the presence of iron oxidation on the streambed. Iron concentrations in groundwater are often



Figure 4.8: Radon measurement setup using the RAD H_2O in combination with the RAD7 (DURRIDGE, 2016)

higher compared to the surface water due to the anoxic conditions in the subsurface. When groundwater discharges to the surface and comes into contact with oxic conditions, the dissolved Fe^{2+} oxidizes resulting in an insoluble ferric-iron mineral (Walter, 1997). This iron mineral precipitates on the streambed as an easy recognizable red layer. Another visible seep-

age indicator is a rare plant called the Chrusosplenium alternifolium or Golden-Saxifrage (in Dutch 'Goudveil'). This plant can be found along wetlands where iron-rich groundwater is constantly available (Moore, 1984). Furthermore the presence of wetlands and springs along a stream indicates a high groundwater level with respect to the stream level, which often results in groundwater seepage in the stream. The locations of these visible seepage indicators were mapped and linked to the temperature measurements to confirm the seepage zones found from the DTS data.

4.7 Air-stream temperature correlation

As explained before, air temperature often has a major influence on the stream temperature, although often delayed. Gu et al. (1998) showed that an increasing correlation between the air and stream temperatures can be found with increasing distance from the source of the stream. To see how strong this correlation is for different zones along both tributaries the cross correlation function (CCF) was calculated. For the air temperature the HOBO temperature sensors are used (Weather station T2 for the Elsbeek and weather station T8 for the Springendalse Beek) and for the stream temperature an average temperature was calculated over 10 meter in each zone along the streams. The first step was to calculate the cross covariance which is defined as:

$$COV[Z_t, Y_{t+k}] = E[(Z_t - \mu_Z)(Y_{t+k} - \mu_Y)]$$
(4.8)

With Z being the independent variable (air temperature), Y being the dependent variable (stream temperature), k being the time lag and μ the mean of the two variables. Next, the cross correlation coefficient was calculated using the cross covariance and the standard deviation (σ) of both Z and Y (Bierkens and van Geer, 2016).

$$\rho_{ZY,k} = \frac{E[(Z_t - \mu_Z)(Y_{t+k} - \mu_Y)]}{\sigma_Z \sigma_Y}$$

$$(4.9)$$

By plotting time lag k against the cross correlation coefficient for each zone along the streams, spatial differences in correlation between air and stream temperature were determined. Furthermore the CCF also showed the difference in response time of the stream temperature to changes in air temperature.

Chapter 5

Results

5.1 Laboratory tests

The results of the laboratory tests of the DTS are shown in Figure 5.1. As can be seen, the CTC LSZH fiber-optic cable reacts quickly to sudden temperature changes, but takes some time to stabilize at a new temperature. The thermal response time for a temperature increase of 5- 7° C was approximately 2 minutes and for an increase of $25-30^{\circ}$ C approximately 3 minutes. Compared to the response time for a sudden increase in temperature, the response time of a decrease in temperature was slightly longer. Furthermore, two different measurement times of 15 and 30 seconds were tested. It was found that a longer measurement time, meaning the average temperature value is determined over a longer time period, resulted in less noise in the temperature measurement. The measurement time of 15 seconds had an accuracy of \pm 0.30 °C while the measurement time of 30 seconds had an accuracy of only $\pm 0.15^{\circ}$ C. So, this doubling in measurement time resulted in 50% less noise. Lastly, a significant temperature difference could be seen between the temperatures measured by the fiber optic cable and measured by the TP-100 temperature sensors. This temperature gap was later found to be caused by the single-ended DTS configuration. During the field measurements this was prevented by averaging multiple channels of the Oryx unit and by doing duplexed single-ended measurements with a double ended configuration.

5.2 Calibration methods of DTS

Two different calibration methods were tested during the processing of the temperature data: a pre-installed calibration of the Oryx unit and the raw-data calibration provided by Hausner et al. (2011). The temperatures calculated by the Oryx unit itself using the pre-installed calibration only had to be corrected for attenuation, since the automatic setting for correction of attenuation was not used. The raw-data calibration already included the correction for the attenuation as was described in Chapter 4.1.3. In Figure 5.2 the differences between the calibration methods for both the Elsbeek and Springendalse Beek can clearly be seen. In the figures 5.2a and 5.2b the temperature of the TP-100 sensors in calibration bath 1 of both the Elsbeek and the Springendalse Beek is compared with the DTS-temperatures calculated using both calibrations. As can



Figure 5.1: Laboratory test results of the distributed temperature sensing using a CTC LSZH fiber-optic cable.

be seen, the temperatures calculated by the pre-installed Oryx calibration of both the Elsbeek and Springendalse Beek is in good agreement with the 'real' temperature given by the TP-100 sensor. Temperatures calculated using the raw-data calibration showed the right frequency in the diurnal fluctuations, however the amplitude of the calculated temperature is much lower compared with the other calibration method and reference temperature.

Additionally, the same test was done by comparing the calculated temperature of the fiberoptic cable with independent HOBO temperature sensors in the streams (Figure 5.2c and 5.2d). Again the temperature calculated with the pre-installed Oryx calibration showed the same patterns as the independent HOBO temperature sensor at both the Elsbeek and the Springendalse Beek. Temperatures calculated with the raw-data calibration again showed a lower amplitude than the reference temperature of the HOBO temperature sensors and the temperature calculated by the Oryx unit. Moreover, an irregular diurnal fluctuation for the Springendalse Beek can be seen. From these findings it can be concluded that the calibration method provided with the Oryx unit gives a better agreement between the fiber-optic temperatures and the temperatures measured with the independent temperature sensors and is therefore used in the upcoming sections of this research.



Figure 5.2: (a) and (b): Temporal variation of the temperature of the Elsbeek and Springendalse Beek, calculated using both calibration methods, compared with the reference temperature in calibration bath 1 measured by a TP-100 temperature sensor. (c) and (d): Temporal variation of the temperature of the Elsbeek and Springendalse Beek, calculated using both calibration methods, compared with the reference temperature of the Independent HOBO temperature sensors.

5.3 Elsbeek

5.3.1 Stream temperature description

The stream temperature of the Elsbeek was measured from 14 July till 8 December using DTS, however from September till the end of October the stream dried out. Therefore the temperature measurements done within this period do not represent the correct stream temperature. Moreover, at the end of October the fiber-optic cable in the midsection of the stream broke due to mowing activities whereafter no temperature measurements were performed in the upstream reach.



Figure 5.3: Examples of a temperature profile of the Elsbeek during day and night, measurement taken on 16 August 2016 15:13 and 17 August 2016 06:43. With A and C the open/agricultural zones and B and D the shaded/forested zones as been indicated in Figure 4.4a.

Within the measurement period of 16 to 29 August 2016 the stream temperature of the Elsbeek fluctuated between 13.2 and 23.8°C while the air temperature fluctuated between 5.6 and 29.4°. Figure 5.3 shows two temperature profiles made with the DTS data which are characteristic for the Elsbeek during daytime and nighttime. In both profiles a sinusoidal temperature fluctuation along the stream can be seen. Interesting to see is that the sinusoidal fluctuations of the daytime and nighttime are opposite of each other. Furthermore, many small-scale temperature variation can be seen along the profile with peaks up 1°C difference compared with the surrounding stream temperature, occurring every 5 to 30 meters.

On the left side of the figure, which is the upstream part, the daytime temperature profile shows a relatively stable temperature for 100 meters, which corresponds with the open area indicated in Figure 4.4a. Next, in the shaded area the stream temperature during the day rapidly declines from 17.4 to almost 15° C and increases back to 17.4° C in the next open area. The last 650 meter downstream towards the Oryx unit, which is again shaded, shows a slow decrease in temperature to 16.4° C. Just like the daytime profile, the nighttime temperature profile shows a stable temperature in the upstream open area, although the stream temperature is 3.5° C cooler than the daytime temperature profile. Instead of a decrease in temperature, an increase from 13.5° C to 14.5° C can be seen in the first shaded area. Next, the temperature slowly decreases

until 500 meter from downstream and then slowly increases to a temperature of 13.9°C up to the beginning of the cable. The temperature peaks found in both profiles around 1000 meter are caused by the fiber optic cable laying above water which therefore represents the air temperature at that location, which has a more extreme temperature compared with the water temperature.

5.3.2 Seepage zones

As described in Chapter 4.3, literature gives four methods to detect seepage zones from the DTS data. The first method was to identify step changes in the temperature along the stream at a specific time. The temperature profiles of the Elsbeek in Figure 5.3 seem to have several negative step changes in the daytime profile between 1450 and 1100 meter and a positive step change around 1090 meter. However, these step changes cannot clearly be seen in the nighttime profile. Next, the standard deviation for the entire measurement period of the Elsbeek was calculated to see how much the temperature varies at each location along the cable (Figure 5.5a). Along most of the stream the standard deviation lies between 1.5 and 2.0° C. However, from 1100 to 1130 and from 1160 to 1200 meter, a significantly lower standard deviation is present compared to the surrounding standard deviation values. These zones with lower standard deviation can also be seen in Figure 5.4 as colder vertical columns. The 24-hour mean temperature profile (Figure 5.5b) made of the measurements on August 16^{th} shows a lower temperature compared to the surrounding stream temperature between 1150 and 1180 meter and at several locations along the downstream part of the study area. For the last method to locate seepage zones from DTS data, the difference between the maximum stream temperature found at August 18^{th} at 17:43 and minimum stream temperature found at August 19th at 06:43 is plotted in Figure 5.5c. The differences between the maximum and minimum temperature are the smallest from 1150 to 1200 meter and from 1090 to 1120 meter. Again several low temperature differences can be seen in the downstream part.



Figure 5.4: Spatial and temporal temperature distribution along the Elsbeek. The grey vertical lines between 900 and 1000 meter are placed to cover the temperature data at places where the fiber-optic cable lies above the water. Flow direction is from left to right.



Figure 5.5: (a) Standard deviation along the profile of the Elsbeek. (b) 24-hour mean temperature profile. (c) Temperature difference between the minimum and maximum temperature.



Figure 5.6: Time-water depth graph with increasing water level inside PVC pipe relative to the stream water level. Fitted to a third order polynominal R=0.99. Measurement performed at 22 November 2016.

Figure 5.7: Locations flux measurements including their corresponding seepage velocity if present and vertical temperature profiles made along the Elsbeek

5.3.3 Seepage flux

In Figure 5.6 the result of one of the flux measurements performed around 600 meter from the Oryx unit on November 22^{nd} is shown. During this measurement the water level inside the pipe increased from 4 cm below stream water level to 0.2 cm above stream water level. A third order polynominal line was fitted through the data points so the slope can easily be calculated to determine the seepage velocity. After 100 minutes the water level inside and outside the pipe were equal. A seepage velocity of 149 ± 50 mm/day was found in the middle of the stream which corresponds with a seepage flux of ~0.002 m³/day when multiplying the seepage velocity with the surface area of the PVC pipe. Other flux measurements performed on December 8^{th} did not show seepage, instead the water depths inside the pipe slightly fluctuated over time around the stream water level (Appendix E, Figures E.1b, E.2e and E.2h) or the water level inside the pipes stabilized below the stream water level (Appendix E, Figures E.1a, E.1c and E.2d).

5.3.4 Vertical temperature profiles

Figures 5.8a to 5.8c show the vertical temperature profiles made along the Elsbeek on November 22^{nd} . A map with all locations of the vertical temperature profiles is given in Figure 5.7. The vertical temperature profiles made near the Zoekerveldweg (Location 3) all show a relatively slow but steady increasing temperature with depth, resulting in steep temperature envelopes (Figure 5.8c). However, the temperature profile made in the middle of the stream had a slightly cooler profile compared to the profiles made on the sides of the stream. The temperature profiles made near the bridge of the Glanerbrugdijk (Location 2) showed a larger increase in temperature with depth, however this increase in temperature stagnated after 30 cm (Figure 5.8b). The largest increase of temperature with depth was found in the downstream area of the Elsbeek near the Oryx unit (Location 1). The profile made on the northern side of the stream at this location





(a) Location 1: Farm Glanerbrugdijk (22-11-16)





(c) Location 3: Bridge Glanerbrugdijk (22-11-16)

Figure 5.8: Vertical temperature profiles within the streambed of the Elsbeek.

showed an increase in temperature of 0.9° C in the first 60 cm below the streambed, while the other two profiles at this location only showed limited increase in temperature of $0.1-0.3^{\circ}$ C in the first 60 cm (Figure 5.8a). The vertical temperature profiles which were taken close to the seepage flux measurement near the bridge on the Glanerbrugdijk showed a rapid increase in temperature in the first 30 cm below streambed, whereafter the temperature increase seems to slow down and stabilizes. Another noticeable finding when performing the vertical temperature profile measurements was that it was much easier to push the TEC-probe into the streambed at the northern side of the stream compared with the southern side and the middle of the stream.
Table 5.1: Summary of the water	chemistry results	performed on	8 December in	the Elsbeek.
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#	Location	EC [μ S/cm]	NO ₃ [mg/L]	Radon [Bq/m ³]
1	Kremersveenweg	439	8.97	194 ± 170
2	Zoekerveldweg	441	12.24	117 ± 130
3	Glanerbrugdijk bridge	443	11.89	117 ± 130
4	Glanerbrugdijk farm	443	12.29	77.7 ± 110

5.3.5 Seepage indicators

Water chemistry

A summary of the most interesting chemistry results along the Elsbeek are given in Table 5.1, and all results from the measurements performed on August 16^{th} and December 8^{th} are presented in a table in Appendix A.1. During summer, the stream had a relative constant EC value between 418 to 430 μ S/cm along its path. However, the drainage pipe close to the Kremerveenweg had a slightly higher EC value of 500 μ S/cm. Compared to these measurements, the EC levels found in December were slightly increased as could be seen in Table 5.1. Also the concentrations of Fe²⁺ were relatively stable in August, with concentrations ranging between 0.289 and 0.359 mg/L. The Fe²⁺ concentration found in the drainage pipe was slightly higher with a concentration of 0.376 mg/L. In December the Fe²⁺ concentrations along the stream decreased to a value below 0.2 mg/L. Nitrate concentrations were relatively low in summer, with the highest value of 16 mg/L found near the bridge along the Glanerbrugdijk. In December, the nitrate measurements showed a slight increase in nitrate levels at most of the locations, only near the bridge of the Glanerbrugdijk the nitrate concentration decreased. The radon measurements showed a decreasing radon concentration when moving downstream from 194 ± 170 Bq/m³ upstream to 77.7 ± 110 Bq/m³ close to the beginning of the fiber-optic cable.

Visible seepage indicators

Other than some iron-oxidation found in the downstream part of the Elsbeek during summer, no other visible seepage indicators were present.

5.4 Springendalse Beek

5.4.1 Stream temperature description

The DTS data showed that the stream temperature of the Springendalse Beek fluctuated between 9.9 and 17.6° C while the air temperature fluctuated between 7.4 and 31.6° C within the measurement period. A characteristic temperature profile of the Springendalse Beek made of the temperature measurements from 11 August 2016 is shown in Figure 5.9. In the upstream part of the northern branch of the stream, the temperature was 11.4°C. In the following 160 meter downstream the temperature showed a steadily increase till a temperature of 11.7° C was reached. Next, the warming trend along the stream was interrupted, resulting in a relatively stable temperature until 1200 meter from the Oryx unit. Within this zone a sudden drop in temperature to 11.2°C was seen at 1285 meter. Here the fiber-optic cable was coiled and placed in a small spring, which had a substantial lower temperature compared to the stream temperature. Between 1130 and 1180 meter the fiber-optic cable laid in the southern branch of the tributary. With a temperature of 12.3° C, the southern branch was substantially warmer than the northern branch. After the two branches of the stream confluenced together a mixing zone appeared, which caused a fluctuation in stream temperature for about 75 meter. Once the two branches were fully mixed, the stream temperature again showed a steady increase in temperature from 11.8 to 11.9°C in the following 70 meter. At 970 meter a small stream originating from a small seepage lake confluenced with the main stream of the Springendalse Beek. This small stream had a temperature of 11.5°C, which was 0.4°C lower than the main stream at this position. The mixing of the two streams caused a decrease of the main stream temperature of 0.2° C. From this point on the stream temperature increased steadily until the warming slope was again interrupted at 580 meter by the presence of a zone of 100 meter with multiple zones with low temperatures. At 475 meter a high temperature peak (16° C) was present which corresponds with the outlet of a large seepage lake. The mixing of the main stream with the outlet of the large seepage lake resulted in a rapid temperature increase of the main stream to 12.8°C. At 280 meter the fiber-optic



Figure 5.9: Temperature profile Springendalse Beek at 11-08-16 16:55. Sections of the profiles correspond with zones along the stream as been indicated in Figure 4.4b.

cable was coiled and placed in the outlet of a small swamp lake. Although this outlet had again a substantially higher temperature $(13.2^{\circ}C)$ compared to the stream temperature, the downstream stream temperature does not seem to be affected much by the swamp lake. From this point up to the end of the fiber-optic cable, the temperature increased slowly to $12.9^{\circ}C$. Except for the peak of the large seepage lake, the other high temperature peaks in Figure 5.9 correspond with the locations where the fiber-optic cable laid above the water and therefore represent air temperature.



5.4.2 Seepage zones

Figure 5.10: Spatial and temporal temperature distribution along the Springendalse Beek. The grey vertical lines are placed to cover the temperature data at places where the fiber-optic cable lies above water. Flow direction is from left to right.

In the same way as has been done for the Elsbeek, the four methods to identify seepage zones from the DTS data were used for the Springendalse Beek. When looking at Figure 5.9, several step changes can be seen along the stream of the Springendalse Beek. Most of these step changes correspond with the outlets of seepage lakes and the southern branch of the stream. In Figure 5.11a the standard deviation profile of the stream is showed. Low standard deviation values were found upstream in the northern branch, along the southern branch, at the outlet of the small seepage lake and along several location between 850 and 920 meter. The lowest standard deviation of 0.55° C was found in the spring in the northern branch of the stream while high standard deviations, up to 5° C, were found at places where the fiber-optic cable laid above water. The zones with little temporal variation in temperature can be seen in Figure 5.10 as vertical grey columns. The 24-hour mean temperature profile of the stream is shown in Figure 5.11b. The average profile shows similar characteristics as the single temperature profile in Figure 5.9, although the lower stream temperatures between 480 and 580 meter are more clear in Figure 5.11b. The last applied method to locate seepage zones, by plotting the difference between the diurnal minimum and maximum temperature showed the same locations of interest (Figure 5.11c). Moreover, at 280 meter the profile shows an area with little difference between



Figure 5.11: (a) Standard deviation along the profile, calculated over the whole measurement period of 10 to 23 August. (b) 24-hour mean temperature profile on August 16. (c) Temperature difference between the minimum and maximum temperature found along the stream.

the maximum and minimum temperatures which corresponds with the outlet of a swamp lake. Also noticeable is that the temperature difference in the southern branch of the stream was significantly lower than the northern branch.

Additionally to the four methods described in literature, the overall warming slope of the Springendalse Beek was used as an indicator for seepage zones. Since there was no reference section present along the stream where it was certain no seepage was occurring, the warming slope was only used in a qualitative way. The Springendalse Beek springs just a few hundred meter upstream from the start of the fiber optic cable, causing the stream temperature in the upstream part to be highly correlated with the groundwater temperature. More downstream, the stream temperature was influenced by air temperature and solar radiation resulting in a relatively steady warming slope. At two places along the stream this warming trend was interrupted and cooler stream temperatures were found. In the northern branch at 1330 meter the warming of the stream stagnated and the stream temperature even decreased until 1250 meter. The same phenomena was seen in the mid-section of the stream, the stream was steadily warming until 550 meter after which the warming stagnated and the temperature slightly decreased.

5.4.3 Seepage flux

Seepage velocities found along the Springendalse Beek varied between 233 and 490 mm/day. An example measurement for a location with seepage is shown in Figure 5.12a. During the measurement the water level inside the PVC pipe increased from 5.8 cm below stream level to 1.2 cm above stream water level. By the time the seepage measurement was ended, the water level inside the pipe was still increasing, meaning the hydraulic head laid higher than 1.2 cm above stream level. After 180 minutes the water levels inside and outside the pipe were equal. At this time the seepage velocity was calculated from the slope in the graph. A second order polynominal was fitted to the data to ease the determination of the slope and to calculate the seepage velocity. The seepage velocity next to the large seepage lake was found to be 233 ± 13 mm/day. With the surface area of the PVC pipe being 123 cm^2 , the seepage flux at this location was ~0.003 m³/day. At locations 2 and 3 the flux measurement showed a linear correlation between the time and depth relative to the stream level. Due to the linear correlation, the uncertainty in determining the water height has no influence on the flux, therefore no uncertainty interval was given for these measurements.

Furthermore, one measurement first showed an increasing water depth and after 50 minutes the water level in the pipe decreased again (Appendix E Figure E.2g). Another two measurements made at location 4 first showed a slight increase, whereafter the water level fluctuated around the stream water level. The last three measurements showed a clear decreasing water level within the pipe over time, with infiltration velocities between 86.4 and 105.1 mm/day. As can be seen in Figure 5.12b, as the water level inside the pipe decreased until the water level stabilized at -3.5 cm below the stream water level. For this measurement an infiltration velocity of 105.1 mm/day was found which corresponds with an infiltration flux of ~0.001 m³/day. All time-depth graphs are shown in Appendix E and Figure 5.13 shows the locations of the measurements with their corresponding seepage or infiltration velocities.



Figure 5.12: Examples seepage flux measurements along the Springendalse Beek with (a) a timedepth graph of an increasing water level relative to the stream level performed on 15 November and (b) a time-depth graph of a decreasing water level relative to the stream level performed on 8 December.

5.4.4 Vertical temperature profiles

The vertical temperature profiles made on several locations along the Springendalse Beek are shown in Figure 5.14. A map with the locations of the profiles is given in Figure 5.13. Due to the presence of a coarse layer in the streambed along most of the path of the stream, some temperature profiles did not reach below 80 cm. Although the profiles do not reach deep below the streambed, Figures 5.14a and 5.14e show that the temperature was slowly increasing with depth in the first 60 cm. Moreover, at these locations. limited difference was seen between the vertical temperature profiles on the sides and in the middle of the stream. The temperature profiles made on Novem-



Figure 5.13: Locations flux measurements including their corresponding seepage and infiltration velocity if present and vertical temperature profiles made along the Springendalse Beek

ber 15^{th} showed some interesting characteristics. The profiles made closest to the large seepage lake (Figure 5.14b) showed a fast increase in temperature within the first 50 cm below the streambed, whereafter the increase slowed down and slowly approached a stable temperature of 11.5° C. Compared to the other two profiles made at this location, the profile on the northern





(a) Location 1: Downstream (22-11-16)



(c) Location 3: Southwest of large seepage lake (15-11-16)



(e) Location 5: Northern branch (15-11-16)

Figure 5.14: Vertical temperature profiles along the Springendalse Beek



11-16)

(d) Location 4: Bridge midsection stream (22-11-16)

	T			P_{1} (P_{2})
#	Location	EC [μ S/cm]	$NO_3 [mg/L]$	Radon [Bq/m ³]
1	Northern branch upstream	302	>60.0	537 ± 310
2	Northern branch weir	306	54.7	441 ± 290
3	Southern branch	175	14.5	731 ± 350
4	Small seepage lake	239	38.2	941 ± 410
5	Stream piezometers	263	42.5	136 ± 160
6	Upstream of large seepage lake	254	42.6	465 ± 270
7	Large seepage lake	186	20.1	90.2 ± 130
8	Blauweweg	238	36.1	155 ± 160

Table 5.2: Summary of the water chemistry results performed on 22 September in the Springendalse Beek.

side of the stream (closest to the seepage lake) showed an even higher temperature below the streambed.

Contrary to the profiles close to the lake, the vertical temperature profiles made approximately 15 meter more upstream did not show an immediate increase in temperature below the streambed (Appendix E Figure E.1c). The first 30 cm showed a small increase or even a decrease in temperature. After 50 cm the temperature of all three profiles quickly increased. An observation made while measuring the vertical temperature profiles, was that at locations where temperature quickly increased with depth it was much easier to push the TEC-probe into the streambed compared to locations with slow increasing temperatures with depth.

In addition to the vertical temperature profiles, the shallow groundwater temperature was measured with a CTD diver between September 14^{th} and November 22^{nd} in a piezometer placed close to the stream. During this measurement period the groundwater temperature first increased and reached its maximum temperature of 13.2° C on September 23^{th} whereafter the groundwater temperature temperature decreased to 11.5° C (see Figure C.1 in Appendix C).

5.4.5 Seepage indicators

Water chemistry

In Tabel 5.2 a summary of the most important water chemistry results performed on 22 September is given and in Appendix A a table is given with all chemistry results measured on August 16th, September 22nd and December 8th along the Springendalse Beek. The electrical conductivity along the stream spatially varied between 175 and 306 μ S/cm but did not change significantly over time. The highest EC levels were found in the northern branch, which had an average EC of $\pm 300 \ \mu$ S/cm, while the lowest EC level of $\pm 175 \ \mu$ S/cm was found in the southern branch. Overall a decreasing trend in EC concentration was seen when going downstream at all measurement days. The groundwater had an EC of approximately 140 μ S/cm in the midstream and an EC of 310 μ S/cm in the northern branch. The measurements of Fe²⁺ showed high values (>0.5 mg/L) in the groundwater samples taken from the piezometers in the midstream and upstream in the northern branch, the other water samples had a Fe²⁺ concentration of 0.285 mg/L or lower. Just like the EC measurements, the nitrate measurements also showed significant



(a) Nitrate levels

(b) Radon levels

Figure 5.15: Spatial variation of nitrate on August 16th and radon concentrations on September 22nd along the Springendalse Beek. The uncertainty intervals of the radon measurements can be found in Tabel A.2 (Source map: ESRI Nederland).

difference between the northern and southern branch (see Figure 5.15a). In the northern branch, as well as in the groundwater samples, the nitrate levels exceeded the drinking water limit of 50 mg/L set by the World Health Organization (WHO). On the other hand, the southern branch had low nitrate concentrations of approximately 15 mg/L. Further downstream the nitrate concentration slowly decreased after the inlet of the two seepage lakes which had a lower nitrate concentration compared to the stream concentration. The nitrate concentrations in both seepage lakes were increasing over time. The pH values in the stream ranged between 6.40 and 7.02 and in the groundwater samples between 4.57 and 4.80.

The radon concentrations found along the Springendalse Beek during low discharge conditions on September 22nd are shown in Figure 5.15b and in Tabel A.2. Upstream in the northern branch a radon concentration of 537 ± 310 Bq/m³ was found. Further downstream this concentration decreased to 441 ± 290 Bq/m³ while the southern branch had a higher radon concentration of 731 ± 350 Bq/m³. In the midsection of the stream the radon concentration decreased to 136 ± 160 Bq/m³ whereafter the concentration increased again tillo 465 ± 270 Bq/m³ just before the large seepage lake. After the outlet of the seepage lake the radon concentration in the stream decreased again to 155 ± 160 Bq/m³. The highest radon concentration of 5800 ± 1000 Bq/m³ was found in the groundwater samples. Lastly, the large seepage lake had a radon concentration of 90.2 ± 130 Bq/m³ and the small seepage lake had a radon concentration of 941 ± 410 Bq/m³.

The radon measurements performed on December 8^{th} showed decreased concentrations compared to September upstream in the northern branch and before the outlet of the large seepage lake. However, significantly increased concentration were found in the small and large seepage lake and in the midsection of the stream. Near the Blauweweg the radon concentration remained the same.

Visible seepage indicators

Along the Springendalse Beek several visible seepage indicators were present. At multiple locations spread over the entire length of the Springendalse Beek little springs were located on the stream banks. The combination of high stream banks (see Figure 5.16) relative to the stream water level and high groundwater levels on these stream banks often resulted in wetlands. Moreover, a red layer of iron oxidation was found at many places along the streambed of the midsection and downstream. This iron oxidation was often located to the side of the stream. As explained in Chapter 4.6.2 most of the iron originates from the groundwater and oxidizes when it comes into contact with oxygen on the surface, these iron oxidation layers are therefore a clear indicator for seepage. Another visible seepage indicator found along large reaches of the Springendalse Beek was a rare small plant called the Golden-saxifrage, or in Dutch 'Goudveil'. Since this plant is highly related to wet soils and to the availability of iron, its presence along the stream indicates groundwater discharge. It was often found within a few meters of the stream and along the many wetlands and springs present. A map with the visible seepage indicators along the Springendalse Beek is showed in Appendix B.



Figure 5.16: Visible seepage indicators found along the Springendalse Beek. Left picture: Little springs on the stream bank. Upper picture: Golden-Saxifrage. Lower picture: Iron oxidation on the streambed. Right picture: High streambanks relative to the stream water level.

Chapter 6

Discussion

6.1 Laboratory tests, calibration and installation of the fiber-optic cable

The longest response time found during the testing was 5 minutes for a temperature decrease of 25-30°C. However, this did not influence the field measurements as no measurement times less than 5 minutes were used and therefore there was enough time for the measurement to stabilize. Furthermore, temperature changes as large as simulated in the laboratory did not naturally occur in the streams. Laboratory experiments showed a 50% decrease in noise when the measurement time was doubled from 15 to 30 seconds. In first instance this did not agree with the inverse square-root relationship between measurement time and accuracy as stated by the user manual of the Oryx unit (Sensornet, 2007). However, a constant amount of time is necessary to transfer the data to the memory of the Oryx. For small measurement times such as below 30 seconds this has influence on the fraction of time actually available for measuring temperatures and therefore on the accuracy (Sensornet, 2007). Since a measurement time of 5 minutes was used during field measurements, the amount of noise was negligible compared to the natural temperature changes along the streams.

Hausner et al. (2011) stated that the calibration method they developed would be more accurate than the pre-installed calibration of the Oryx unit. However, as the Figures 5.2a to 5.2d showed, the calibration of the Oryx unit showed better results when compared with the TP-100 temperature sensors in the calibration baths and in the stream. Most likely this was caused by the averaging of C and $\Delta \alpha$ (attenuation). While in this study was assumed that C was constant over time, C can still slightly vary over time due to the thermal sensitivity of the detectors (Van De Giesen et al., 2012). Not accounting for changes in instrument temperatures can therefore lead to a deviation in temperature. The attenuation was calculated for each time step, but the assumption was made that the attenuation was equal over the entire length of the fiber-optic cable. However, with splices, stresses and bents being present along the cable it was almost certain that differential attenuation did occur. When not corrected for this differential attenuation, the temperature measurements are less accurate (Van De Giesen et al., 2012).

In earlier research the problem of burial of the fiber-optic cable by sedimentation was already mentioned. During this study the effect of burial of the cable could be seen in the many small

scale fluctuations in the temperature profiles along the Elsbeek (Figure 5.3). That the fluctuations were not the result of noise along the fiber-optic cable can be concluded from the fact that the temperature fluctuations were too large to be caused by noise with the used measurement time and the fluctuations occurred at constant locations. These constant locations were found to be 5 till 30 meter apart, which correspond with the distance between the pegs securing the fiber-optic cable on the streambed. Since the pegs were holding parts of the fiber-optic cable down while other parts were able to slightly move along the streambed, the cable around the pegs was covered with sediment more quickly due to the dynamic environment and redistribution of streambed sediments (Sebok et al., 2015). Due to the damped temperature oscillation below the streambed, cooler temperatures were found compared to the stream temperature during day and warmer temperatures during night (Figure 6.1). Moreover, the decrease in oscillation amplitude and increase of delay shows that the cable was buried deeper over time. The burying can also be confirmed by the overall lower temperature found at the location of the peg even during night in the last 4 days, because with a thicker layer of sediment covering the cable over time, the temperature was more influenced by the cooler groundwater temperature.



Figure 6.1: Influence of pegs on the measured temperature by the fiber-optic cable at the Elsbeek.

6.2 Elsbeek

6.2.1 Seepage zones

The four methods to locate seepage zones from the DTS data did not show clear zones with focused groundwater discharge for the Elsbeek. Although several step changes were present in the temperature profile made on August 16^{th} (Figure 5.3), which could correspond with location of focused groundwater discharge according to Selker et al. (2006a), another reason for these step changes was found. When looking at the streambed geometry at the locations of these step changes, the water depth suddenly increased. As Sebok et al. (2013) stated, with increased water levels solar radiation will not warm the entire water column resulting in thermal layering and therefore causing a relatively cool temperature on the streambed where the fiber-optic cable

was placed. The absence of the step changes during night also confirmed this, since temperature stratification does not occur without the input of solar radiation. Moreover, the constant movement within the stream caused the water column to fully mix.

In addition to the step changes, a substantial lower standard deviation was found between 1100 and 1200 meter compared to the surrounding stream and limited difference between the maximum and minimum temperature was found. As the standard deviation is depending on the temperature over time, the temperature of this zone was compared with a location which had a more characteristic standard deviation in Figure 6.2. This figure showed that the daily oscillation in temperature was fainting over time in the zone with low standard deviation, while the temporal variation of the other location showed a clear daily temperature oscillation. As explained earlier in this chapter, sedimentation caused the fiber-optic cable to be covered over time, resulting in fainting of the daily oscillation and a larger time lag with increasing depth of sediments covering the cable. So although a low standard deviation and limited difference between the maximum and minimum temperature can be explained by groundwater discharge according to Lowry et al. (2007) and Matheswaran et al. (2014), the zone between 1100 and 1200 meter is highly affected by sedimentation instead of seepage. This confusing between whether a location with low temperatures and a low standard deviation is experiencing groundwater seepage or sedimentation was also discussed by Sebok et al. (2015), who saw that a layer of 0.1 m on top of the fiber-optic cable already decreased the daily temperature amplitude and standard deviation.



Figure 6.2: Temporal temperature variation at two locations along the Elsbeek, one location with a low standard deviation and one location with an average standard deviation.

Although the spatial variation in temperature during summer did not showed signs of seepage, the vertical temperature measurements and flux measurements performed during November and December 2016 did show that seepage was present along the Elsbeek. During one of the flux measurements the water level in the pipe rose above the water level in the stream (Figure E.1), which indicated that the hydraulic head below the streambed laid above the stream water level. In combination with the sandy streambeds it can therefore be concluded that seepage occurred at these places. The flux measurements performed in December did not show the presence of seepage, instead infiltration was found as the water levels in the pipes decreased below stream water level. This indicated that the hydraulic head laid lower than the stream water level and therefore infiltration must have been occurring. The presence of seepage was also confirmed by the vertical temperature profiles made near the farm along the Glanerbrugdijk (Figure 5.8a). At this location the vertical profiles made perpendicular to the stream showed completely different characteristics. The quickly increasing temperature with depth and the concave shape of the profile made on the northern side of the stream showed that the relatively warm groundwater was moving up, while the other two profiles showed a limited increase in temperature with depth indicating that these temperatures are more influenced by the stream water and are therefore infiltrating. From the combination of the temperature and flux measurements it can be concluded that both groundwater seepage and infiltration occurred along the stream, though it was spatially distributed. The spatial distribution of seepage and infiltration are most likely caused by the natural surface elevation in the area, which is relatively high on the western side towards the ice-pushed ridge of Oldenzaal and relatively low on the eastern side towards the Dinkel river. Moreover, at some places the Elsbeek is deeply eroded in the surface, causing the groundwater level to reach the streambed in times of high groundwater levels and creating seepage towards the stream. Unfortunately the fiber-optic cable along the Elsbeek broke in October due to mowing activities along the streambank. Therefore, at this moment the findings from the flux measurements and vertical temperature profiles cannot be compared with the stream temperature.

The EC, pH and Fe²⁺ concentrations of both August and December were relatively stable both spatially and temporally, and therefore did not show signs of groundwater seepage along the stream. The increased nitrate levels found in December compared to August can be explained by the increase in precipitation which results in more surface runoff which brings more fertilizers from the fields towards the stream. The only chemistry parameter found which indicated the presence of seepage along the stream was radon. Although the results showed an overall decreasing trend in the radon concentration along the Elsbeek, the concentration in mid-



Figure 6.3: Spatial distribution of radon along the Elsbeek, measured on 8 December. (Source map: ESRI Nederland).

section stabilized at 117 Bq/m³ (Figure 6.3). The fact that the same radon concentrations were found 400 meter apart in combination with the short half life time and volatile character of radon indicates that radon must be added to the stream within this zone. Since the groundwater is the main and most likely source of radon (Wu et al., 2004), it can be concluded that the stream must be affected by groundwater seepage. The overall trend of decreasing radon concentrations in

the downstream direction also indicates that the upstream part of the Elsbeek contains more recently seeped groundwater than the part of the Elsbeek within the research area. First of all, this is caused by the fact that the upstream part of closer to its source. Another explanation for the higher radon concentrations upstream is that due to the fact that the upstream part of the Elsbeek lies on top of the ice-pushed ridge of Oldenzaal. As explained earlier in Chapter 3, the ice-pushed ridge contains alternating clay and sand layers and whenever the Elsbeek outcrops an impermeable layer the groundwater is able to discharge directly in the stream.

When combining all the measurements performed along the Elsbeek it can be concluded that no focused zones of seepage were present along the stream which influenced the stream temperature. However, as Sebok et al. (2013) mentioned, another explanation for not detecting seepage could be that the detection of seepage using DTS is highly dependent on the right placement of the fiber-optic cable in the stream. This could be the reason that no changes in stream temperature or water chemistry were found. Another reason could be for not detecting seepage from the temperature and chemistry measurements is that instead of focused groundwater discharge, diffusive seepage zones were present along the stream. Moreover, the fact that the Elsbeek can fall dry in summer also indicates that the system is highly variable in time. It is therefore possible that during winter groundwater levels are higher which induces more groundwater seepage than during summer.

6.2.2 Effect of shade and air temperature on stream temperature

As explained before in Chapter 2, solar radiation and air temperature are the dominant factors influencing stream temperatures. From the presence of diurnal temperature fluctuations, seen in Figure 5.4, it is clear this also applies for the Elsbeek. Figure 6.4 shows the cross correlation function (CCF) of air and stream temperature for four zones along the Elsbeek as indicated before in Figure 4.4a. The highest correlation coefficient found for each zone were 0.94 for the upstream open area, 0.91 for the upstream shaded area, 0.92 for the downstream open area and 0.93 for the downstream shaded area. There was no trend visible with increasing correlations when moving downstream as was expected from the study of Zwieniecki and Newton (1999). This can be explained by the difference riparian vegetation and in stream geometry along the stream. For instance, zone C had a narrow streambed and a high water level while zone D had a wide streambed and shallow water level. This caused zone D to have a larger surface area available for energy exchange with the atmosphere, which has, as Malcolm et al. (2004) described, also a large influence on the diurnal temperature range and response time. With the combination of higher water levels and small surface area found in zone C, the short wave radiation only warms the upper layers of the stream, resulting in relatively cool temperatures on the streambed even though the open zone laid more upstream than the shaded zone. Besides differences in correlation coefficient, also a difference in response time was seen between the zones. It took 1 to 1.5 hours for the stream temperature in the open zones to react to changes in air temperature, while for the shaded zones an even larger response time of 2.5 to 3 hours was seen. The larger response times of the shaded zones compared to the open zones is caused due to the fact that warm water must be transported to the shaded zones as the water is not directly warmed by solar radiation.

As became clear from the characteristic sinusoidal shape of the temperature profiles (Figure



Figure 6.4: Correlation the stream and air temperatures using a cross correlation function.

5.3), the stream temperature distribution along the Elsbeek was also highly affected by shade. The increasing stream temperatures within open reaches and decreasing stream temperature in shaded reaches can be explained by the amount of direct solar radiation reaching the water surface. As was explained in previous researches such as Johnson (2004), Malcolm et al. (2004) and citetmatheswaran2014seasonal, riparian vegetation reduces the incoming solar radiation and therefore reduces the stream temperature compared to an open area. On the other hand, during night the riparian vegetation acts as a temperature buffer by emitting long wave radiation resulting in relative high stream temperatures compared to the open areas.

Differences in response time between open and shaded reaches can also be seen when plotting the average diurnal stream temperature variation (Figure 6.5). A clear time-lag is present between the two curves: the shaded zone reached its minimum temperature one hour and its maximum temperature two hours later than the open zone. Besides the time-lag, a difference in temperature amplitudes was found; the open zone had a amplitude of 3°C while the shaded zone had a amplitude of 2.4 °C. Similar to the finding by Johnson (2004) the maximum temperature was significantly reduced with 0.8°C. The last phenomena which can be seen in both curves is the difference in cooling and warming speed. Both curves show a steeper warming curve and a less steep cooling curve, which again can be explained by the buffering effect of riparian vegetation.

To quantify the effect of solar radiation on the stream temperature, the changes in daily mean temperature and daily maximum temperature per 100 meter were calculated for the open reach (zone C) and the shaded reach (zone D). As can be seen in Table 6.1, a significant increase in both the mean and maximum daily temperature was found in the open reach. Within the shaded reach the mean daily temperature only slightly decreased while the maximum temperature significantly decreased. To compensate for the relatively fast increase in daily mean temperature in 100 meter of the open reach at least 600 meter of shaded reach is necessary. Compared with the findings by (Verdonschot et al., 2014), the change in daily mean and maximum temperature for the open reach of the Elsbeek was much higher and for the shaded reach the change in daily mean temperature similar.

To make a better comparison between the open and shaded zone, zones must be used with the



Figure 6.5: Average diurnal stream temperature of open/agricultural zone C and shaded/forested zone D along the Elsbeek.

Table 6.1: Daily mean temperature change and daily maximum temperature change over 100 meter of open reach of the Elsbeek (zone C) and a shaded reach (zone D) as been indicated in Figure 4.4a.

	Daily temperature [°C/100m]				
	Mean	Range	Max	Range	
Open (zone C)	0.64	0.12 to 1.13	0.94	4 0.01 to 1.77	
Shaded (zone D)	-0.10	-0.22 to 0.05	-0.4	-0.67 to -0.05	

same stream geometry, however these were not present along the Elsbeek. Still, it is clear that the stream temperature of the Elsbeek was more affected by the air temperature and the presence of riparian vegetation/shade than by the limited amount of groundwater seepage occurring along the stream.

6.2.3 Stream temperature through the year

As the DTS measurements were performed from July until December 2016, the change in stream temperature could be examined over this half a year. Unfortunately, the fiber-optic cable was broken due to mowing activities along one of the agricultural fields next to the stream in October. Therefore the temperature data of October and November was only available in the first 700 meter of the downstream part of the Elsbeek. In Figure 6.6 the average daily temperature profiles of the warmest day (20 July), coolest day (5 December) and two days in August and October are shown. Within this half a year the average stream temperature fluctuated from 1°C up to 20°C. The temperature profiles of 20 July and 20 August showed similar characteristics besides the lower temperature on 20 August. As the stream dried up in September and most of October, the temperature profile of 10 October is not representative for the stream temperature along most of its part as the fiber-optic cable laid above water. In the downstream part of the temperature profiles of 5 December more extreme temperature fluctuations are seen compared to the profiles

of July and August. As explained before, this is caused by the burial of the fiber-optic cable over time, creating relatively warm peaks in the temperature profile in winter. Besides the much cooler temperature, no change in temperature characteristics could be seen.



Figure 6.6: Average daily stream temperature profiles through the year along the Elsbeek.

6.2.4 Implications for the aquatic ecology

The results indicate that stressors related to groundwater seepage are minimal in the downstream reach of the Elsbeek during summer. On the other hand, the influence of shade on the stream temperature was substantial by lowering both the mean and maximum stream temperatures. With global warming in mind, the adding of riparian vegetation along stream can therefore create a stable temperature habitats for aquatic species which are sensitive for temperature changes and therefore create a higher chance of preserving these species. Whereas shade could have a positive effect on the aquatic ecosystem, the fact that the Elsbeek often dries up during summer is an important stressor for the aquatic ecosystem.

6.3 Springendalse Beek

6.3.1 Seepage zones

In the same way as has been done for the Elsbeek, the four methods to locate seepage zones from the DTS data described in Chapter 4.3 were used for the Springendalse Beek. As was seen in Figure 5.9 several step changes were present in the temperature profiles of the Springendalse Beek. However, these are not caused by groundwater discharge but correspond with the places where the fiber-optic cable was placed in the southern branch and in the outlets of both seepage lakes, which all had a substantial different temperature compared to the stream. Although the other methods indicated groundwater seepage, as will be explained in a moment, the amount of seepage did not contributed enough to the total amount of stream discharge to cause a temperature step change. The standard deviation method (Lowry et al., 2007) gave a

good indication for groundwater seepage. As was seen in Figure 5.11a the standard deviation along the Springendalse Beek was relatively low compared to the Elsbeek, indicating that the stream temperature fluctuated less over time. This is caused by the fact that the stream water springs from the groundwater only a few hundred meter upstream from the research area and is therefore highly related to the stable groundwater temperature. As the stream temperature is getting more correlated to the atmospheric conditions with increasing distances from the source and less correlated to the groundwater temperature, an overall increasing standard deviation in the downstream direction was seen. However, at places where groundwater seepage occurred, the standard deviation decreased again which was seen at the little spring in the northern branch, at the small seepage lake and at multiple places in the midsection of the stream.



Figure 6.7: Average diurnal stream temperature at two locations along the Springendalse Beek, one location where the warming slope had stagnated and one location with the normal warming slope.

The warming slope of the stream was also used to identify the groundwater seepage zones by again using the assumption that the stream is getting more correlation to atmospheric conditions when moving in the downstream direction. Without the presence of groundwater seepage or other external influences such as outlets of lakes, a general warming trend of 0.6° C/km for small streams was found by Zwieniecki and Newton (1999), though this warming trend eventually decreases over large distances due to a decreasing warming potential caused by the smaller differences between the stream and air temperature (Caissie, 2006). Because the distances along the Springendalse Beek are relatively short, a linear warming should be seen along the stream. However, the fact that the warming slope in both the northern branch and between 450 and 550 meter in the midsection stagnated without a significant change in riparian vegetation or streambed geometry, indicates that these areas experience a substantial amount of groundwater seepage. Another possible process which could explain the decrease in temperature in the reach between 450 and 550 meter is the burial of the fiber-optic cable by streambed sediments as was also the case along some parts of the Elsbeek. In this reach with stagnating warming slope, the average daily temperature change was compared to a location approximately 100 meter downstream which showed a constant warming slope (Figure 6.7). The temperature amplitude of the

	Daily temperature [°C/100m]							
	Mean Range Max Range							
Normal warming slope, upstream	0.35	0.13 to 0.52	0.63	0.27 to 0.95				
Seepage zone, upstream	0.06	0.01 to 0.10	0.15	-0.03 to 0.36				
Normal warming slope, midreach	0.18	0.06 to 0.24	0.24	0.12 to 0.34				
Seepage zone, midreach	0.03	-0.07 to 0.10	0.42	0.08 to 1.45				

Table 6.2: Daily mean temperature change and daily maximum temperature change over 100 meter between two normal warming slope with their downstream seepage zones.

seepage zone was 0.4°C lower than the reach with normal warming slope. Moreover, no time lag was observed within the period. The fact that no time lag was present between the reaches means that the burial of the cable was at most only minor and therefore this difference in temperature must been caused by groundwater seepage.

To even better see how the stream temperature is affected by the presence of groundwater seepage, the temperature change over 100 meter was calculated for both seepage zones and the reaches upstream of the seepage zones which had a normal warming slope. As can be seen in Table 6.2, the increase in mean daily temperature over 100 meter was significantly higher for both reaches with a normal slope compared to the seepage zones. This has to do with the fact that relatively cool groundwater was added to the stream, causing less warming by solar radiation within the seepage zones. The same was found for the daily maximum temperature in the northern branch; whereas the maximum temperature within the reach with normal warming slope increased with 0.63°C/100m, the maximum temperature of the seepage zone only increased with 0.15°C/100m. However, the seepage zone in the midreach of the Springendalse Beek did show a higher in crease in maximum daily temperature compared to the reach with the normal warming slope. This can be caused by the fact that the fiber-optic cable was slightly buried in the upstream part of this seepage zone, while close to the large seepage lake, the cable laid on top of the sediment and therefore had a higher maximum temperature.

The presence of groundwater seepage along the Springendalse Beek was also confirmed by the flux measurements. The measurements at several locations showed that the hydraulic head laid above the water level of the stream (Figures 5.12a and E.2g to E.2i in Appendix E). However, the measurements done on December 8^{th} showed that infiltration also occurred. This spatial variation of seepage and infiltration was also observed in the vertical temperature profiles. Even at locations where multiple profiles were made perpendicular to the stream, significant differences were present. The most striking differences were seen in the profiles made at location 5 where one profile was significantly warmer compared to the other two (Figure 5.14b). This can be explained by the flow paths of the groundwater towards the stream as the northern profile was made closest to the large seepage lake and therefore it is more likely to find higher seepage rates on the northern side than on the southern side and in the middle of the stream. Still the concave character of the profiles made on this location indicate that relatively warm groundwater was moving upward in all three profiles. In comparison, the profiles made at location 3 showed a more convex shape (Figure E.1c) indicating that the upper part below the streambed was more responding to temperature changes from the stream compared to location 2. However, this does not necessarily mean that infiltration was occurring at this location, since it is also possible that a smaller seepage flux was present and therefore the thermal diurnal oscillation surface laid deeper below the streambed. For the other profiles it was more difficult to say whether seepage or infiltration was occurring due to the relatively high stream temperatures at these locations causing less temperature difference between the groundwater and surface water. For the upstream profiles the stream temperature was highly related to the groundwater temperature, therefore limited amount of temperature increase was seen in these profiles. An interesting observation made while making vertical temperature profiles along both the Elsbeek and the Springendalse Beek was that the TEC-probe could easily be pushed in the streambed when the temperature in the streambed was rapidly increasing. This could be an effect of the presence of groundwater seepage. The upward groundwater flux brings relatively warm water to the surface and due to the upward flux the streambed sediment, which mainly consists of sand, becomes more loose (quicksand is an extreme example) causing the TEC-probe to move down more easily.

The spatial variation of seepage and infiltration along the Springendalse Beek is mainly caused by the geological setup of the research area. As explained earlier in Chapter 3 the Springendalse Beek lays on top of an ice-pushed ridge with alternating clay and sand layers. Due to erosion, the stream outcrops some of the impermeable clay layers resulting in groundwater discharge at these places. Moreover, the presence of relatively high laying seepage lakes relative to the nearby stream results in groundwater flow from the seepage lakes directly towards the stream.

From the measured water chemistry, the radon measurements were used as a groundwater tracer and showed that the surface water was indeed affected by groundwater Overall, relat several places. atively high radon concentrations were found compared to the Elsbeek, indicating that the Springendalse Beek is highly affected by groundwater seepage. The seepage zone earlier found by the temperature results, between 450 and 550 meter, was also found from the radon measurements performed in August as higher radon concentration were found downstream of this seepage zone compared to upstream of this reach. In summer an overall



Figure 6.8: Spatial distribution of radon along the Springendalse Beek, measured on 8 December. (Source map: ESRI Nederland).

decrease in radon concentration in the downstream direction was seen (Figure 5.15b) which indicates that more groundwater discharge occurred in the upstream reach than the downstream reach of the research area. The fact that the upstream reach is closer to the source of the stream explains this radon distribution. However, the radon measurements performed in December showed another radon distribution: relatively high radon concentrations were found in the midstream reach and in the the small seepage lake compared with the upstream and downstream reach of the Springendalse Beek (Figure 6.8). This is again partly caused by the input of groundwater to the stream in the midsection, but it is also likely that the high concentrations of radon found in the outflow of the small seepage lake is influencing the amount of radon found in the midsection of the stream.

Lastly, the visible seepage indicators were useful to locate seepage zones along the Springendalse Beek. The locations of the iron oxidation and Golden-Saxifrage confirmed the two main seepage zones found from the DTS data in the northern branch and between 450 and 550. However, the presence of the indicators at many more locations along the stream indicated that seepage occurred at much more locations then was showed by the temperature results. This could be the result of diffusive instead of focused seepage, as diffusive seepage still brings dissolved iron towards the surface resulting in the presence of both iron oxidation banks and the golden-saxifrage on the stream banks but the total flux by diffusive seepage too small to cause changes in stream temperature.

6.3.2 Other stream characteristics of the Springendalse Beek

The difference in temperature between the two seepage lakes can be explained by the residence time of the water in the lakes. The relatively low temperatures of the small seepage lake in summer in combination with the high radon concentrations suggest that the surface water only recently originated as groundwater because with the short half life time of radon and volatile character, concentrations would quickly disappear from the lake. This also means that the water temperature is highly related to the groundwater temperature explaining the relatively low temperatures in the small seepage lake in summer. On the other hand, the relatively high temperature found in the large seepage lake in combination with the low radon concentration shows that the water had a much longer residence time in the lake. A longer residence time results in more decay and degassing of radon and more time for the water to warm up. With the assumption that the water depth of the seepage lakes is approximately 2 meters together with the known surface areas and discharge of the lakes, the residence time was also calculated. The residence time of the small seepage lake was found to be 14 days while a residence time of 44 days was found for the large seepage lake. The fact that the half life time of radon is 3.8 days causes the radon concentration to be negligible within a couple of days, therefore preferential flow paths towards the outlet of the lakes must be present.

Although the principle of residence time explains the difference in temperature in the seepage lakes, the principle did not seem to hold for the difference in temperature between the northern and southern branch of the Springendalse Beek as radon concentrations in the southern branch were found to be significantly higher. The combination of high stream temperatures and high radon concentrations found in the southern branch relative to the northern branch is most likely caused by groundwater seepage in the downstream part of the southern branch. As the southern branch is longer than the northern branch, there was more time and distance to warm, explaining the relative high stream temperature. With groundwater seepage present in the downstream reach of the southern branch the combination of relatively warm stream temperatures and high radon concentrations could be explained. However, more research in the southern branch must be done to confirm this.

6.3.3 Effect of shade and air temperature on stream temperature

The Springendalse Beek was divided into three zones: upstream (zone A in Figure 4.4b), midstream (zone D) and downstream (zone E). Within these zones the average temperature was calculated over a representative 10 meter stretch for the entire zone. For each of these zones a correlation was made between the stream temperature and air temperature. Figure 6.9 shows the cross correlation functions of these zones. The lowest correlation coefficient (0.92) was found in the upstream part of the stream while the highest correlation coefficient of 0.95 was found in the downstream part. For the midsection a correlation coefficient of 0.93 was found. As a result an increasing trend in correlation between air temperature and stream temperature was seen in the downstream direction. This is caused by the fact that with increasing distances from the source of the stream the temperature is less related to the groundwater temperature and more related to the air temperature and solar radiation (Zwieniecki and Newton, 1999). Compared to the differences in response time found along the Elsbeek, the stream temperature of the Springendalse Beek only shows small differences in response time relative to the air temperature along its path. A response time of 0.5 hour was found the upstream part, 1 hour for the downstream part and 1.5 hour for the midstream part of the Springendalse Beek. The difference in response time between Elsbeek and Springendalse Beek is caused by both the lower discharge rates of the Springendalse Beek and the difference in stream geometry. Due to the high width:depth ratio of the Springendalse Beek, a larger surface area receives direct solar radiation and due to the relatively shallow depths the entire water column is quickly warmed. This caused a higher correlation between the stream temperature measured on the streambed and the air temperature than at the Elsbeek.



Figure 6.9: Correlation the stream and air temperatures using a cross correlation function.

Although the effect of groundwater seepage was clearly present in the stream temperature, the effect of diurnal oscillation in air temperature and solar radiation was found to have the largest effect on the stream temperature. Since no distinct zones with or without shade were present along the Springendalse Beek, it was not possible to quantify the effect of shade on the stream temperature.

6.3.4 Stream temperature through the year

As the DTS measurements were performed from July until December 2016, the change in stream temperature could be examined over this half a year. In Figure 6.10 the average temperature profiles of the warmest day (25 August), coolest day (29 November) and two days in August and October are shown. The average stream temperature ranged between 5°C and 16°C from July until December. While in the temperature profile of 25 August a warming slope was seen, the profile of 29 November showed a cooling slope causing limited temperature variation over time in the upstream reach of the Springendalse Beek and a large temperature variation over time in the downstream reach. The limited temperature variation over time in the upstream reach can be explained by the fact that the stream springs only a few hundred meter more upstream than the first temperature measurements, causing the upstream temperature to be highly correlated to the groundwater temperature. As the groundwater temperature is relatively stable over the year, the temperature amplitude in the upstream reach of the Springendalse Beek is reduced. On the other hand, when moving in the downstream direction the temperature variation over time increases whereas the correlation with the groundwater temperature is decreasing and the correlation with the atmospheric conditions is increasing.



Figure 6.10: Average daily stream temperature profiles through the year along the Springendalse Beek.

Besides a difference in temperature amplitude between the upstream and downstream reach, also a difference between the small and large seepage lake could be seen; the small seepage lake had a significant smaller temperature amplitude through the year compared to the large seepage lake. As been earlier discussed, this difference in temperature amplitude is caused by the difference in residence time of the water inside the lakes. Due to the fact that the small seepage lake had a significantly higher radon concentration than the large seepage lake, it can be concluded that the small seepage lake had more recently added groundwater resulting in the

lake temperatures to be highly correlated to the stable groundwater temperature.

Whereas groundwater seepage in August and September caused a decrease in the warming slope, in November the seepage caused a decrease in the cooling slope by creating relatively warm zones in the stream. In the temperature profile of 29 November the seepage zone between 450 and 550 meter showed a increase of 3°C relative to the stream temperature. The burial of the fiber-optic cable may have been a significant factor in this large temperature difference. However, as the repetition time of the Oryx unit was changed from 48 to 4 times a day in October, it is not possible to see whether the temperature within the seepage zone was experiencing a time-lag, which suggests burial of the cable.

6.3.5 Implications for the aquatic ecology

Groundwater seepage in the Springendalse Beek has a damping effect on the stream temperature and causes a significant reduction of the maximum stream temperature. As such, groundwater seepage is an advantage for aquatic species which are sensitive to large temperature fluctuations. However, the high amount of nitrate found at several places along the stream and in groundwater samples showed that groundwater also transports stressors towards the stream.

6.4 Differences between the streams

As was found from the measurements during this research, the Springendalse Beek is more influenced by groundwater seepage than the Elsbeek. This resulted in different stressors and different measures that must be taken to assure a healthy aquatic ecology for both streams. This section shortly summarizes and compare the systems of both streams.

The Elsbeek is mainly fed from the agricultural fields along the stream. As the water from these fields is quickly transported via drains, the discharge of the Elsbeek shows high peak discharges in winter while in summer, when limited amount of precipitation occurs, the stream dries up. The lack of discharge in summer is an important stressor for the aquatic ecosystem of the stream. On the other hand, the Springendalse Beek is mainly fed by groundwater seepage, resulting in a stable discharge throughout the year and a constant baseflow. Although this stream will not dry up during summer, the groundwater seepage can add stressors to the stream by for example transporting nutrient levels towards the stream since the groundwater within the research area originates from the many agricultural fields in the east.

The fact that the Springendalse Beek receives more groundwater than the Elsbeek can also be seen when comparing the temporal variation in average stream temperature of both streams. As can be seen in Figure 6.11 groundwater seepage caused the average stream temperature of the Springendalse Beek to be significantly cooler in summer and to be warmer in fall compared to the average stream temperature of the Elsbeek. Moreover, groundwater seepage also reduced the stream temperature amplitude; the temperature amplitude of the Springendalse Beek was approximately 10°C between July and December while in the Elsbeek an amplitude over 20°C was found.

Since the stream temperature of the Elsbeek was mainly influenced by shading instead of groundwater seepage, the effect of shading and groundwater seepage can be compared.



Figure 6.11: Temporal variation of the average stream temperature of both the Elsbeek and Springendalse Beek.

Whereas groundwater seepage only reduced the warming slope along the Springendalse Beek from 0.35°C/100m to 0.06°C/100m, shading caused a decrease in stream temperature from 0.64°C in the open reaches to -0.10°C in the shaded reaches. However, from this data it cannot concluded whether shading or seepage is more effective for decreasing the stream temperature, as their effect is depending on stream geometry, discharge, leaf area index (LAI) of the riparian vegetation and the groundwater flux to the streams (Caissie, 2006; Verdonschot et al., 2014). With global warming in mind, both groundwater seepage and shading will create stable temperature habitats for aquatic species which are sensitive for extreme temperatures. As creating shading is an easier measure than increasing the amount of groundwater seepage towards a stream, adding riparian vegetation would be the most useful measure along lowland streams to reduce the stream temperature.

6.5 **Recommendations**

- The main difficulty for DTS measurements performed along the Elsbeek and along some parts of the Springendalse Beek was the burial of the fiber-optic cable by sedimentation. As was shown for the Elsbeek, at places where the fiber-optic cable was buried the temperature signal can be misinterpreted as seepage. For future temperature measurements using DTS it is therefore recommended to invent a new method to secure the cable to the streambed to prevent the cable to be buried or by placing the entire length of the cable at a consistent depth below the streambed.
- For more accurate temperature data differential attenuation must be taken into account. This can be done by using the double-ended calibration described by Van De Giesen et al. (2012) instead of using the calibration method described by Hausner et al. (2011) for single-ended configurations.

- The repetition time used in fall of 6 hours made it hard to see whether the fiber-optic cable was significantly buried with sediments as no time-lag could be observed with only a few measurements per day. It is therefore recommended to always use short repetitions times, and therefore more measurements per day, so the effect burial but also the effect of short term processes such as precipitation could clearly be seen.
- To fully understand the temporal temperature variation of the streams, also high intensity or long lasting precipitation events can be examined on their effect on the stream temperature.
- To study the effect of shade even better, days with similar air temperature but with different solar radiation levels can be compared. In this way, you can better distinguish the effect of air temperature and solar radiation on the stream temperature.
- For the vertical temperature profiles to be more useful in indicating whether a stream is infiltration or whether seepage does occur, more measurements through the year are needed. Different locations can be better compared using the yearly temperature envelopes.

Chapter 7

Conclusions

The Springendalse Beek and the Elsbeek have completely different systems resulting in different temperature distributions along the streams. From the DTS temperature data it can be concluded that the stream temperature of the Elsbeek was not much affected by groundwater seepage during the summer period. Additional measurements did indicate the presence of seepage, but also showed that it was highly heterogeneous in space. This could be the reason that seepage was not shown in the DTS data as the fiber-optic cable was often placed in the middle of the stream. Moreover, seepage might have been more diffusive than focused which also explains the limited effect on the stream temperature. The radon and flux measurements indicated that most seepage occurred in the midsection of the stream.

While groundwater discharge had a negligible effect on the stream temperature of the Elsbeek, shade had a major effect as riparian vegetation reduced the amount of direct solar radiation reaching the stream. A significant decrease in the mean and maximum daily stream temperature was seen in the shaded reaches, creating stable temperature habitats. An additional stressor important for the aquatic ecosystem of the Elsbeek is the limited discharge during summer.

For the Springendalse Beek the effect of groundwater seepage on the stream temperature was clearly seen in the northern branch and in the midsection between 450 and 550 meter. Along the seepage zones the mean and maximum stream temperature was significantly reduced. The best method to identify the seepage zones from the DTS data was by using the warming slope of the stream. Besides the two main seepage zones, multiple other locations with seepage were found by locating visible seepage indicators along the stream and from the radon and flux measurements. While on the one hand groundwater seepage acted as an advantage for the aquatic ecosystem of the Springendalse Beek by creating a stable temperature habitat, on the other hand seepage transported nutrients to the stream which acts as a stressor to the aquatic ecosystem.

Although no conclusions could be made whether groundwater seepage or shading is more effective in reducing the stream temperature, creating shading along a stream is an easier measure compared to increasing the amount of groundwater seepage to a stream. Since the system of both lowland streams are completely different, each streams needs its own measures to assure a healthy aquatic ecosystem.

Chapter 8

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Appendix A

Water chemistry

Table A.1: Water chemistry results of the Elsbeck, measurements performed on August 16^{th} (white rows) and on December 8^{th} (blue rows).

#	Location	Coordinates UTM	EC [μ S/cm]	Fe^{2+} [mg/L]	NO ₃ [mg/L]	pН	Radon [Bq/m ³]
1	Kremersveenweg stream	32U 362656 5789843	430	0.334	5.6	7.26	
			439	< 0.2	9.0	7.43	194 ± 170
2	Kremersveenweg drainage	32U 362650 5789847	500	0.376	39.7	7.30	
3	Zoekerveldweg	32U 362968 5789642	430	0.348	9.2	7.29	
			441	0.247	12.2	7.40	117 ± 130
4	Glanerbrugdijk bridge	32U 363288 5789584	425	0.289	16.0	7.15	
			443	< 0.2	11.9	7.40	117 ± 130
5	Glanerbrugdijk farm	32U 363656 5789905	418	0.359	8.1	7.47	
			443	< 0.2	12.3	7.58	77.7 ± 110

#	Location	Date	Coordinates UTM	EC [μ S/cm]	Fe^{2+} [mg/L]	NO ₃ [mg/L]	pН	Radon[Bq/m ³]
1	Northern branch upstream	16 Aug	32U 356106 5811442	298	<0.2	>60.0	6.47	
		22 Sep		302	0.499	>60.0	6.61	537 ± 310
		8 Dec		306	< 0.2	55.1	6.84	233 ± 190
2	Northern branch piezometer	8 Dec	32U 356160 5811433	310	< 0.2	52.3	5.94	
3	Northern branch weir	16 Aug	32U 356255 5811366	299	< 0.2	52.9	6.40	
		22 Sep		306	<0.2	54.7	6.63	441 ± 290
4	Southern branch	16 Aug	32U 356294 5811252	179	< 0.2	15.3	6.30	
		22 Sep		175	< 0.2	14.5	6.81	731 ± 350
		8 Dec		194	< 0.2	14.7	6.82	
5	Bridge 1	16 Aug	32U 356448 5811253	277	< 0.2	42.3	6.80	
6	Small seepage lake	16 Aug	32U 356464 5811295	235	< 0.2	35.4	6.03	
		22 Sep		239	< 0.2	38.2	6.39	941 ± 410
		8 Dec		237	< 0.2	40.6	5.99	1130 ± 420
7	Bridge 2	16 Aug	32U 356608 5811207	261	0.205	40.9	6.89	
8	Stream piezometers	22 Sep	32U 356640 5811197	263	< 0.2	42.5	6.86	136 ± 160
		8 Dec		261	< 0.2	41.3	6.88	311 ± 220
9	Upstream of large seepage lake	16 Aug	32U 356775 5811238	253	< 0.2	40.7	6.92	
		22 Sep		254	0.21	42.6	6.99	465 ± 270
		8 Dec		256	< 0.2	38.7	6.78	331 ± 220
10	Large seepage lake	16 Aug	32U 356774 5811269	181	< 0.2	19.6	7.02	
		22 Sep		186	< 0.2	20.1	7.23	90.2 ± 130
		8 Dec		199.4	< 0.2	29.0	6.28	157 ± 160
11	Downstream swamplake	16 Aug	32U 356866 5811159	235	< 0.2	38.3	6.88	
12	Blauweweg	16 Aug	32U 356980 5811150	235	< 0.2	33.2	6.84	
		22 Sep		238	0.243	36.1	7.02	155 ± 160
		8 Dec		241	< 0.2	35.5	6.70	159 ± 160
13	Piezometer 1	22 Sep	32U 356642 5811211	141	0.284	11.1	4.57	4170 ± 900
		8 Dec		142.6	0.231	14.1	4.67	
14	Piezometer 2	22 Sep	32U 356639 5811205	137	1.233	12.3	4.80	5800 ± 1000
		8 Dec		141.2	1 1 38	10.0	4 58	

Table A.2: Water chemistry results of the Springendalse Beek, measured on August 16^{th} 2016 (white rows), September 22^{nd} (green rows) and on December 8^{th} (blue rows).

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Appendix B

Visible seepage indicators



Figure B.1: Visible seepage indicators along the Springendalse Beek.

Appendix C

Groundwater temperature



Figure C.1: Shallow groundwater temperature measured in a piezometer along the Springendalse Beek.

Appendix D

Temperature measurements HOBO weather stations



Figure D.1: Air and stream temperatures measured by the HOBO weather stations along the Elsbeek



Figure D.2: Air and stream temperatures measured by the HOBO weather stations along the Springendalse Beek



Figure D.2: Continuation of air and stream temperatures measured by the HOBO weather stations along the Springendalse Beek

Appendix E

Seepage flux results



(a) Flux measurement 2a: Midsection north (08-12-16)



(c) Flux measurement 2c: Midsection north (08-12-16)



(e) Flux measurement 3b: Midsection south (08-12-16)



(b) Flux measurement 2b: Midsection north (08-12-16)



(d) Flux measurement 3a: Midsection south (08-12-16)



(f) Flux measurement 3c: Midsection south (08-12-16)

Figure E.1: Flux measurement results, Elsbeek



(a) Flux measurement 1: South of large seepage lake (15-11-16)



(c) Flux measurement 3: Northern branch (22-11-16)



(e) Flux measurement 4b: Downstream of large seepage lake (08-12-16)



(b) Flux measurement 2: Downstream of swamp lake (22-11-16)



(d) Flux measurement 4a: Downstream of large seepage lake (08-12-16)



(f) Flux measurement 4c: Downstream of large seepage lake (08-12-16)

Figure E.2: Flux measurement results, Springendalse Beek



Depth relative to stream level [cm] -2.5 -3 -3.5 -4 -4.5 0 50 100 150 Time [min]

-2

(g) Flux measurement 5a: Stream piezometers (08-12-16)

(h) Flux measurement 5b: Stream piezometers (08-12-16)

Water level inside PVC tube



(i) Flux measurement 6: Bridge 2 midsection (08-12-16)

