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Ph.D. Thesis

Investigation of Groundwater-Surface Water Interactions with Distributed Temperature Sensing (DTS)

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by

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“... all that we need to make us really happy is something to be enthusiastic about.”

Charles Kingsley

To my family

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Abstract

Groundwater-surface water interactions are a vital necessity for aquatic ecosystems as they control the water temperature, the availability of nutrients, dissolved oxygen and the water quality in the hyporheic zone. A lack of groundwater-surface water interactions may result in the deterioration of ecosystem health and functioning. Studies between 1997 and 2008 have shown that 22 % of Swiss water courses were severely degraded, e.g. engineered or covered. As a consequence, river restoration was made a legal obligation, stipulating the restoration of 4000 km of degraded rivers and streams over the course of the next 80 years. For this thesis a review of Swiss river restoration data between 1979 and 2012 for 13 of the 26 Swiss cantons was performed. Results indicated that restoration activities had steadily increased since 1979, with an average restoration rate of 9.8 km/year. An analysis of the restoration techniques revealed interesting geographical trends. In western Switzerland, more sustainable combinations of restoration measures, such as bioengineering or water quality improvements, were favoured. Cantons in central and eastern Switzerland, on the other hand, preferred single restoration measures with a higher degree of mechanical intervention. In general, the evaluation of restoration effects was only reported for less than 10 % of all investigated restoration projects. These mainly focussed on the number of flagship species, such as trout. None of the investigated projects tested whether river restoration had re-established groundwater-surface water interactions. Hence, this thesis aims at investigating the effects of river restorations on groundwater-surface water interactions. A number of techniques are commonly used to investigate groundwater-surface water interactions, including geochemical, hydrogeological and physical approaches. In the present study a combination of approaches is employed, with the main focus being on the physical parameter of water temperature. The latter is investigated with Distributed Temperature Sensing (DTS). DTS is used to measure temperature differences between ground- and surface water in surface water bodies. So far, the existing DTS methods have enabled the investigation of groundwater-surface water interactions under gaining conditions in small brooks. In order to investigate the effect of river restoration on groundwater-surface water interactions, however, a method applicable in both gaining and losing conditions, and which is suitable for water courses of all sizes is required. For this purpose, a new methodology, the **PAB** approach, has been developed, which combines passive (P) and active (A) DTS methods with the burying (B) of the fibre-optic cable in the subsurface. This approach enables long-term distributed investigations of groundwater-surface water interactions under gaining and losing conditions in water courses of all sizes. The active DTS method in the PAB approach, however, requires the direct presence of an operator controlling the heating of the fibre-optic cable. In order to circumvent this limitation and enable long-term temperature measurements with the PAB approach in remote areas, an autonomous DTS system (ADTS system) has been developed. This system combines several advantages, such as remote control, automated data transfer, and automated heating. By aid of the ADTS system and the PAB approach, the effect of river restoration on groundwater-surface water interactions has been investigated in an urban stream. Results indicate that the installation of gravel islands increased the rate of surface water downwelling. Generalising the results, it may be assumed that such changes to river morphology will have a positive effect on the rate of groundwater-surface water interactions. Therefore, river restoration may be successful in enhancing groundwater-surface water interactions. Concerning the newly-developed DTS method and measurement system, it could be shown that the combination of the ADTS system and the PAB approach is a powerful tool for the investigation of groundwater-surface water interactions. In future river restoration projects, this tool should be employed for evaluating its success in re-establishing groundwater-surface water interactions.

Zusammenfassung

Grundwasser-Oberflächenwasser-Interaktionen sind eine notwendige Voraussetzung für gesunde aquatische Ökosysteme, da diese die Verfügbarkeit von Nährstoffen und gelöstem Sauerstoff, aber auch die Wassertemperatur und –qualität in der hyporheischen Zone beeinflussen. Ein Fehlen dieses Austauschs kann Zustand und Funktion solcher Ökosysteme stark beeinträchtigen. Zwischen 1997 und 2008 durchgeführte Untersuchungen haben gezeigt, dass sich in der Schweiz bis zu 22 % der Fliessgewässer in einem ökomorphologisch schlechten Zustand befinden und z.B. künstlich oder eingedolt sind. Als Folgerung dieser Ergebnisse wurde die Revitalisierung von 4000 Flusskilometer über einen Zeitraum von 80 Jahren gesetzlich vorgeschrieben. Für die vorliegende Doktorarbeit wurden Daten von Schweizer Flussrevitalisierungen, welche zwischen 1979 und 2012 durchgeführt wurden, erhoben und ausgewertet. Die Ergebnisse der Erhebung, bei der 13 der 26 Schweizer Kantone teilnahmen, zeigten, dass die Gesamtlänge revitalisierter Fliessgewässer seit 1979 stetig zugenommen hat. Dabei lag die mittlere Revitalisierungslänge bei 9.8 km pro Jahr. Bezüglich der eingesetzten Revitalisierungsmassnahmen zeigten sich geographische Trends. In der West-Schweiz wurden eher auf Nachhaltigkeit ausgerichtete Kombinationen von Revitalisierungsmassnahmen favorisiert, wie z.B. biologischen Verfahrenstechniken und Massnahmen zur Verbesserung der Wasserqualität. Kantone der Zentral- und Ost-Schweiz hingegen bevorzugten einzelne bauliche Massnahmen, wie beispielsweise das Ausbaggern und Neugestalten des Flussbetts. Bei den Erfolgskontrollen ergaben sich keine geografischen Trends. Generell wurden diese nur bei 10 % aller untersuchten Revitalisierungsprojekte durchgeführt, wobei sich diese häufig nur auf die Anzahl von Leitarten, wie z.B. Forellen, konzentrierten. Grundwasser-Oberflächen-Interaktionen wurden in keinem der vorliegenden Projekte untersucht. Vor diesem Hintergrund wurde im Rahmen dieser Doktorarbeit untersucht, wie sich Flussrevitalisierungen auf den Austausch zwischen Grund- und Oberflächenwasser auswirken. Für die Untersuchung von Grundwasser-Oberflächenwasser-Interaktionen sind diverse geochemische, hydrogeologische oder physikalische Messmethoden verfügbar und wurden in dieser Arbeit verwendet. Das Hauptaugenmerk richtet sich hierbei auf die Wassertemperatur, welche mit Distributed Temperature Sensing (DTS) untersucht wurde. DTS misst hierbei die Wassertemperatur in Fliessgewässern, wobei es sich die Temperaturunterschiede zwischen Grund- und Oberflächenwasser zu Nutze macht. Bisherige DTS-Standardverfahren ermöglichen ausschliesslich die Untersuchung von Grundwasser-Oberflächen-Interaktionen in effluenten (Grundwasser gewinnenden) Bächen. Untersuchungen in grösseren oder in influenten(Wasser abgebenden) Fliessgewässern sind nicht möglich. Um jedoch die Auswirkungen der Flussrevitalisierung auf die Grundwasser-Oberflächenwasser-Interaktionen untersuchen zu können, dürfen keine Beschränkungen bezüglich der hydrologischen Situation oder der Grösse des Fliessgewässers bestehen. Daher wurde im Rahmen dieser Doktorarbeit eine neue Messmethode entwickelt. Diese sogenannte PAB-Methode vereint Elemente der bestehenden passiven (P) und aktiven (A) DTS-Methoden mit der Verlegung eines Glasfaserkabels in das Flussbett (buried, B). Damit werden langfristige Untersuchungen der Grundwasser-Oberflächenwasser-Interaktionen in influenten sowie effluenten Fliessgewässern aller Dimensionen ermöglicht. Für die aktiven DTS-Messungen wird jedoch eine Person zur Bedienung der Glasfaser-Heizung benötigt. Dies erschwert die langfristige Anwendung der PAB-Methode in abgelegenen Gebieten. Um diese Limitierung zu umgehen wurde ein autonomes DTS-Messsystem (ADTS) entwickelt. Letzteres ist ferngesteuert, beheizt das Glasfaserkabel vollautomatisch und sendet seine Daten regelmässig an einen Online-Datenspeicher. Auf diese Weise können die Grundwasser-Oberflächenwasser-Interaktionen auch in abgelegenen Gebieten längerfristig untersucht werden. Mit Hilfe des ADTS Systems und der PAB-Methode wurden die Auswirkungen der Flussrevitalisierung auf die Grundwasser-Oberflächenwasser-Interaktionen exemplarisch in einem revitalisierten urbanen Fliessgewässer untersucht. Die Ergebnisse dieser Studie weisen darauf hin, dass die Errichtung von Kiesinseln das Eindringen von Oberflächenwasser in den Untergrund verstärkt hat. Basierend auf diesen Untersuchungen lässt sich schliessen, dass bestimmte Veränderungen der Flussmorphologie, wie z.B. das Einbringen von Kiesinseln, die Grundwasser-Oberflächenwasser-Interaktionen erhöhen können. Somit können Flussrevitalisierungen eine wirksame Methode zur Verstärkung der Grundwasser-Oberflächenwasser-Interaktionen darstellen. In Bezug auf die entwickelten DTS Methode und DTS Messsystem konnte gezeigt werden, dass die Kombination der PAB-Methode mit dem ADTS System sehr gut geeignet sind, um Grundwasser-Oberflächenwasser-Interaktionen in Fliessgewässern zu untersuchen. Daher sollte die Kombination der PAB-Methode mit dem ADTS System bei der Erfolgskontrolle zukünftiger Revitalisierungsprojekte Berücksichtigung finden.

Résumé

Les interactions entre les eaux souterraines et les eaux de surface sont vitales pour les écosystèmes aquatiques car elles influencent sur la température de l’eau, la disponibilité en nutriments et en oxygène dissous et sur la qualité de l'eau dans la zone hyporhéique. Un déficit dans ces interactions pourrait conduire à la détérioration de la santé et du fonctionnement de ces écosystèmes. Entre 1997 et 2008, des recherches ont montré que 22 % des cours d’eau suisses se trouvent dans un état critique écomorphologique (artificielles ou couvertes par exemple). En conséquence, la restauration des rivières est devenue une obligation légale, stipulant la revitalisation de 4000 kilomètres de cours d’eaux et de rivières endommagés sur une période de 80 ans. Dans le cadre de cette thèse, les données sur la revitalisation des cours d’eaux suisses ont été recueillies pour 13 des 26 cantons suisses, pour une période allant de 1979 à 2012. Les résultats ont montré que la longueur totale restaurée a augmenté constamment depuis 1979, avecune longueur moyenne de revitalisation de 9.8 km par an. L’analyse des mesures de revitalisation utilisées a montré des tendances géographiques. Dans la Romandie, des combinaisons des mesures de revitalisation plus durables ont été favorisées, par exemple des méthodes de bio-ingénierie et d’amélioration de la qualité de l’eau. En revanche, les cantons de la Suisse centrale et orientale, préfèrent une seule mesure de restauration avec un degré élevé d’intervention mécanique. En général, les contrôles d’efficacité des restaurations n’ont été réalisés dans moins de 10 % des projets de revitalisation étudiés. La plupart de ces contrôles concerne seulement le nombre des espèces indicatrices, comme les truites. Le rétablissement des interactions entre les eaux souterraines et les eaux de surface n’a été analysé dans aucun des projets. Dans ce contexte, la présente thèse a pour objectif d’analyser l’influence des mesures de revitalisation sur les interactions entre les eaux souterraines et les eaux de surface. Il existe un grand nombre de techniques d’analyse des interactions entre les eaux souterraines et les eaux de surface, parmi lesquels les méthodes des mesures géochimiques, hydrogéologiques et physiques. Dans la présente étude, une combinaison de ces approches est utilisée, avec une attention particulière à la température de l’eau. Cette dernière est examinée par Distributed Temperature Sensing (DTS). La méthode standard DTS utilisée jusqu’à présent permet seulement d’étudier les interactions de l’eau souterraine avec les eaux de surface dans des ruisseaux exfiltrants. Afin d’étudier les effets de la revitalisation des cours d’eaux sur les interactions de l’eau souterraine avec les eaux de surface, une méthode applicable dans des conditions exfiltrantes et infiltrantes pour tout taille de cours d’eau est nécessaire. En conséquence, une nouvelle méthode de mesure a été développée dans cette thèse. Cette méthode dite PAB combine des éléments des méthodes

DTS passives (P) et actives (A) existantes avec l’enterrement du câble à fibre optique sous le lit de la rivière. Cette méthode permet des investigations à long terme des interactions de l’eau souterraine avec les eaux de surface dans les cours d’eau exfiltrants et infiltrants de toute dimension. Toutefois, une personne doit être présente pour contrôler le chauffage du câble à fibre optique pendant la mesure DTS active. . Pour contourner cette limitation et permettre l’application à long terme de la méthode PAB dans les régions éloignées, un système DTS autonome (ADTSS) a été développé. Ce dernier cumule plusieurs avantages dont la commande à distance, le transfert automatique des données et le chauffage automatique du câble à fibre optique. Avec l’aide de l’ADTSS et la méthode PAB, les effets de la revitalisation des cours d’eaux sur les interactions entre les eaux souterraines et les eaux de surface ont été analysés pour un cours d’eau urbain. Les résultats indiquent que la construction d’îlots de graviers augmente l’infiltration de l’eau de surface dans le lit du cours d’eau. Sur la base de ces recherches, on peut conclure que certaines modifications de la morphologie des rivières ont un effet positif sur les interactions entre les eaux souterraines et les eaux de surface. Ainsi, la revitalisation des cours d’eau peut être une méthode efficace pour améliorer les interactions de l’eau souterraine avec les eaux de surface.

Keywords

Groundwater-surface water interactions, groundwater upwelling, surface water downwelling, river restoration, Distributed Temperature Sensing (DTS), Autonomous DTS System (ADTS), PAB approach.

Schlüsselwörter

Grundwasser-Oberflächenwasser-Interaktionen, Grundwasserexfiltration, Oberflächenwasser-infiltration, Flussrevitalisierung, Distributed Temperature Sensing (DTS), Autonomes DTS System (ADTSS), PAB Methode.

Mots clés

L’interaction des eaux souterraines et des eaux de surface, l’émergence des eaux souterraines, l’infiltration des eaux de surface, revitalisation des eaux courantes, Distributed Temperature Sensing (DTS), système DTS autonome (ADTS), méthode PAB.

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Chapter 1

Introduction

1.1 *Background and Motivation*

This Ph.D. thesis focusses on the investigation of groundwater-surface water interactions with Distributed Temperature Sensing (DTS), with particular emphasis on the effects of river restoration on groundwater-surface water interactions. In the following, a short introduction to river restoration and groundwater-surface water interactions, as well as some background on the DTS technology is provided. This is complemented by the motivation for and objectives of this Ph.D. thesis.

1.1.1 *River restoration*

Recently, more and more surface water bodies are being negatively impacted by human activities, e.g. by urbanisation, agriculture and hydropower generation (Mill. Ecosyst. Assess. 2005). The resulting damage to ecosystems, the economy and society exceeds the benefits gained from exploiting these riverine ecosystems (Zeh Weissmann et al. 2009). As a consequence, the restoration of degraded surface water bodies has become a pressing issue and several countries, including Switzerland, have decided to make the restoration of degraded surface water bodies an obligation (EU WFD 2000; Swiss Water Protection Act 814.20). In Switzerland a standardised test, the ecomorphology module of the Modular Stepwise Procedure (Modul-Stufen-Konzept Ökomorphologie Stufe F) (BUWAL 1998) was applied to 24 of the 26 Swiss cantons between 1997 and 2008 to identify the necessity for river restorations in Switzerland. The results indicated that 14,000 km or 22 % of Swiss rivers and streams were in an ecomorphologically poor state, including 3,000 km of artificial and 4,000 km of covered rivers and streams (Zeh Weissmann et al. 2009). Based on these findings, it was decided that 4,000 km of degraded rivers and streams are to be restored over the course of the next 80 years (BAFU 2011). In order to optimise these restoration efforts, several standardised tests (various modules of the Modular Stepwise Procedure) and evaluation guidelines (Woolsey et al. 2005) were developed to aid in identifying areas with the highest restoration potential and for providing a code of practice for success evaluations after the restoration measures were completed. Additionally, several research projects, such as the Restored Corridor Dynamics (ReCorD) project, have aimed at investigating the effects of river restoration on e.g. the morphological variability of a river, its water quality or the biodiversity in the restored area (Schirmer et al. 2014). These investigations, however, have left unanswered the question of the effect these morphological changes have had on a river's vertical connectivity, i.e. on the extent of its groundwater-surface water interactions.

1.1.2 *Groundwater-surface water interactions*

Groundwater-surface water interactions play a major role in ecosystem health (Bardini et al. 2002; Wondzell 2011) and functioning (Boulton et al. 1998; Malard et al. 2002; Thorp et al. 2006), as they control, amongst others, the water temperature (Bencala 2005; Hannah et al. 2009; Norman and Cardenas 2014), the nutrient availability (Fuller and Harvey 2000; Gooseff et al. 2002; Butturini et al. 2003), and the water quality (Boulton et al. 1998; Findlay 1995; Fuller and Harvey 2000) in the hyporheic zone (Fig. 1.1). Upwelling groundwater has a relatively constant temperature close to the mean annual air temperature. Hence, zones with groundwater upwelling are favourable for aquatic species which depend on stable water temperatures for living and breeding. Downwelling surface water, on the other hand, is richer

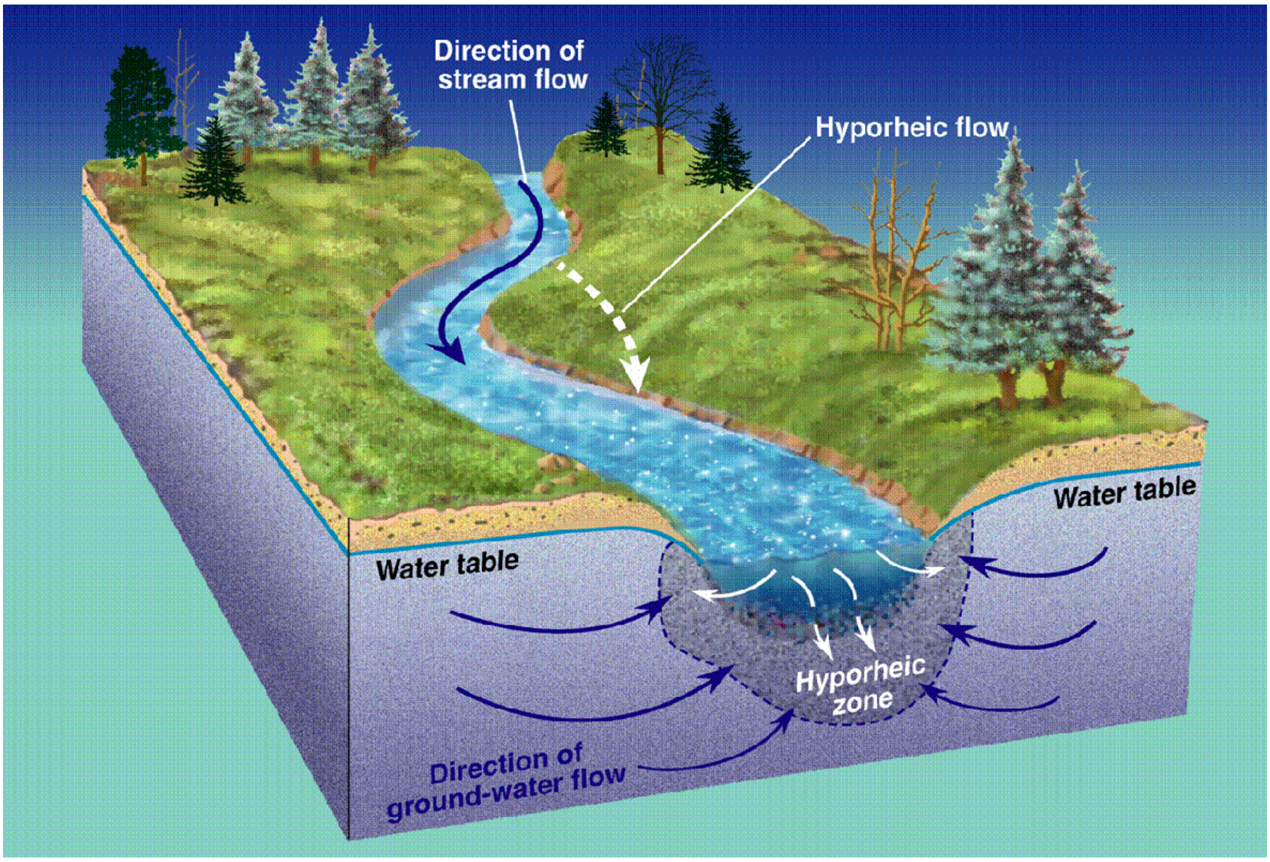

Figure 1.1. Groundwater-surface water interactions in an effluent stream (© USGS 2011).

in dissolved oxygen and nutrients, such as plant debris, dissolved organic matter (DOM), dissolved organic carbon (DOC), or nitrate and sulphate, on which the aquatic species and thus the trophic chain in the hyporheic zone are highly dependent (Younger 2008). Additionally, the water quality in contaminated or polluted surface or groundwater bodies might be significantly improved by dilution with uncontaminated/unpolluted ground- or surface water, respectively. Therefore, (aquatic) ecosystem health and functioning is highly dependent on the mixing of groundwater and surface water, i.e. groundwater-surface water interactions, in the hyporheic zone. Anthropogenic disturbance to groundwater-surface water interactions may therefore have a severe impact on the local aquatic ecosystem, e.g. causing variations in the abundance and composition of type-specific communities or the total disappearance of disturbance-sensitive species (EU WFD 2000). Both of these effects may lead to severe deterioration of aquatic ecosystem functioning and their services to humankind, such as the purification of water or the provision of food (Mill. Ecosyst. Assess 2005). Hence, a thorough understanding of the causes for the degradation of groundwater-surface water interactions is of major importance. Findings in this area will support the identification of possible remediation methods aiding in enhancing groundwater-surface water interactions in degraded water courses.

A number of chemical and physical parameters may be examined for investigations of groundwater-surface water interactions, such as Radon-222 concentrations (Cartwright et al. 2014; Cook 2013; Hoehn et al. 1992) or water temperatures (Anderson 2005; Schneider 1962). The latter, in particular, is easily measured and relatively inexpensive. Investigations of groundwater-surface water interactions based on water temperatures thereby take advantage of the temperature difference between ground- and surface water (Anderson 2005). This effect is most pronounced in summer and winter, when the differences between groundwater and surface water temperatures are greatest. Investigations of groundwater-surface water interactions in spring and autumn are less conclusive, as the temperature difference between ground- and surface water may be too small. The shallow groundwater temperature fluctuates around the mean annual air temperature (Schneider 1962), while the surface water temperature varies depending on the weather and climatic conditions. Investigations of the water temperature thus allow conclusions to be drawn on the extent and behaviour of groundwater-surface water interactions in gaining conditions. In winter, for example, areas with higher water temperatures close to the groundwater temperature would indicate groundwater infiltration into the colder stream. A convenient method for such temperature measurements is Distributed Temperature Sensing.

1.1.3 *Distributed Temperature Sensing (DTS)*

DTS is a fibre-optical method for temperature measurements along a glass fibre based on the Raman effect (Farahani and Gogolla 1999; Soto et al. 2007a, b). The optoelectronic DTS instrument consists, amongst others, of a laser source and a detector unit. The laser source emits light pulses of subnanometer to nanometer length, depending on the instrument settings (see below) (Tyler et al. 2009). The length of the laser pulse depends on the refractive index of the silica glass of the glass fibre and the velocity of light therein:

$$(1.1) \quad v = \frac{c}{n}$$

with v being the light's velocity in the glass fibre in [m/s], c being the velocity of light in a vacuum in [m/s], and n being the refractive index of the silica glass in the glass fibre in [/] (Eberlein et al. 2010). According to equation (1.1), with c = 299'792'458 m/s and n = 1.47 a spatial resolution of 1 m requires a laser pulse length of 5 ns.

The laser pulse is injected into the glass fibre. The multimode glass fibre used in Raman-based DTS consists of a core of 50 μm thickness made of GeO_2-doped silica glass (SiO_2), and a cladding of 125 μm thick un-doped SiO_2 (Fig. 1.2). Apart from mechanical protection against breaking and intrusion of OH^--ions, which would dampen the signal due to absorption, this difference in optical densities, and therefore refraction indices, is necessary for the guidance of the laser light beam within the glass fibre (Eberlein et al. 2010). The laser light beam is refracted at the glass/glass interface between the optically denser core and the less optically dense cladding. If the angle of the laser light beam is above the critical angle α_{crit}, refraction changes to total reflection and the laser light beam is contained within the core of the glass fibre (Fig. 1.3).

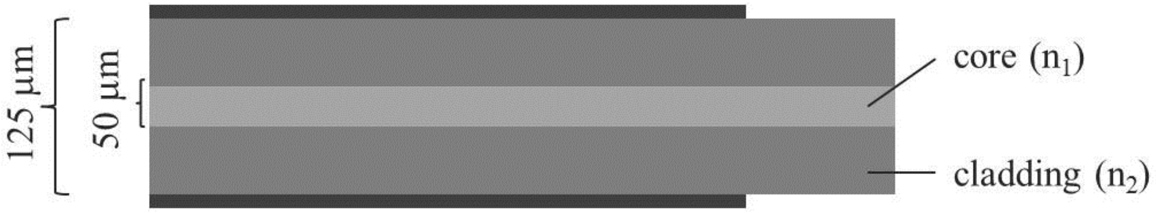

Figure 1.2. Structure of a multimode glass fibre. The light-grey core of GeO_2-doped SiO_2 has diameter of 50 μm, the grey cladding of un-doped SiO_2 125 μm. The thickness of the darkgrey plastic coating is not specified and depends on the type of the end product.

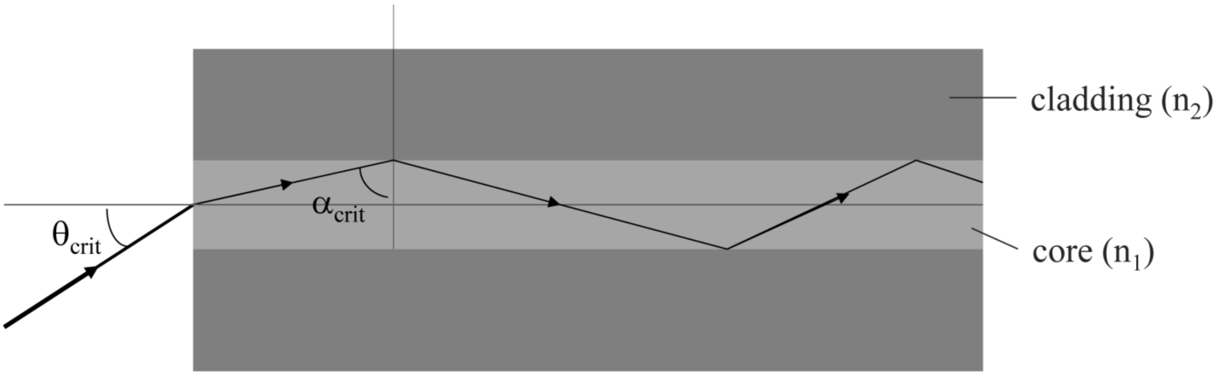

Figure 1.3. Light propagation with total reflection in the glass fibre (Eberlein et al. 2010, edited).

The critical angle α_{crit} is defined as

$$\alpha_{crit} = \arcsin\frac{n_2}{n_1} \tag{1.2}$$

with n_1 and n_2 being the refractive indices of the core and the cladding, respectively, and where $n_1 > n_2$. In the case of the fibre-optic cable n_1 is the refractive index of the optically denser core glass and n_2 the refractive index of the less optically dense cladding (Eberlein et al. 2010).

The laser light beam must be contained within the core of the glass fibre, as otherwise light would be lost to the cladding of the glass fibre, prohibiting light propagation within the glass fibre. In order to facilitate this total reflection of light in the core of the glass fibre, however, the angle of incidence of the laser light beam must be smaller than a critical angle, θ_{crit}, also termed the acceptance angle (Fig. 1.3).

The sine of θ_{crit} is known as the numerical aperture, NA, which is defined as

$$NA = \sin\theta_{crit} = \sqrt{(n_1^2 - n_2^2)} \tag{1.3}$$

Laser light beams inserted with an angle smaller than θ_{crit} will be totally reflected with an angle larger than α_{crit}, thus propagating within the core of the glass fibre (Eberlein et al. 2010).

During propagation of the laser light beam in the glass fibre, laser light photons interact with the glass molecules of the glass fibre, being scattered either elastically (Rayleigh scattering) or inelastically (Raman scattering). In elastic Rayleigh scattering the scattered photons have

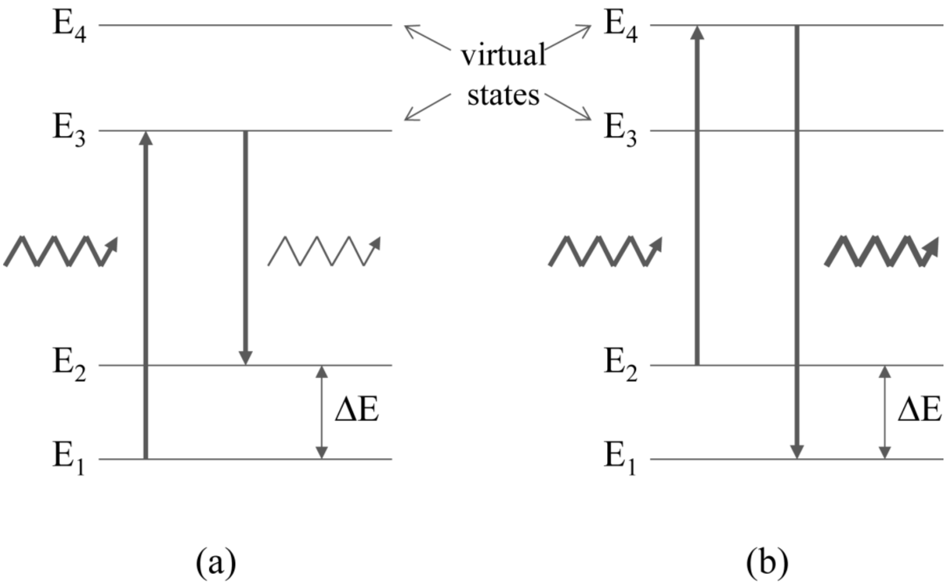

Figure 1.4. Schematic diagram of (a) Stokes and (b) Anti-Stokes scattering (Farahani and Gogolla 1999, edited).

the same energy, i.e. frequency and wavelength, as the incident photons. In inelastic Raman scattering, the scattered photons' energy is either higher or, usually, lower than that of the incident photons. This loss or gain of energy is due to excitation scattering: the photon interacting with a glass molecule either excites the latter, thereby losing the energy required for the excitation; or, the photon interacts with an already excited glass molecule, thereby gaining the energy that was released by the glass molecule falling back to its ground state. Those photons losing energy generate the Stokes signal, while photons gaining energy produce the Anti-stokes signal (Fig. 1.4).

Due to thermodynamic equilibrium, more glass molecules will be in a lower transitional state, causing the Stokes signal, than those in an excited state, causing the Anti-Stokes signal. Hence, the Stokes signal will usually be stronger than the Anti-Stokes signal (Fig. 1.5). This however, depends on the temperature of the glass fibre. The higher the temperature of the glass fibre, the more glass molecules will be in an excited state (Farahani and Gogolla 1999). This effect is used by Raman-based DTS instruments: by measuring the ratio of the Stokes to the Anti-Stokes signals, the temperature of the glass fibre, and therefore its surroundings, e.g. water in a stream, can be determined, using the following relationship:

$$(1.4) \quad \frac{I_{AS}}{I_S} \propto \exp\frac{-h\Delta\nu_R}{kT}$$

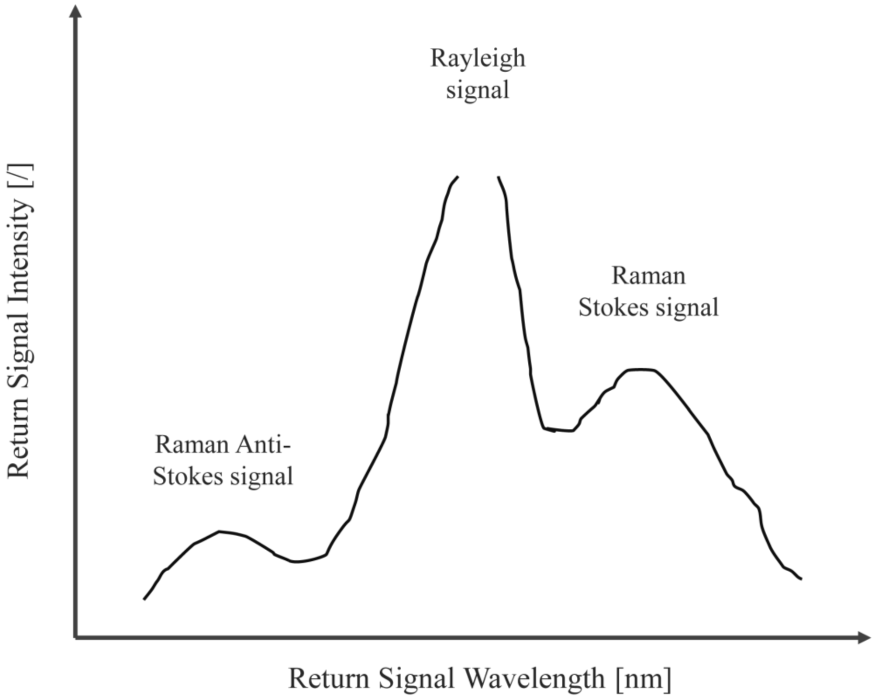

Figure 1.5. Spectrum of backscattered light, return signal wavelength versus return signal intensity (Hurtig et al. 1994, edited).

with I_{AS} and I_S being the signal intensity of the Anti-Stokes and Stokes signal, respectively, in [/], h the Planck constant in [J s], $\Delta\nu_R$ the frequency separation between the Anti-Stokes/Stokes- and the Rayleigh-scattered light in [1/s], k the Boltzmann constant in [J/K], and T the absolute temperature of the glass fibre in [K] (Soto et al. 2007a).

Using Optical Time Domain Reflectometry (OTDR), the position of each temperature signal can then be determined. In OTDR, similar to RADAR, time-of-flight between the injection of a laser light pulse and its detection after arriving back at the DTS instrument is used to determine from which section of the glass fibre the temperature signal originated (Farahani and Gogolla 1999). Thus, the glass fibre is transformed into a linear temperature sensor, enabling temperature measurements along the whole length of the glass fibre.

The drawback of Raman-scattering, though, is that it only makes up a minute proportion of the total backscattered light, and high peak power of the laser and long measurement times are required to increase signal strength and reduce the signal-to-noise ratio. This issue can be overcome by the complementary-code correlated Golay coded OTDR technique (Nazarathy et al. 1989). This technique allows the use of low-power semiconductor lasers which have a long life-time and low power consumption. Furthermore, at a given spatial resolution, either a higher temperature resolution or a higher temporal resolution, i.e. a shorter sampling interval, is possible (Soto et al. 2007b).

Thereby, spatial resolution defines the length of the glass fibre required to see 80 – 90 % of a temperature change, e.g. a 1 m spatial resolution requires 1 m to detect the temperature change between an ice bath and ambient temperatures. The temporal resolution is the time the DTS instrument collects the return Raman signals. The lower the spatial resolution and the temporal resolution, the lower the signal-to-noise ratio and the more accurate the temperature determined by the DTS instrument. However, information might be lost with a low spatial and temporal resolutions and the trade-off between the two settings has to be carefully considered during DTS measurements (Tyler et al. 2009). Currently available Raman-based DTS instruments offer spatial resolutions of up to 12.5 cm and temporal resolutions of 1 s. The DTS instruments employed in this research project had a minimum sampling resolution of 1 m and a minimum temporal resolution of 30 s.

The temperature data derived with DTS instruments has been used by various authors to estimate rates of groundwater upwelling (Briggs et al. 2012; Selker et al. 2006 b; Westhoff et al. 2011). These estimations were based on the methodology first described by Kobayashi (1985) and are suitable for gaining first-order streams. The upwelling of groundwater and the downwelling of surface water in higher order streams may be characterised with models described by Hatch et al. (2006), Hyun et al. (2011) and Vogt et al. (2010).

The DTS’ ability for high spatial, temporal and temperature resolution renders it a convenient method for high-resolution investigations of groundwater-surface water interactions in streams and brooks (Selker et al. 2006b; Lowry et al. 2007). Hence, this Ph.D. thesis employs DTS technology to investigating groundwater-surface water interactions, focussing on whether morphological changes to a river bed have an effect on groundwater-surface water interactions. This is done within the framework of the Record project and its follow-up project, Record Catchment.

1.2 Objectives and structure of this thesis

The overall goal of this Ph.D. thesis is the development of a DTS-method that will enable investigations of groundwater-surface water interactions in gaining and losing conditions, thereby answering the question of whether river restorations are an appropriate means of enhancing groundwater-surface water interactions in degraded rivers and streams. This is achieved by a combination of laboratory investigations, field work and technical experiments.

The special focus of this thesis is the effect of river restoration on groundwater-surface water interactions. In order to understand the correlation between river restoration and groundwater-surface water interactions, it was necessary to get a general idea about the river restoration techniques employed in Switzerland. Hence, the first objective of this Ph.D. thesis is a thorough review of the river restoration history of Switzerland, including the restoration techniques, success evaluations and possible spatial and temporal trends in river restorations. The results of this investigation are presented in Chapter 2.

In order to investigate the effects of river restoration on groundwater-surface water interactions, a suitable investigation method had to be selected. Distributed Temperature Sensing (DTS), measuring the temperature along a glass fibre of several hundred meters length, enables the simultaneous investigation of large sections of streams. The temperature difference between groundwater and surface water, as occurring in summer and winter, thereby allows investigations of groundwater-surface water interactions.

Well-established DTS methods have to date only been applied in investigating groundwater-surface water interactions under gaining conditions and in small streams and brooks (Selker et al 2006b; Lowry et al. 2007). However, groundwater-surface water interactions are likely to be equally important in larger streams and rivers and under losing conditions. Hence, the second objective of this work is the development of a DTS method that will enable measurements in all kinds of surface waters and hydrological conditions, including losing rivers and streams. However, this method required further developments of the so called active DTS method, first described by Perzlmaier et al. (2004), in which the metal components of the fibre-optic cable are heated. The active DTS method requires the presence of a direct operator, rendering active DTS measurements very time consuming, and limiting the areas in which active DTS could be applied. Hence, the third objective of this work is the development of an autonomous DTS system (ADTS system), which combines assets such as remote control, automatic heating of the fibre-optic cable and automatic data transfer. Chapter 3 specifies the components and construction of such an ADTS system, and discusses applications and limitations.

By aid of this newly constructed system, a new DTS methodology was developed, the PAB approach. The PAB approach combines passive (P) and active (A) DTS methods with a fibre-optic cable buried (B) in the streambed. This approach enables temperature measurements, and thus investigations of the groundwater-surface water interactions, in gaining and losing conditions in water courses of all sizes. The sole limitation is the grain size of the sediment in the streambed, as the installation of the fibre-optic cable is very challenging in coarse sediments. Chapter 4 describes the PAB approach in more detail and presents data obtained with the PAB approach in a restored urban stream.

Based on the outcomes from the first three objectives, the fourth objective of this Ph.D. thesis is the investigation of the effects of river restoration on groundwater-surface water interactions. This objective is met by comparing field investigations in an urban stream before and after its restoration to two natural and near-natural reference streams. Chapter 5 presents the results and conclusions from these investigations.

Chapter 6 summarises the findings of this Ph.D. thesis and provides an outlook with recommendations for future research on groundwater-surface water interactions with DTS and river restoration practice.

Chapter 2

Thirty years of river restoration in Switzerland: implemented measures and lessons learned

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Abstract

In the age of climate change and ecosystem degradation, governments realise more and more that it is crucial to protect ecosystem health, to preserve water resources, and to maintain flood protection. Therefore, several countries, among those Switzerland, have implemented laws to make the restoration of riverine ecosystems a legal obligation. In Switzerland, restoration projects were implemented as early as 1979, prior to these laws coming into force. For this article, 848 Swiss restoration projects, implemented between 1979 and 2012, were investigated, spanning a total of 307 river kilometres. No correlation was found between the geographical distribution of total restored lengths in a way that larger cantons performed more restorations. Neither was there a correlation between the total restored length and the cantons population density or financial status. Restoration activities increased steadily after 1992, with most restorations being reported for the years 2004, 2005 and 2009. The average restoration rate was 9.8 km per year, ranging between 0.5 km in 1979 and 23.9 km in 2004. Restoration measures were very diverse, ranging from measures that directly affected the wildlife, e.g. by providing habitats, to measures which indirectly enhanced conditions for the ecosystem, such as water quality ameliorations. Data regarding success evaluation was only available for 232 of the 848 projects, making it difficult to state whether the implemented restoration projects reached the intended objectives. Over the next 80 years, a further 4’000 km of Swiss rivers will be restored, requiring a restoration rate of 50 km per year, which, according to the data, is an achievable goal.

Keywords

ecosystem, flood protection, hydromorphology, river restoration, success evaluation

2.1 Introduction

Over the last 150 years, human activities, such as urbanisation, agriculture and hydropower generation, have led to a gradual degradation of riverine ecosystems (Mill. Ecosyst. Assess. 2005). In recent decades, it has become apparent that further degradation must be inhibited, as the damages to ecology, economy and society surmount the benefits gained from exploiting riverine ecosystems (Zeh Weissmann et al. 2009). Nowadays, river restoration is the globally accepted means to protect ecosystem health, to preserve water resources, and to maintain flood protection (Andrea et al. 2012; Palmer et al. 2005; Wortley et al. 2013). Hence, river restoration projects are being financed by governments and made a legal obligation in several countries (EU WFD 2000; Swiss Water Protection Act 814.20). As available funds for river restoration increased, the number of implemented restoration projects and literature published on this topic grew as well (Wortley et al. 2013). However, most scientific publications focus on the success evaluation of restoration projects rather than the restoration measures themselves (Palmer 2005; Suding 2011). This gap is closed by showing, with the example of Switzerland, how river restoration was performed and how restoration practice changed over time. Despite its small size, Switzerland offers a large spectrum of restoration experiences due to its topographical diversity. Over the course of the next 80 years, 40 million Swiss Francs or 44 million US Dollars are being allocated per year to restore 4’000 km of degraded rivers and their ecosystems (BAFU 2011). This article presents the geographical distribution of restoration projects in Switzerland and investigates spatial and temporal trends. Furthermore, information on implemented restoration measures, a comparison of Swiss and international restoration data, and project success is presented. The article concludes with recommendations for the international restoration practice and science.

2.2 Data acquisition and definition of terms

The term restoration, the expression most commonly utilized in literature (e.g. Amoros 2001; Bernhardt and Palmer 2011; Haase et al. 2013), is used to describe a variety of measures to enhance, improve or rehabilitate the structure and function of riparian and fluvial ecosystems (Roni et al. 2005; Roni and Beechie 2013). Thereby, each restoration project may involve several restoration measures, which either directly or indirectly rehabilitate the ecosystem. Thereby, *direct* measures specifically improve conditions for the ecosystem, e.g. by providing habitats, while *indirect* measures have a different objective, such as flood protection, which improve conditions for the ecosystem due to e.g. the reconnection of floodplains. Hence, measures, such as bioengineering or flood protection were included whenever they were implemented together with direct restoration measures.

In Switzerland, the cantonal authorities are responsible for the management of water bodies, and thus the planning of restoration projects. Hence, data sets were obtained from the cantonal offices or their web pages. In total, data from 848 restoration projects from 13 of the 26 cantons, recorded between 1979 and 2012 (Fig. 2.1) were investigated. Data sets contained information about the name of the river, the total restored length per river, the start and end time of the implementation of the restoration measures, the type and objective of the restoration measures, if and how success was evaluated and the results of this evaluation. Nonetheless, data sets were not exhaustive, as some cantonal offices only recorded projects of a specific size or after the year 2000; other projects did not contain information about the length or the date of the restoration, and some cantons only had data records until the year 2010. Hence, numbers represented are not absolute, but rather reflect the available data at this time.

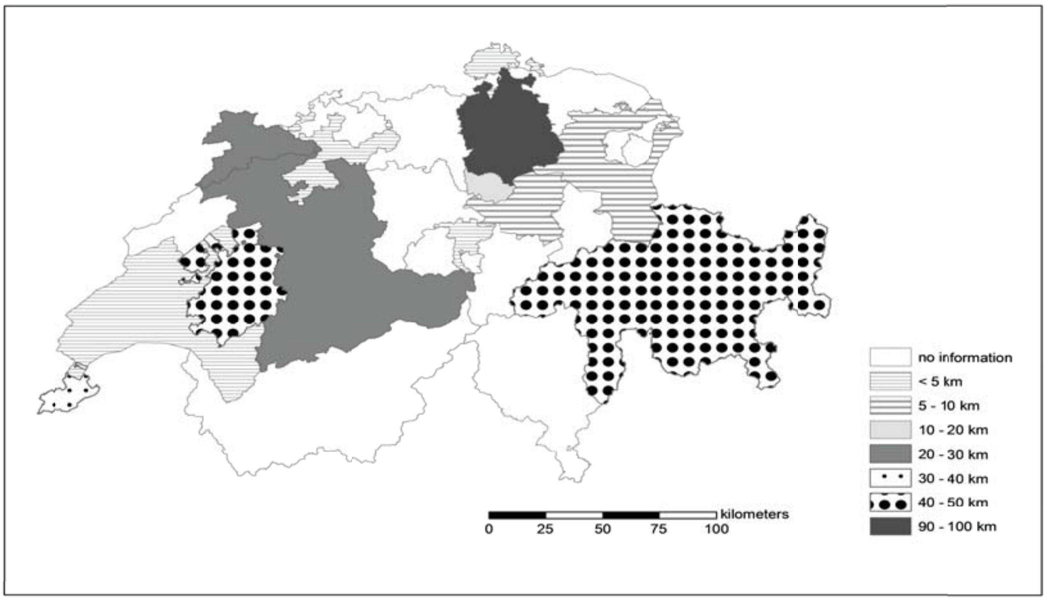

Figure 2.1. Geographical distribution of total restored length per canton between 1979 and 2012. Data from 13 of the 26 Swiss cantons are included (Berne, Fribourg, Geneva, Grisons, Jura, Nidwalden, Schaffhausen, Schwyz, Solothurn, St. Gall, Vaud, Zug and Zurich).

Additionally, data on the financial status and the level of urbanisation of the cantons was acquired in order to analyse spatio-temporal trends in river restoration (BFS 2009, 2012). Hereby, the financial status was represented by the gross domestic product of the year 2011 (GDP in Swiss Francs); the level of urbanisation by the population density of the year 2012 (inhabitants/ km^2; BFS 2009 – 2013). The following two hypotheses were tested: (1) cantons with a higher GDP might have had more funds to finance river restoration projects, and (2) urbanised cantons might have more rivers in a degraded state than rural cantons and therefore a higher need for river restoration.

2.3 Spatial trends in Swiss river restoration

In order to analyse spatial trends in river restoration, data on the total restored length per canton was combined with the geographical map of Switzerland (Fig. 2.1). Hereby, the investigated cantons span an area of 25’335 km^2 (61 % of the total area of Switzerland) and contain 37’699 km of rivers (62 % of the total Swiss river network).

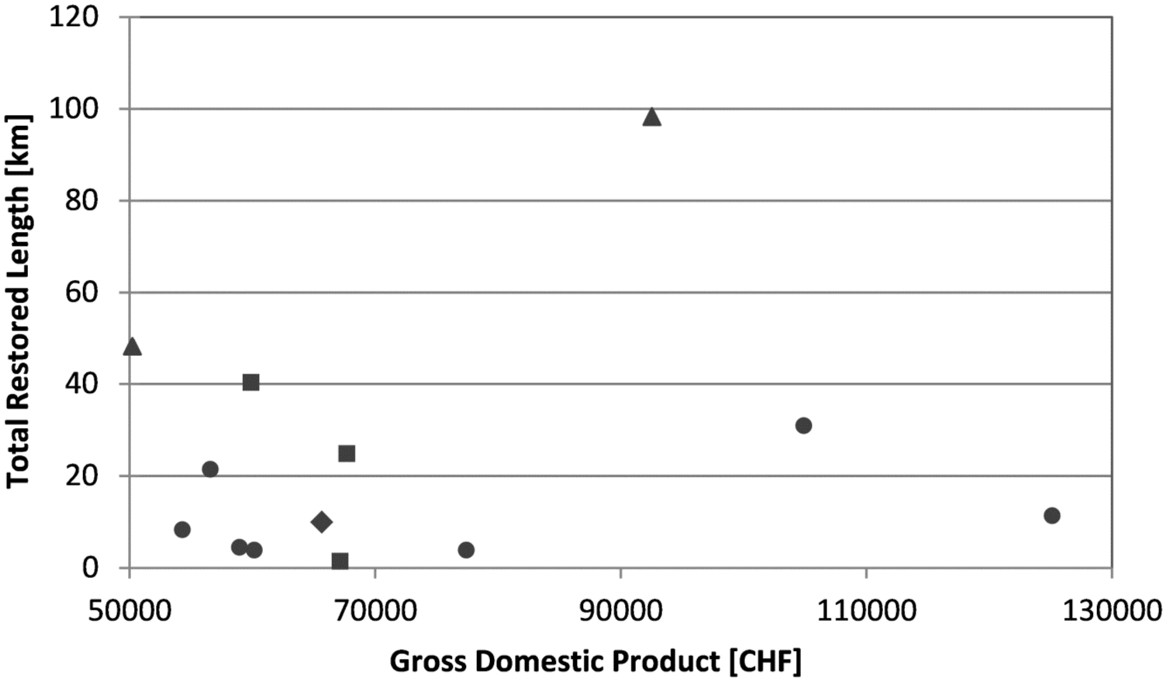

Figure 2.2. Relationship between the total restored length and the canton’s financial status (gross domestic product in Swiss francs). The symbols represent the sizes of the cantons involved: a circle symbolises cantons with a total area below 1000 km^2, a triangle cantons with 1000 – 2000 km^2, a diamond stands for areas of 2000 – 3000 km^2, and a square represents a cantonal area of more than 3000 km^2.

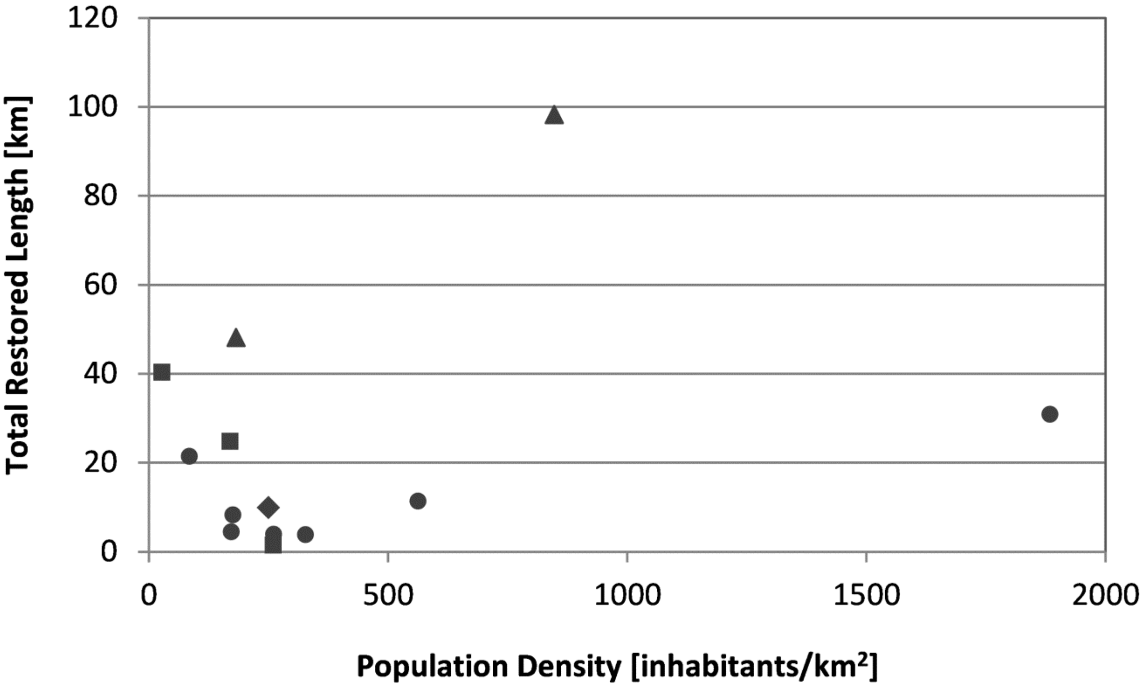

Figure 2.3. Relationship between the level of urbanisation, as determined by the population density of the cantons, and the total restored lengths. The symbols represent the sizes of the cantons involved: a circle symbolises cantons with a total area below 1000 km^2, a triangle cantons with 1000 – 2000 km^2, a diamond stands for areas of 2000 – 3000 km^2, and a square represents a cantonal area of more than 3000 km^2.

Of these, about 307 km were restored, ranging between total restored lengths of 1.5 km and 98 km per canton. However, due to gaps in data recording, these numbers might be significantly higher. As can be seen in Figure 2.1, there is no clear spatial trend, such as a higher total restored length for e.g. larger cantons. Hence, the relationship between the total restored length and the financial status of the cantons (Fig. 2.2) and their level of urbanisation (Fig. 2.3) was investigated. However, as can be seen in the charts, there is no such trend. Further investigations in land use and the political situation, i.e. election results, in the cantons showed no clear trend either (BFS 2009 – 2013, see Section 2.10).

2.4 Temporal trends in Swiss river restoration

Apart from the spatial trends in river restoration, the temporal trends were investigated, so as to determine whether the number or lengths of restoration projects increased over time. Figure 2.4 provides information about the time and length of implemented restoration projects for the

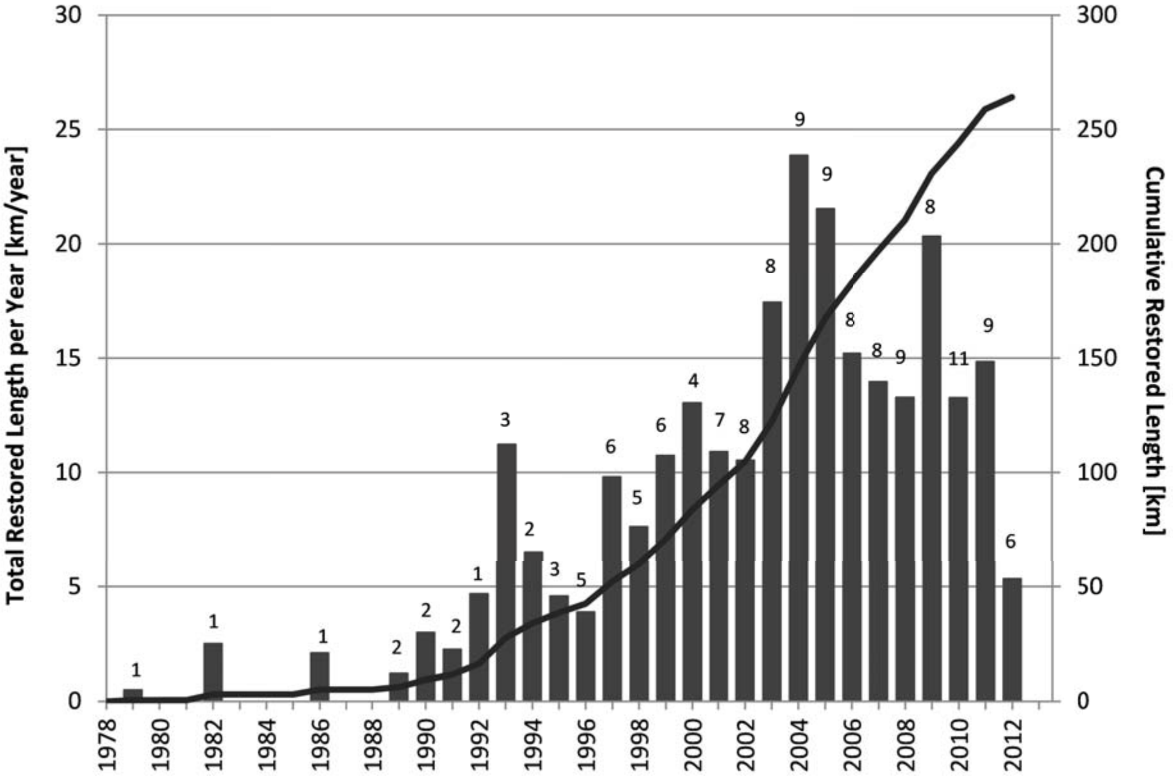

Figure 2.4. Primary axis: overview over the total restored length in Swiss water courses between 1979 and 2012 in [km/year]. The number of cantons involved is shown above each column. Secondary axis: increase of total restored length between 1979 and 2012 in [km]. Please note the different scales of the axes.

cantons, the increase in total restored length for all of the 13 cantons, and the number of cantons performing restoration projects per year.

As can be seen in Figure 2.4, the total restored length and the number of cantons implementing restoration projects increased steadily after 1992. The decrease in the total restored length in the year 2012 is due to several data sets ending in 2010. On a Swiss-wide basis, most restoration projects were being performed in the years 2004, 2005 and 2009. On a cantonal basis, however, most restoration projects were implemented after the year 1997, with maximum restoration activities varying for each canton: while some cantons, e.g. Grisons and Zurich, continuously performed and recorded river restoration projects since the 1990s, other cantons, such as St Gall and Solothurn only started recording them in recent years. According to Figure 2.4, the total restored length for 13 of the 26 Swiss cantons accumulates to 270 km, as only projects where date and length of restoration were known were included. The total cumulative restored length, i.e. the cumulative length including those projects in which the date of restoration was unknown, is close to 307 km, though, and would be even higher if data sets were conclusive. In 2011 it was decided to restore 4’000 km of the total 14’000 km of degraded streams (BAFU 2011) over the course of the next 80 years. This would require 50 km of river restoration per year in all of Switzerland. According to our data, restoration rates varied between 0.5 km in 1979 and 23.9 km in 2004, averaging to 9.8 km per year. Extrapolated to all of Switzerland, a restoration rate of 50 km per year therefore seems achievable, although challenging.

2.5 Implemented measures

The 848 investigated projects included a total of 1’661 restoration measures implemented between 1979 and 2012. Related restoration measures were separated into eleven categories (Table 2.1). Hereby, each category comprised a multitude of restoration measures. Those either directly or indirectly rehabilitated the ecosystem, e.g. by providing habitats or by stabilising a rivers’ embankment by planting endemic trees. Some restoration measures were purely mechanical, such as the widening of the river bed, while others enabled the river to rehabilitate itself, e.g. by removing stabilising side walls. Some restoration measures were implemented more frequently than others (Fig. 2.5).

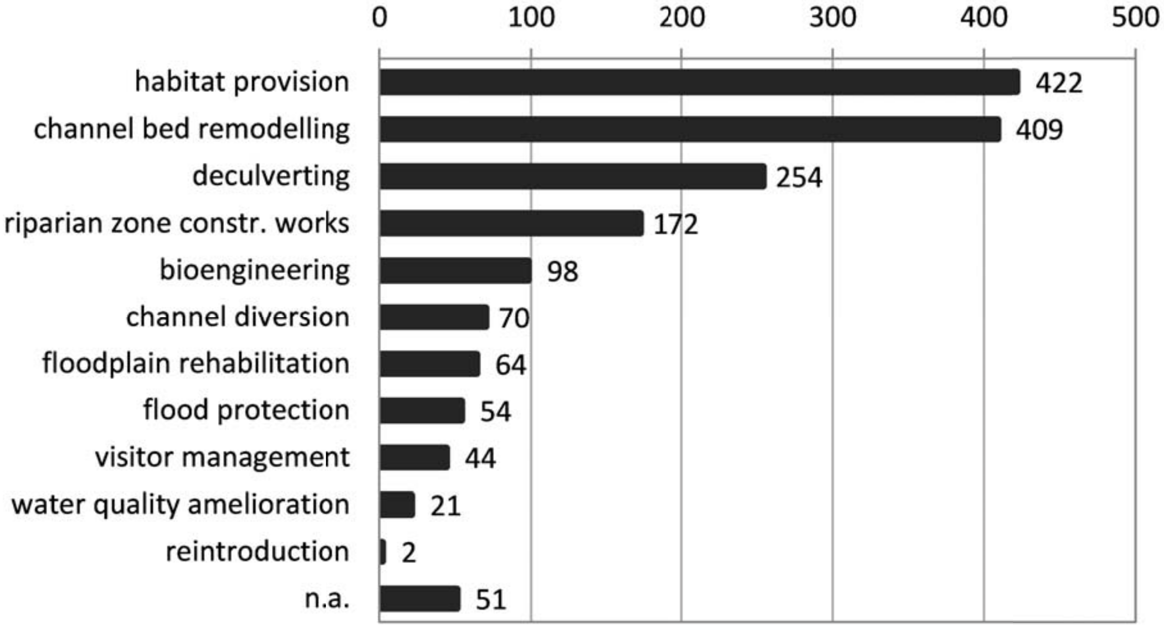

Figure 2.5. Categories of restoration measures implemented in Switzerland between 1979 and 2012. The labels indicate the number of restoration measures in the respective category.

Table 2.1. Restoration measures implemented in Switzerland between 1979 and 2012. A more detailed description of some of the restoration measures may be found in publications by Woolsey et al. (2005) and Zeh (2007).

category	objectives	measures
bioengineering	stabilisation of riparian structures (e.g. fascines); re-vegetation; enclosing of wildlife areas; diversification of the local flora; suppression of neophyte growth; creation of habitats; provision of shade	sowing/planting of endemic and site-specific plants (e.g. pioneer plants, reeds, sedges, shrubs, fruit and riparian trees (e.g. willow)); systematic clearing of trees; pruning of trees; pollarding of willows, poplars, etc.; sawing trees off above the root collar to stimulate stool sprouting; construction of fascines; installation of seeding mats on embankments
channel bed remodelling	bedload management: reduce or encourage channel bed erosion	recreate water course specific flow dynamics; removal or rebuilding of sediment traps and bedload collectors; deposition of eroded material; creation of areas for sedimentation; installation of nets over the sediment; installation of wood/stone weirs and spur dykes; construction of boulder ramps to reduce the flow energy of the water
	channel bed deepening: create a higher water column as habitat and thermal refuge for aquatic organisms	excavation of accumulated sediments; narrowing of the channel bed and increasing of channel slope to induce erosion
	removal of artificial barriers: re-establishment of longitudinal connectivity; recreate water course specific dynamics and structures; bedload management	removal of stone/concrete weirs and dams; re-establishment of fish migration (construction of block/ground/concrete ramps, vertical-slot passages, pool passes and bypass channels); installation of opening in weirs; installation of pools in front of barriers; adjusting the water level of incised channels
	removal of stabilising elements from the river bed: recreate a water course specific dynamic and structure; create habitats for flora and fauna; enable groundwater-surface water interactions	removal of stone blocks and concrete tiles from the channel bed
	structuring of the channel bed: recreate a water course specific dynamic and structure; create habitats for flora and fauna	placement of material (e.g. wooden pegs, deadwood, tree spurs, root stools, gravel, boulders); installation of spur dykes, wood/stone weirs; demolition of anthropogenic structures (e.g. walls, bridges, pumping stations); construction of coves, shore protuberances, gravel banks, stream islands, meanders, or fords; recreation of the original channel bed; reduction of the curvature of meanders
channel diversion	redirection of water courses away from roads; improvement of appearance; amelioration of recreational value	mechanical excavation of a new channel bed
deculverting	establishment of lateral, longitudinal and vertical connectivity; creation of habitats for flora and fauna	uncovering piped streams, combined with channel bed remodelling
floodplain rehabilitation	construction of new side channels: flood protection; creation of habitats for flora and fauna	construction of new channels, drainage trenches, canals and ditches
	reconnection of alluvial forests: flood protection; creation of habitats for flora and fauna	(re-)connecting of unconnected alluvial forests to the main river; opening and lowering of side dams; redirection of rivers into their former channel beds; re-establishment of water course specific dynamics
	rehabilitation of oxbow lakes and side channels: flood protection; creation of habitats for flora and fauna	reconnection of oxbow lakes to the main river; removal of accumulated sediments
flood protection	protecting anthropogenic structures from flood damage	removal or construction of concrete walls, dams or bank reinforcements; relocation of garden sheds, houses and foot paths too close to the water course; construction of retention and temporary storage reservoirs with or without permanent ponds; reconnection of flood plains;increasing the height of existing dams, walls, or weirs, foot paths, village squares, and arable land; construction of weirs to redirect storm water into wetlands and swamps; installation of overflow channels for storm water; construction of separate sewers for storm water and sewage

category	objectives	measures
habitat provision	creation and re-establishment of habitats for flora and fauna	fish: placement of dead wood, root stools, boulders, wooden barriers with hideouts and recesses, fascines and overhanging shores as shelters; varying of water depths; installation of recess zones for flood events; creation of spawning grounds and areas for juvenile fish, with still waters and lose gravel or sand crayfish: excavation of deep water zones and hideouts amphibians and reptiles: construction of pools, permanent and temporary ponds, water-filled ditches or biotopes reptiles: installation of sun terraces, screes, stone walls and dead wood stacks heliophytes: construction of sun terraces birds: installation of nesting sites and perches beavers: installation of hedge screens general: planting of trees, bushes, reeds and hydrophytes; installation and re-establishment of ponds and wetlands; construction of small bays, and of shores with varied inclination; re-establishment of grasslands
reintroduction	encourage and accelerate recolonisation of aquatic fauna	reintroduction of fish and other aquatic organisms
riparian zone construction works	structuring of stream banks: addition or removal of structures and plants as flood protection measure; increase lateral connectivity; creation of habitats for flora and fauna	stabilisation of shores and embankments: placement of boulders, dead wood and root stools; installation of rock-filled log cribwalls, fascines, and rock or wooden groynes; repair or construction of dams and concrete or stone walls; bioengineering methods (see above) removal of stabilising elements: removal of concrete blocks, stone or concrete walls and dams; reduction of size of dams modelling of terrain: lowering or elevation of embankments or reducing/increasing slope; introduction of sand or gravel; refilling of sediments
	local widening of channel bed: increase in flow capacity; flood protection; support development of natural channel structures and dynamics; reduce channel bed erosion; creation of habitats	removal of bank reinforcements, mechanical excavation of sediments
visitor management	encouraging or prohibiting public access: protecting nature; improving recreational value	repair, construction or relocation of foot paths or pedestrian bridges; planting of hedges or tree hedges; installation of fences, playgrounds and observation points, leisure and fishing areas, nature trails and benches
water quality amelioration	enhancement of surface water quality: reduction of harmful substances; improvement of overall health of ecosystem	prohibition of feeding water fowl; relocation of sewage ponds; treatment of agricultural wastewater; construction of washing bays for agricultural vehicles

Habitat provision, channel bed remodelling, and deculverting make up 65 % of all implemented measures, thus being significantly more popular than the remaining 8 categories. To a certain extend this is an artefact, as e.g. the category channel bed remodelling is less clearly defined than e.g. deculverting and hence allows for more sub-categories, leading to a higher number of restoration measures in this group. Some measures, namely from the categories bioengineering, visitor management and water quality amelioration, were exclusively implemented in western Switzerland, while others, such as channel bed remodelling, deculverting, habitat provision and riparian zone construction works, were implemented in nearly all of the investigated 13 cantons.

In order to determine whether specific combinations of restoration measures were particularly popular, the prevalence of all category combinations was analysed. This included the frequency of single categories as well, as most restoration projects implemented a large variety of restoration measures, but from only one category. The most common single categories were habitat provision, deculverting and channel bed remodelling. This was followed by the combination of the two categories channel diversion and deculverting; the prevalent combination of three categories was channel bed remodelling, habitat provision and riparian zone construction works. The four categories channel bed remodelling, flood protection, habitat provision and riparian zone construction works occurred only few times, as did the five-categories-combination bioengineering, channel bed remodelling, habitat provision, riparian zone construction works and visitor management. Combinations of six and more categories rarely occurred, usually combining measures to sustainably recreate a natural terrain while implementing flood protection measures. One or two-category combinations of interventions with a higher degree of mechanical interference, such as deculverting and mechanical recreation of the channel bed, were favoured over more sustainable combinations of three or more categories in which these high-interference measures were combined with measures to recreate a more natural setting and then protect the latter from human intervention. Generally, cantons in western Switzerland favoured the more sustainable combinations of restoration measures, while cantons in central and eastern Switzerland favoured single measures with a higher degree of mechanical interference, such as deculverting.

2.6 Brief description of selected restoration projects in Switzerland

Three water courses were selected to provide an overview over the bandwidth of restoration projects implemented in Switzerland: the Perrentengraben, a small brook in western Switzerland; the Rombach, a stream in south-eastern Switzerland; and the River Thur in north-eastern Switzerland. They were selected from three different categories of stream orders to illustrate the range of restoration projects from small brooks to large rivers in rural areas of perialpine and alpine Switzerland. Restoration projects in urban areas were omitted, in spite of their high number of occurrence, as they mainly focussed on the re-establishment of longitudinal connectivity by removing migration obstacles and the deculverting of previously covered brooks, which were already illustrated by the examples of the Rombach and the Perrentengraben. Further case studies of Swiss restoration projects may be found in Woolsey et al. (2005).

2.6.1 *Perrentengraben, Canton Fribourg*

The Perrentengraben is a small brook with a discharge ranging between 1 m^3/s and 10 m^3/s, situated in a rural area in western Switzerland. In 2001, 0.8 km of the brook were restored to create a more natural environment and support its biodiversity [1]. This river restoration was selected from the 848 projects, as it combined a large variety of restoration measures often found in Switzerland. After deculverting the brook, which improved longitudinal, lateral and vertical connectivity, the channel bed was restructured to enable a more natural flow dynamics and provide habitats and recesses for the local fauna. The banks were remodelled, and stabilised with stones and an indigenous flora. Apart from facilitating habitats for terrestrial animals, these measures also improved lateral connectivity and provided shade, an important factor in water temperature regulation. Furthermore, a retention basin was installed, providing further habitats and flood protection. A more challenging restoration measure was the amendment of the water quality, which was achieved by treating agricultural waste water prior to its discharge into the brook.

The restoration of the Perrentengraben combined various restoration measures from the categories bioengineering, channel bed remodelling, deculverting, flood protection, habitat provision, riparian zone construction works and water quality amelioration to a sustainable river restoration, which encouraged self-regulation of the brook. This river restoration was one of the few projects which acknowledged the importance of “outside” factors, such as water quality, to the successful restoration of an ecosystem.

2.6.2 *Rombach, Canton Grisons*

The Rombach is an alpine stream in south-eastern Switzerland. Its discharge ranges between 1 m^3/s and 23 m^3/s, with an annual mean of 3 m^3/s [2]. Between 1995 and 2010 various sections of the river were restored in order to improve conditions for fish and maintain flood protection [3]. Two restorations at Pizzöl (Fig. 2.6 a, b) and Fuldera (Fig. 2.7 a, b) were selected: the installation of a block pass to ease the migration of fish and the restoration of a 2 kilometre long stretch of a channelized section. The block pass was built in a section of the river, where erosion had formed a migration obstacle impassable for juvenile fish. The migration obstacle

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[1] http://www.maisondelariviere.org/index.php/fr/activites/recherche/projets-termines/projet-renaturadata/330-la-maison-de-la-riviere-activites-recherche-renatura-data-boiron-de-morges-passe-a-poissons-sous-la-route-suisse

[2] http://www.hydrodaten.admin.ch/de/2617.html

[3] http://map.geo.gr.ch/oberflaechengewaesser/oberflaechengewaesser.phtml

was overcome by the insertion of large blocks in the stream bed, which were installed in various depth to encourage the formation of pools along the block pass. By spreading the difference in height over a distance of 50 m even juvenile fish may swim upstream. Positive side effects of the block pass were the reduction of flow energy in the water, which reduced erosion and acted as additional flood protection measure. Furthermore, appearance was improved. This restoration project combined measures from the categories channel bed remodelling, flood protection, habitat provision and visitor management. It was selected, as this kind of restoration is very common in Switzerland.

The second project at the Rombach restored a 2 km-section of the stream. After draining the swampy area and channelizing the stream in 1945, biodiversity decreased dramatically. Hence, it was decided to reverse the negative effect of the drainage and channelization. Therefore, land was repurchased to enable a widening of the stream. Stabilizing elements were removed from the stream banks and the surrounding floodplains lowered to encourage a self-regulated development of a natural stream dynamics and in-stream structures. The insertion of dead wood further encouraged the development of a natural stream dynamics and provided aquatic habitats. Eroded sediment was reintroduced and a downstream sediment trap removed to enable a more natural bedload management. In place of the previous sediment trap habitats for amphibians were created. The reconnection of side arms created further habitats for fish and amphibians and provided crucial spawning grounds for both. Bioengineering methods, such as the installation of willow fascines or the planting of indigenous plants, were selected to stabilize the stream banks, thereby providing terrestrial habitats and shade for water temperature control. As these measures greatly improved the ecological potential of the Rombach, it is planned to reintroduce the stone loach, a fish previously extinct in this stream.

(a) (b)

Figure 2.6. Rombach at Pizzöl (a) before and (b) after restoration (© AJF Graubünden).

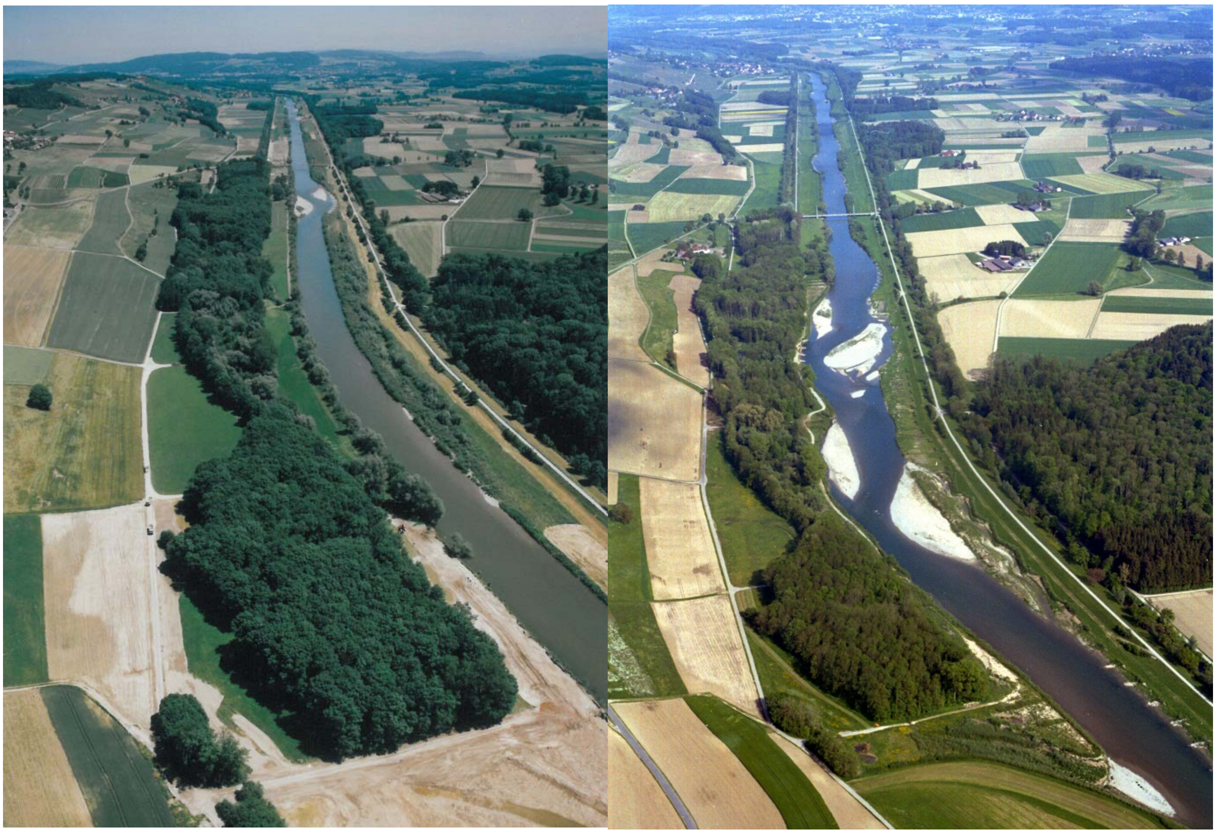
(a) (b)

Figure 2.7. Rombach at Fuldera (a) before restoration and (b) an animation of the planned outcome after restoration of the Rombach (© Pio Pitsch).

This restoration project combined measures from the categories bioengineering, channel bed remodelling, floodplain rehabilitation, flood protection, habitat provision, reintroduction, riparian zone construction works and visitor management to recreate a natural, self-regulated ecosystem. The Rombach restoration was selected as it is a good example for a very effective restoration in a rural, alpine region, in which the ecological conditions and appearance could be greatly improved.

2.6.3 *River Thur, Cantons Zurich and Thurgau*

The River Thur (Fig. 2.8 a, b) is a perialpine river in north-eastern Switzerland. It is the longest Swiss river without a retention basin, leading to a very dynamic discharge regime (Woolsey et al. 2007; Peter et al. 2012). Discharge ranges between 2.2 m^3/s and 1130 m^3/s, with a mean discharge of 47 m^3/s (Pasquale et al. 2011). Due to frequent flooding by the then meandering river, long sections of the River Thur were straightened and channelized in the



(a) (b)

Figure 2.8. River Thur (a) before and (b) after restoration (© BHAteam Frauenfeld).

1890s. However, flood protection was inadequate and several kilometres of the river were thus restored until 2002 (Schneider et al. 2011). This restoration project was selected, as it illustrates the constraints in restoration practice: conditions for the local ecosystem had to be improved without diminishing flood protection or endangering the water quality in river side pumping stations. To nevertheless achieve good ecological status, side dams were removed and the river widened in applicable areas, i.e. river sections without pumping stations or settlements nearby (Schneider et al. 2011).

These measures reconnected alluvial forests and increased the flow capacity of the river, both supporting sustainable flood protection, while at the same time stimulating a more natural flow dynamics and meandering structure, and providing habitats for the local flora and fauna. Further habitats were created by placing dead wood and root stools into the stream and by structuring of the channel bed, partially by reintroduction of eroded materials, which created gravel bars and in-stream islands. The latter were valuable habitats for pioneer plants and ground-breeding birds, such as the little ringed plover (Pasquale et al. 2011). The lowering and structuring of the river banks provided additional habitats and improved lateral connectivity. These measures were supported by a thorough information of the public, mainly with information boards or public events, to encourage a respectful interaction with the newly restored ecosystem, e.g. by respecting the acceptance of certain areas being out of bounds during breeding season.

The restoration of the River Thur combined measures from the categories channel bed remodelling, floodplain rehabilitation, flood protection, habitat provision, riparian zone construction works and visitor management. This restoration project indicates that even with major constraints river restoration can have positive effects on the environment.

2.7 Comparison of Swiss and international restoration practice

In order to draw comparisons between Swiss and international restoration practice, a thorough literature search was performed. Results for Asia, the Americas and Europe can be found in Tables 2.2.1 and Table 2.2.2. As can be seen, the restoration measures reported most often in international literature were channel bed remodelling, habitat provision, floodplain rehabilitation and bioengineering. However, these results do not necessarily represent the full spectrum of restoration measures implemented all over the world, as only a small proportion of restoration projects is being published in international literature. Nevertheless, it is interesting to see that Chinese literature mainly reported bioengineering as their favoured river restoration measure (Wang, Shi and Zhao 2014; Wu et al. 2013; Zhang et al. 2013), while in the Americas and Europe channel bed remodelling and habitat provision were reported most often (Amoros 2001; Buijse et al. 2002; Doll 2003; Filoso and Palmer 2011; Gilvear, Casas-Mulet and Spray 2010; Haase et al. 2013; Habersack and Piégay 2008; Henry, Amoros and Roset 2002; KCI Associates 2003; Kondolf, Podolak and Grantham 2012; Lorenz and Feld 2012; Louhi et al. 2011; Mendiondo 2008; Miller and Kochel 2013; Muhar et al. 2008; North Carolina Department of Transportation 1999; Richardson and Pahl 2005). Furthermore, all investigated European countries except one reported floodplain rehabilitation as implemented restoration measure (Amoros 2001; Buijse et al. 2002; Gilvear, Casas-Mulet and Spray 2010; Haase et al. 2013; Habersack and Piégay 2008; Henry, Amoros and Roset 2002; Lorenz and Feld 2012; Muhar et al. 2008; Pataki, Zsuffa and Hunyady 2013), while only one and two projects reported these restoration measures for China (Wang, Shi and Zhao 2014) and the Americas (Filoso and Palmer 2011; Richardson and Pahl 2005), respectively.

Table 2.2.1. Restoration measures reported in international literature between 2002 and 2014 in Asia and the Americas.

			restoration measure												
river	location	country	bioeng.	channel bed remodelling	channel diversion	decul-verting	floodplain rehab.	flood protection	habitat provision	reintro-duction	riparian zone constr.	visitor manag.	water quality amelioration	other	reference
Asia															
Liaohe River		China	X				X				X		X		Wang, Shi and Zhao, 2014
Liaohe River	Yinzhou district	China	X												Zhang et al., 2013
Nanfeihe River	Anhui province	China	X												Wu et al., 2013
Tarim River	Xinjiang Uyghur auton. region	China												discharge management	Zhang et al., 2013
Americas															
Tijuco Preto	São Carlos	Brazil	X	X					X		X			stakeholder engagement	Mendiondo, 2008
Howard's Branch	Anne Arundel County/Maryland	USA	X				X								Filoso and Palmer, 2011
Rocky Branch	North Carolina	USA	X	X					X			X	X		Doll, 2003. In: Sudduth et al., 2011
Sandy Creek	North Carolina	USA		X			X								Richardson and Pahl, 2005. In: Sudduth et al., 2011.
Spa Creek	Anne Arundel County/Maryland	USA	X	X					X		X				Filoso and Palmer, 2011
Selby Creek	California	USA		X											Kondolf, Podolak and Grantham, 2012
Third Fork Creek	North Carolina	USA	X	X					X		X				KCI Associates, 2003. In: Sudduth et al., 2011.
various	North Carolina	USA		X											Miller and Kochel, 2013
tributary to Walnut Creek	North Carolina	USA		X											North Carolina Department of Transportation, 1999. In: Sudduth et al., 2011.
Weems Creek/Bristol	Anne Arundel County/Maryland	USA		X					X						Filoso and Palmer, 2011

Table 2.2.2. Restoration measures reported in international literature between 2002 and 2014 in the Americas and Europe.

river	location	country	restoration measure												reference
			bioeng.	channel bed remodelling	channel diversion	decul-verting	floodplain rehab.	flood protection	habitat provision	reintro-duction	riparian zone constr.	visitor manag.	water quality amelioration	other	
Americas															
Weems Creek/Moreland	Anne Arundel County/Maryland	USA		X					X						Filoso and Palmer, 2011
Weems Creek/Mall	Anne Arundel County/Maryland	USA		X					X						Filoso and Palmer, 2011
Wilelinor Stream Valley	Anne Arundel County/Maryland	USA	X				X								Filoso and Palmer, 2011
Europe															
Upper Drau River	Carinthia	Austria		X			X		X		X				Muhar et al., 2008
various	alpine regions	Europe	X	X			X		X		X			increase minimum flow; raise groundwater level	Habersack and Piégay, 2008
various		Finland		X					X		X				Louhi et al., 2011
Upper Rhône	Brégnier-Cordon plain	France		X			X		X						Amoros, 2001; Henry, Amoros and Roset, 2002
various		Germany		X	X		X	X	X		X		X	extensification of landuse	Haase et al., 2013
various		Germany		X			X		X		X				Lorenz and Feld, 2012
Danube	Báta oxbow	Hungary					X								Pataki, Zsuffa and Hunyady, 2013
Lower Rhine	Beneden Leeuwen	Netherlands					X		X						Buijse et al., 2002
Lower Rhine	Gameren	Netherlands					X		X						Buijse et al., 2002
Lower Rhine	Opijnen	Netherlands					X		X						Buijse et al., 2002
various	Scotland	UK	X	X			X	X	X	X	X	X	X	stakeholder engagement; non-native animal species removal and monitoring	Gilvear, Casas-Mulet and Spray, 2010

In Switzerland, only a minor proportion of restoration projects implemented floodplain rehabilitation as restoration measure. However, in Switzerland the majority of restoration projects were small-scale projects, while international literature may only report large-scale river restorations. Therefore, if merely restoration projects of similar dimensions were compared, the restoration measures preferred in Switzerland might actually be very similar to those reported in international literature. Unfortunately, project dimensions were rarely reported in the investigated articles and therefore it is difficult to compare Swiss and international restoration practice.

2.8 Success evaluation

Data regarding success evaluations were available for 232 of the 848 restoration projects. Of these, 77 projects evaluated the success of their project, of which 76 were regarded successful; 37 projects were planning to evaluate success at some point in the future; for 15 projects a success evaluation was regarded unnecessary, while 103 projects did not perform or plan success evaluations.

Those projects performing success evaluations employed a multitude of methods: from the more comprehensive characterisation of ecological and ecomorphological conditions, to the monitoring of discharge, vegetation and population growth of amphibians, crayfish, fish and macrozoobenthos, to the investigation of public acceptance and cost control. The majority of success evaluations, though, investigated the effects on fish, particularly salmonids, by counting the number of fish swimming through a fish pass, or by monitoring their spawning and the development of their juveniles. Each project had its specific aim and hence evaluated their success in a different way, which makes it difficult to compare their results with each other and with the international literature. In Switzerland, river restoration would be successful if the natural functioning of the river was re-established (Swiss Water Protection Act 814.20). Most of the investigated projects, however, only improved specific aspects of the rivers natural functioning. This leads to a major issue in success evaluations, which is reflected in the international literature as well: the outcome of the success evaluation of a project largely depends on how success was defined in the first place (Higgs 1997; Wortley et al. 2013). As all of the 232 investigated projects had different definitions of success, it is difficult to state whether these restorations were indeed successful or not.

2.9 Conclusions

In Switzerland more than 307 km of degraded rivers have been restored since 1979, with the number of restoration projects increasing steadily over the course of time. While there was no clear correlation between the total restored lengths and the size of the cantons, their population density or financial status, there was a geographical trend in the types of restoration measures being implemented. It is difficult to come to a definite conclusion regarding the success of the restoration projects, as there was not enough data available and completed success evaluations only tested specific aspects, such as the migration of fish, rather than improvements for the whole ecosystem. However, this did indicate that project planning might not have had a three-dimensional approach to restoration, as only aspects, such as the migration of fish, were considered rather than the rehabilitation of lateral, longitudinal and vertical connectivity. Furthermore, water quality ameliorations, which would have a profound effect on the ecosystem, were rarely considered. Based on our findings, it is therefore recommendable to making success evaluations a legal obligation, thereby clearly defining how to evaluate success and what would be considered a successful restoration, with respect to the environment, but also society and economy. This would include the performance of detailed predefined investigations of a river prior to its restoration to clearly define the issues and identify potential causes for these issues, to define restoration goals based on these findings, and to re-investigate the water course after restoration following a regulated predefined code of practice. These actions are crucial to allow learning from past experiences so that future projects will have maximum benefit with minimum expenses. Restoration efforts clearly are a step in the right direction, but further efforts are required to identify the issues leading to ecosystem degradation and establish best practices for the restoration of these degraded ecosystems. To achieve these goals, it is crucial to perform comparable success evaluations in all restoration projects and to publish these results in freely accessible online data banks. In general, the results of our investigation were encouraging, demonstrating that over the last 30 years river restoration has evolved from a disputed rarity to an accepted practice, leading to a further 4’000 km of degraded rivers being restored over the course of the next 80 years.

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2.10 Supporting information

Data correlating the land use and political situation as represented by the results of the parliamentary elections in 2011 with the total restored length was mentioned, but not included in the publication. The data was investigated to test the hypothesis that (i) cantons with a higher degree of urbanisation might have a higher number of artificial and covered streams, due to urban development, and (ii) that cantons with a preference of left-wing parties might be more open to implementing river restoration projects. However, data from the Federal Agency for Statistics (BFS) listed in Table 2.3 does not indicate such a correlation (Fig. 2.9).

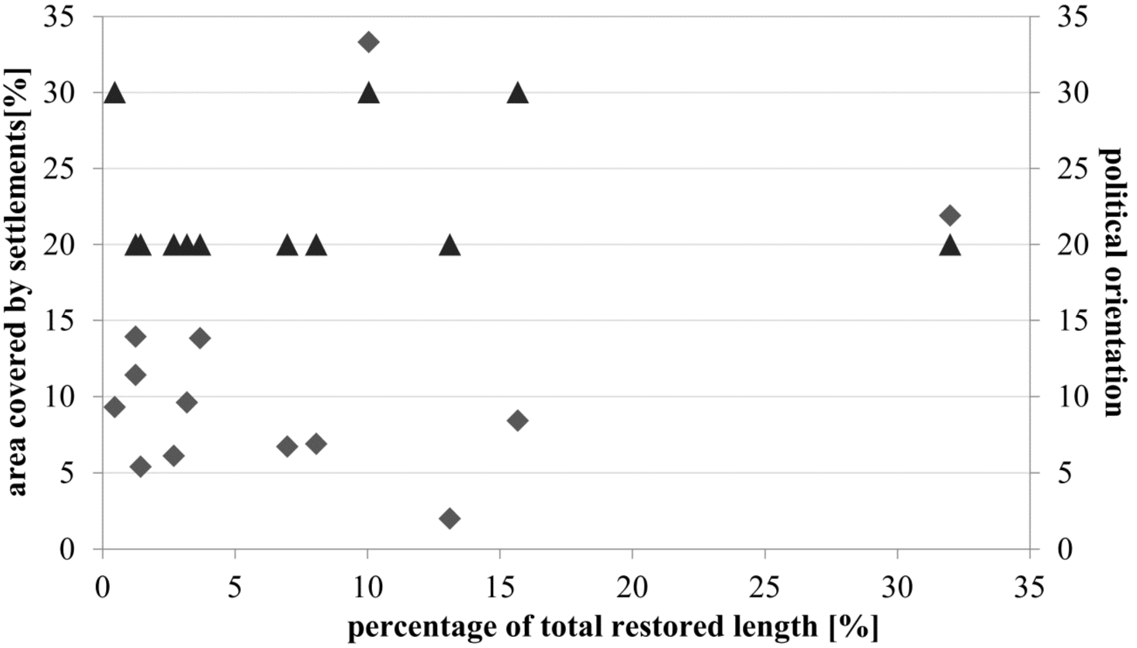

Figure 2.9. Primary axis (diamonds): relationship between the area covered by settlements and the percentage of the total restored length. Secondary axis (triangles): relationship between the political orientation and the total restored length. Hereby, the conservative parties have the value 20, the socialist parties the value 30. These values were chosen for ease of viewing.

Table 2.3 Statistical data regarding political situation, as represented by the result of the parliamentary election 2011, and the land use in the investigated cantons (BFS 2009 - 2013).

canton	restored length [km]	percentage of total restored length (2012) [%]	majority of votes in parlamentary elections (2011)	land use [%] (2004-2009)			
				settlements	agriculture	forests	unused area
Berne	24.80	8.08	conservatives (SVP)	6.9	42.6	31.3	19.2
Fribourg	48.15	15.69	socialists (SPS)	8.4	56.3	26.9	8.4
Geneva	30.91	10.07	socialists (SPS)	33.3	39.7	12.4	14.9
Grisons	40.30	13.13	conservatives (SVP)	2	28.8	27.6	41.6
Jura	21.45	6.99	conservatives (CVP)	6.7	48.8	43.5	1.1
Nidwalden	4.47	1.45	conservatives (SVP)	5.4	36.9	33.3	24.3
Schaffhausen	3.87	1.26	conservatives (SVP)	11.4	43.9	43.2	1.3
Schwyz	8.30	2.70	conservatives (SVP)	6.1	40.5	33.7	19.6
Solothurn	3.86	1.26	conservatives (SVP)	13.9	42.3	42.8	1.1
St Gall	9.82	3.20	conservatives (SVP)	9.6	46.6	30.6	13.2
Vaud	1.46	0.47	socialists (SPS)	9.3	42.4	32.1	16.1
Zug	11.36	3.70	conservatives (SVP)	13.8	43.6	27.2	15.5
Zurich	98.26	32.01	conservatives (SVP)	21.9	41.6	30.4	6.1

Chapter 3

Autonomous Distributed Temperature Sensing for long-term heated applications in remote areas

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Abstract

Distributed Temperature Sensing (DTS) is a fiber-optical method enabling simultaneous temperature measurements over long distances. Electrical resistance heating of the metallic components of the fiber-optic cable provides information on the thermal characteristics of the cable's environment, providing valuable insight into processes occurring in the surrounding medium, such as groundwater-surface water interactions, dam stability or soil moisture. Until now, heated applications required direct handling of the DTS instrument by a researcher, rendering long-term investigations in remote areas impractical due to the often difficult and time-consuming access to the field site. Remote-control and automation of the DTS instrument and heating processes, however, resolve the issue with difficult access. The data can also be remotely accessed and stored on a central database. The power supply can be grid-independent, although significant infrastructure investment is required here due to high power consumption during heated applications. Solar energy must be sufficient even in worst case scenarios, e.g. during long periods of intense cloud cover, to prevent system failure due to energy shortage. In combination with storage batteries and a low heating frequency, e.g. once per day or once per week (depending on the season and the solar radiation on site), issues of high power consumption may be resolved. Safety regulations dictate adequate shielding and ground-fault protection, to safeguard animals and humans from electricity and laser sources. In this paper the autonomous DTS system is presented to allow research with heated applications of DTS in remote areas for long-term investigations of temperature distributions in the environment.

3.1 Introduction

Temperature measurements have been recognized to be a powerful tool in natural sciences (Leap 2006; Schneider 1962). They may be employed to investigate hydrologic systems (Selker et al. 2006a), stream dynamics (Selker et al. 2006b), groundwater-surface water interactions (Slater et al. 2010), atmospheric processes (Keller et al. 2011; Thomas et al. 2012) or soil moisture (Sayde et al. 2010; Steele-Dunne et al. 2010; Striegl and Loheide II 2012). Fiber optic temperature measurements may also be used in engineering, e.g. for the detection of illicit sewage connections (Hoes et al. 2009), hot spot identification in power cables (Yilmaz and Karlik 2006) or the investigation of dam stability (Wang et al. 2010).

There are several ways to investigate temperature distribution patterns, the most common being locally logged temperature probes (Anderson 2005; Schmidt et al. 2006; Gardner et al. 2011). While these devices provide accurate point measurements of temperature, they have several disadvantages when utilized in the monitoring of extended areas, i.e. when more than 10 data loggers are in use: (i) data collection is very time consuming, as each data logger has to be manually retrieved, (ii) each data logger provides one individual data set, leading to a multitude of records, and (iii) data handling is relatively time consuming as data sets have to be combined prior to data analysis; (iv) sensor calibration is only possible at the start and end of installations, thus mid-installation data are subject to possible sensor drift. Additionally, the acquisition of large numbers of data loggers is quite costly.

Alternatively, Distributed Temperature Sensing (DTS) measures temperature along a fiber-optic cable, thereby allowing (i) the simultaneous collection of distributed temperature data, (ii) over long distances, with (iii) a temperature resolution of ±0.01 °C under ideal conditions (e.g., Selker et al. 2006a).

DTS is a fiber-optical method for temperature determination along a fiber-optic cable connected to a DTS instrument. The fiber-optic cables utilized in environmental applications usually consist of one or several protected glass fibers. The required protection depends greatly on the environment of installation; however when crushing risks are present this often includes metal armoring, and almost always an outer protective plastic sheath for protection against water, corrosion, and for electrical isolation. The DTS instrument`s main components are (i) a laser and (ii) a detector. During a temperature measurement a laser pulse is sent into the fiber-optic cable; the photons of the laser pulse are backscattered within the glass fiber and analyzed (i) for their energy and (ii) time of arrival. The energy of the photons indicates their backscatter history: no loss of energy indicates elastic backscattering of the photons, whereas loss or gain in energy indicates inelastic backscattering (Smith et al. 2007). In Raman DTS temperature measurements the ratio of the number of inelastically backscattered photons with energy above and below the injected light wavelength is applied to calculate the temperature of the fiber-optic cable, as the backscatter intensity largely depends on the vibrational level of the interacting molecule (Smith et al. 2007) and therefore on the temperature of the silica glass in the glass fiber of the fiber-optic cable. The DTS therefore measures the temperature of the surroundings by determining the temperature of the glass fiber. Here it is assumed that the fiber-optic cable is in thermal equilibrium with the surrounding medium. The resolution of the time of arrival of the photons by the detector allows the allocation of the measured temperature to a specific section of the fiber-optic cable. Temperature measurements with the DTS are spatial averages rather than point measurements, as the temperature reported at point x is actually the integration of all photons being backscattered in the section of cable about the point x within a distance defined as the instrument resolution. Currently available commercial Raman-based DTS systems have resolutions of between 0.3 m and 4.0 m. Nonetheless, the temperature distribution along the whole length of the fiber-optic cable can be determined in a single measurement, thereby replacing a large number of data loggers. This shows the practicality of DTS for temperature monitoring over long distances and thus large areas.

DTS is most often employed in passive mode, i.e. the unaltered ambient temperature is determined along the fiber-optic cable. The DTS may also be used in an active mode, in which the response to injection of heat is studied, for instance following thermal resistance heating of the metal armor surrounding the fiber-optic cable. This provides additional information, not only on (i) the background temperature of the fiber-optic cable prior to its heating, but on (ii) its heating and cooling behavior, which again reflects the conditions in the environment of the fiber-optic cable. So far, this technique has been used to investigate dam stability (Etzer et al., 2012), soil moisture (Sayde et al. 2010), and hyporheic zone processes (article in preparation).

The heating of the fiber-optic cable usually has to be directly handled by an operator, rendering it impractical for long-term measurements, particularly in remote areas. In remote settings, e.g. mountainous regions, which might be difficult to access and without power infrastructure, long-term active, heated DTS applications have previously been difficult to implement due to the time consuming data collection. However, as seen in the previous paragraph, there are numerous applications for active DTS in these areas, particularly in the environmental sciences and engineering. An autonomous DTS system, i.e. a DTS system for heated applications that is independent of the physical presence of an operator, is therefore required to enable research in scientifically interesting remote areas. One such application will be the investigation of the effect of river restoration on hyporheic exchange in Swiss rivers and streams.

The autonomous DTS system proposed here consists of various components that enable remote access to the DTS, collection of the temperature data and control of the heating of the fiber-optic cable. These components are (i) a computer, (ii) a control box for the automated heating of the fiber-optic cable, and (iii) a remote connection, such as a 3G modem or wireless connection. Another, optional, feature is a grid-independent power supply, such as solar panels or wind generators. However, there are several issues with the development of an autonomous DTS system depending on the DTS type and measurement location: (a) the remote control of the DTS has to be compatible with the DTS instrument and the heating control box, safe and stable, and available in undeveloped or remote areas without internet or mobile phone connection; (b) the power consumption of the heating of the fiber-optic cable can be high, depending on the material and the length of the fiber-optic cable, which are difficult to provide with grid-independent power supplies; (c) the high voltage of the heating might be dangerous to humans and animals, particularly rodents; and (d) the power connections to the fiber-optic cable have to be safe, i.e. the fiber-optic cable has to be of a specific type to enable standard electrical connections.

This paper provides guidance on how to upgrade a standard DTS to an autonomous DTS system, enabling long-term passive and active heated DTS temperature measurements in remote areas without a direct operator.

3.2 Instrumental Set-Up

3.2.1 *System Components*

The autonomous DTS system consists of various building blocks: (i) the passive DTS set-up, (ii) components for the active, heated, employment of the DTS, and (iii) the control/communication components. The separate components for each of the aforementioned three building blocks will be described in more detail in the subsections below.

3.2.1.1 *Passive DTS components*

The basic components required for the passive employment of the DTS instrument are (i) the DTS instrument, (ii) a computer for data storage and DTS operation, (iii) a fiber-optic cable, and (iv) temperature controlled enclosures for reference temperature measurements (“water baths”), required for the calibration of the DTS instrument.

The DTS instrument and the fiber-optic cable are the two most important components of any autonomous DTS system. Prior to purchase of a DTS instrument there are a number of things to be considered: (i) the type and (ii) location of the experiment, (iii) the data resolution, particularly with regard to spatial, temporal and temperature resolution, and (iv) the data format. The type and location of the experiment define the demand on the DTS instrument, such as long-term or short-term, indoor or outdoor experiments, high or low temperatures, dry or humid climates, corrosive environments, occurrence of rock slides or avalanches, and other conditions that might damage the instrument. Several manufacturers offer instruments for temperature ranges of -40 °C to +65 °C and provide steel enclosures for the instruments, to allow for installation without further environmental protection. The DTS instruments differ in many important regards, amongst others, in (i) the intensity and pulse-length of the laser, (ii) the sensitivity, signal-to-noise, and temporal resolution of the detector system, (iii) the wavelength of the laser, and (iv) the data storage capabilities and interpretation software. Hence, the temperature and spatial resolution, as well as the signal to noise ratio, and therefore the data quality, of the various DTS instruments differ considerably (e.g., each by over a factor of 10) and have to be carefully evaluated prior to purchase of the DTS instrument.

For DTS systems without built-in computer control and data storage, there are a number of suitable computers to choose from, ranging from small PCs to notebooks, the choice depending on the requirements of the experimental set-up. However, the main point to consider is power consumption and performance reliability, as well as ruggedness, particularly with regard to climatic conditions. As the data acquisition is hardware-based, the computational capabilities of the PC are never limiting. A key consideration is how the computer responds to a power outage. In remote applications the ability to program the computer to autonomously reboot to a fully functioning data collection state is essential. In order to connect to the network, either a mobile network modem (GPRS/3G/UMTS/LTE) or a Wi-Fi card is required according to the scenario. We have found many integrated options for this, but a USB solution is also possible.

3.2.1.2 *Cable Considerations*

As mentioned above, the fiber-optic cable is one of the most important components of any autonomous DTS system. It has to be responsive enough to rapidly resolve minute changes in temperature yet strong enough to withstand tensile stress and strain, crushing and bending, as well as solar radiation and environmental stresses, such as corrosive fluids or extreme temperatures. Additionally, for active deployments the fiber-optic cable must have metal components to enable thermal resistance heating via application of electrical currents. The voltage may be applied either across the steel armor or across supplementary copper wires (Freifeld et al. 2008; Sayde et al. 2010). Heating of the fiber-optic cable via the steel armor is suitable for short fiber-optic cable sections up to 250m, whereas heating via copper wires is suitable for longer fiber-optic cable sections. The copper wires may be either (i) directly integrated in the steel armor or (ii) wound separately around the central glass fiber core. The first type of fiber-optic cable is highly stress and crush resistant, but more difficult to electronically connect to the power source, while the second type of fiber-optic cable can be easily and safely connected like any other electrical cable, but may be prone to microbending issues due to the copper wires pressing on the central glass fiber core, particularly when buried in coarse sediment (unpublished data).

In general, the temperature change in the fiber-optic cable largely depends on the material and the length of its metal armor. It may be estimated by calculating the electrical resistance R (Eq. 3.1) and, with Joule’s heating law, the power P (Eq. 3.1) applied to the metal armor of the fiber-optic cable in dependence of the power source:

$$(3.1) \qquad R \quad = \quad \rho \frac{l}{A}$$

Thereby, R is the electrical resistance in Ohm [Ω], ρ the electrical resistivity in [Ωm], l the length of the conducting medium in [m], and A the cross sectional area of the conducting medium in [m^2] (Griffiths 2008). The electrical resistivity ρ of austenitic stainless steel is 8.11 x 10^{-7} Ωm at 26.85°C (Hust and Giarratano 1975); copper has a ρ of 1.68 x 10^{-8} Ωm at 20 °C (Griffiths 2008). The power delivered by a heating system is given by

$$(3.2) \quad P = \frac{V^2}{R}$$

where P is the power in Watts [W] and V is the voltage in Volt [V].

Given these formulas it is possible to calculate the power applied to the conducting medium as a function of the cable design and operating conditions and therefore get an estimate of the thermal energy delivery to the armor of the fiber-optic cable.

The application of these relationships can be seen by considering several typical scenarios: (i) a cable length of 50 m, with a diameter of 1 mm^2 of copper strands, a ρ of 1.68 x 10^{-8} Ωm and a voltage of 230 V; (ii) the same scenario, but with a voltage of 24 V; (iii) and (iv) the same scenarios, but with a cable length of 500 m; (v) to (viii) as in scenarios (i) to (iv), but with an austenitic stainless steel armor instead of copper wires. The results are shown in Table 3.1.

Table 3.1. Examples of Heating Parameters[a]

Scenario	Cable Length (m)	Voltage (V)	Electrical Resistance[b] (Ω)	Power (W)	Power/m[c] (W/m)
			Armor Material Copper[d]		
(i)	50	230	8.4	62976	(1259.5)
(ii)	50	24	8.4	686	13.7
(iii)	500	230	84	6298	12.6
(iv)	500	24	84	69	(0.1)
			Armor Material Stainless Steel[e]		
(v)	50	230	405.5	1305	26.1
(vi)	50	24	405.5	14	(0.28)
(vii)	500	230	4055	130	(0.26)
(viii)	500	24	4055	1	(0.003)

[a] Heating parameters describing heating efficiency of the metal armor in fiber-optic cables: electrical resistance ρ, and power P.

[b] cross sectional area A of the conducting material is 10^{-6} m^2

[c] power/m should be 100W/m > power/m > 0.5W/m; values above and below these thresholds are too high or low for thermal resistance heating, respectively.

[d] electrical resistivity of copper ρ_{Cu} 1.68 x 10^{-8} Ωm at 20 °C (in: Griffiths 2008)

[e] electrical resistivity of 20 % nickel/16 % chromium austenitic stainless steel ρ_{ss} 8.11 x 10^{-7} Ωm at 26.85 °C (in: Hust and Giarratano 1975)

In summary we see that heat delivery, per meter, increases with the square of applied voltage, and decreases with the square of cable length (since total power delivered increases linearly, as does the number of meters over which that energy is divided). Thus short fiber-optic cables with a copper armor can be heated at low voltage, and long cables with a stainless steel armor require high voltage. Tests at the River Thur in Switzerland have shown that a 1500 m copper strand with a total cross-section of 0.85 mm^2 wrapped around a 250 m long fiber-optic cable reached a maximum change in temperature of around 2 Kelvin (K) in flowing water of 15.5 °C to 18.0 °C when heated for 15 minutes at 230 V. However, this degree of heating would differ according to the diameter of the fiber-optic cable and the thermal heat capacity of the cable and surrounding material, and if flowing water was present. Hence, pre-tests regarding the heating behavior must be performed prior to the field installation to evaluate the heating behavior in the surrounding medium, e.g. water, soil, gravel etc. In general, the fiber-optic cable should not be kept in loops or on cable drums during heated applications, as this might cause overheating of the metal armor of the cable, leading to cable damage and potentially cable fires. In order to evade this risk only small sections of the fiber-optic cable may be heated. This would exclude sections particularly vulnerable to heating, such as cable sections kept on a cable drum or in tight loops. For safety reasons, an autonomous DTS system should have an alarm that automatically switches off the power, and thereby stops heating of the fiber-optic cable, when temperatures reach a critical level, e.g. the 85 °C which outdoor cables typically resist whilst in continuous operation.

3.2.1.3 *DTS Calibration Reference Baths*

The DTS has to be carefully calibrated in order to acquire reliable temperature data (e.g. Hausner et al. 2011; van de Giesen et al. 2012). The instrument is calibrated prior to the measurement, but always requires post-measurement re-calibration to obtain the highest precision data. In both cases well-mixed insulated water baths are required as reference sections in which the temperature of the fiber-optic cable can be assumed to be constant over the period of calibration data collection (typically <15 minutes). One calibration bath can be constructed from wetted ice, though care must be taken that the ice fully envelopes the test section, as otherwise the average temperature cannot be guaranteed to be 0°C. As it is impossible to install and maintain an ice bath in a remote setting, two continuously mixed water baths at different temperatures may be used instead, e.g. one water bath may be filled with river water, the other water bath may be filled with river water and a small heating device such as used in fish ponds to prevent freezing over in winter. Reference baths must be equipped with additional temperature probes, so that the actual water temperature is known and can be used to calibrate the temperature of the fiber-optic cable section in the respective water baths. Some DTS systems are provided with external temperature probes, however these are not considered to be as precise or reliable as required for such applications. It is advisable to use two water baths at each end of the fiber-optic cable, warmer and colder than the monitored temperatures, so as to avoid error in temperature measurements due to a decrease in signal quality as caused by increasing loss of light over the whole length of the fiber-optic cable. General guidance on instrument calibration is given by Hausner et al. (2011) for single-ended installations and van de Giesen et al. (2012) for double-ended installations.

3.2.1.4 *Active DTS Components*

The two components required for an active employment of the DTS instrument in an autonomous system are (i) a control box for the automated heating of the fiber-optic cable, and (ii) a grid-independent power supply.

The main features of the control box are (i) a time switch (here in form of a relay board and a relay) that automatically controls the electrical current, and thus the heating of the fiber-optic cable, and (ii) a digital multimeter to record the actual current flowing through the metal armor of the fiber-optic cable, so as to be able to correlate heating behavior and voltage applied. Both time switch and digital multimeter are controlled via the PC. Another important feature of the control box is a ground-fault circuit interrupter, also known as residual-current device, which switches off the current in case there is a difference in current between the energized conductor and the return neutral conductor, e.g. caused by a person accidentally touching the energized part of the conductor. In the control box the ground-fault circuit interrupter has to be placed between the relay and the metal armor of the fiber-optic cable (Fig. 3.1). A potential issue with the ground-fault circuit interrupter is the leakage of electricity through the fiber-optic cable’s insulation, which might cause the ground-fault circuit interrupter to trip. Although an increase in the tripping current would prevent tripping of the ground-fault circuit interrupter, it would also increase the risk of harmful electrical shocks. Therefore, individual solutions have to be found to trade between security and scientific aim. Additionally, fuses have to be installed to protect the equipment from

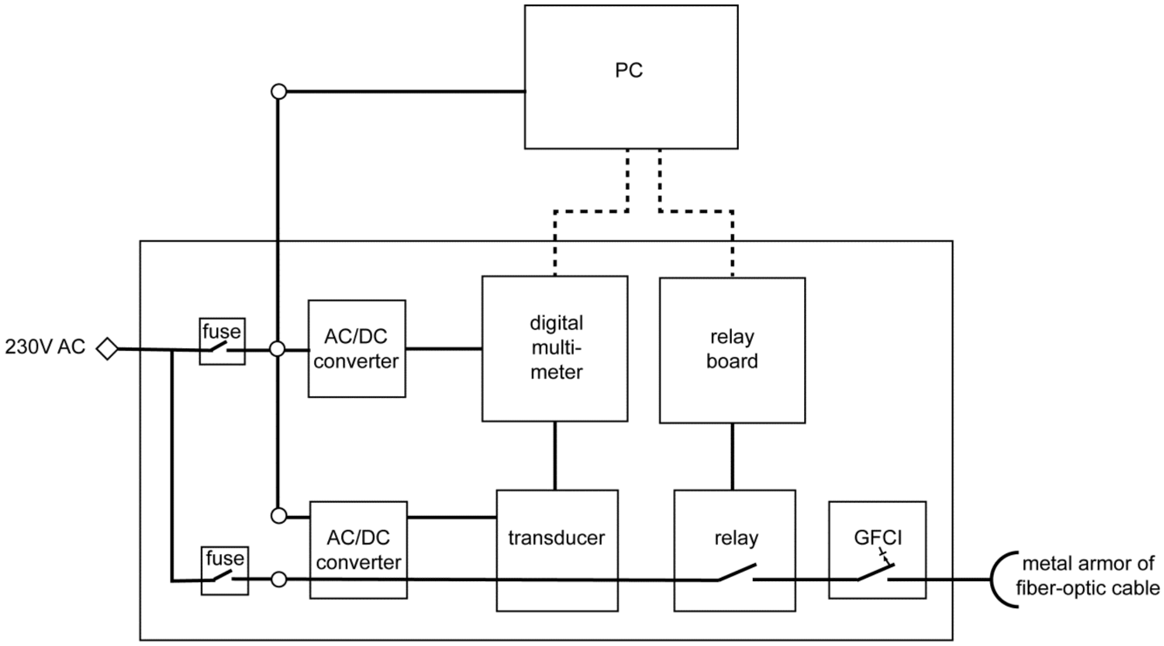

Figure 3.1. Schematic diagram of the heating control for automated heating of a fiber-optic cable in the autonomous DTS system. Bold lines represent power connections, dashed lines are data connections with the PC; the box marked GFCI represents the ground-fault circuit interrupter.

overcurrent or short-circuit conditions. The other features in the control box are AC/DC converters altering the provided voltage into the voltage required by the consumer loads; a transducer converting the current into a voltage to enable the digital multimeter to read the actual current flown through the metal armor of the fiber-optic cable; a relay board enabling the switching function of the PC; and a relay to actually switch the current on and off. Please note that the system is shown for a 230V power supply. In the case where a grid-independent power supply is used with a lower voltage, power converters have to be installed.

Powering the autonomous DTS system in remote areas may well be an issue, as power lines might not run in close vicinity or might not be accessible. Hence, the autonomous DTS system should be powered by grid-independent power supplies, such as solar panels or wind and water turbines. As mentioned in the previous section, ground-fault circuit interrupters have to be placed in between the power source, e.g. the battery of the solar panels, and the consumer loads, e.g. the control box, the DTS or the PC, to prevent accidental electrocution.

The energy demand for the heated cable method presents a critical challenge for remote off-grid powered operations. Typical heating rates for DTS methods were between 3 W m^{-1} and 20.5 W m^{-1} (Striegl and Loheide II 2012; Sayde et al. 2010; Freifeld et al. 2008). Earlier tests with 1500 m copper strands wrapped around a 250 m long fiber-optic cable at the River Thur in Switzerland indicated a power consumption of 869 W at 230 V (0.58 W/m). This was sufficient to generate a maximum temperature change of 3 K in the metal armor of the fiber-optic cable section surrounded by water following a 15 minute heat pulse (unpublished data). This power demand is difficult to supply in a remote field site without access to the power grid. Hence, the fiber-optic cable has to be heated at a higher voltage, but for shorter sequences. Currently, the most feasible options include solar panels or the combination of solar panels and wind generators.

The power supply is highly dependent on the power consumption of (i) the DTS instrument, (ii) the additional components, such as the heating control box, the PC and the time switch, and (iii) the type and length of the fiber-optic cable. The energy demand may be calculated with Equations (3.1) and (3.2) provided in Section 3.1.1. Generally, at lower voltage, fiber-optic cables will have to be heated for longer periods to achieve a measureable change in temperature and might have to be divided into subsections, e.g. four 200 m-subsections, rather than one 800 m long section. However, as mentioned above, this is highly dependent on the type and length of the fiber-optic cable.

3.2.1.5 *Autonomous DTS System Components*

The building blocks that finally turn the components described so far into an autonomous DTS system are (i) a device for remote access to the DTS and the control box via the control PC, and (ii) a script/software to enable automated data transfer to a central server, from which the data can be accessed from anywhere in the world.

The DTS will typically be controlled using a low powered Windows embedded PC with a cellular modem (e.g. 3G). To allow DTS control, the system will typically be accessed over a Virtual Network Computing (VNC) connection from a remote location, such that the native software for the DTS can be used. Data may be retrieved via File Transfer Protocol (FTP). In order to make the data available to a wide audience of collaborators, it might be uploaded directly onto a publicly accessible platform. The authors chose to store and access the data using Global Sensor Network (GSN) middleware (Aberer et al. 2006), which includes web-services and a web-based query download interface, and interfaces to the Open Support Platform for Environmental Research (OSPER). For areas where mobile network coverage is unavailable, a stand-alone Wi-Fi access point may be placed in an area with data coverage and the windows embedded PC hence connected to the Internet over a directional Wi-Fi link. In many cases, this access point will also need to be grid-independent and therefore low power. Several options are available, but two options used by the authors are a MikroTik router box; or a PC engines mini-PC with MikroTik RouterOS. The use of RouterOS was chosen to significantly ease programming of the router. A guide can be found at http://www.swiss-experiment.ch/index.php/SwissEx:Wifi. A directional Wi-Fi antenna should be used to enable communications. Hereby, greater directionality provides higher signal gain, and thus enables communications over long distances. Good results have been gained by the authors using both 2.4GHz and 5.7GHz; however, 2.4 GHz Wi-Fi allows more flexibility in the hardware used. Wi-Fi cards for the computer/router at each end and the corresponding antenna type should be chosen accordingly. This set-up provides direct access to the PC controlling the DTS instrument and the heating control, thus enabling their remote control, as well as access to the data collected during passive and active measurement periods.

3.2.2 *System Assembly*

The building blocks of the Autonomous DTS System will be assembled as follows: all components, i.e. the DTS instrument, the PC, the modem and the control box, are connected to the power supply; the PC is connected to the DTS instrument, the modem and the control box and the DTS instrument and the control box are connected to the fiber-optic cable. It is advisable to store the Autonomous DTS System in a lockable metal box, to avoid causing harm to humans or animals and reduce the risk of environmental impacts, such as hail, frost or humidity, damaging the system.

3.3 Summary

The upgrade of a passive DTS instrument to an active, autonomous DTS system is presented. Autonomous DTS systems enable passive and active, heated long-term temperature measurements over distances of a few hundred meters in remote areas without human presence, which will enable measurements in interesting, but difficult to reach far-off areas. The remarkable features of the autonomous DTS system are (a) that it is remote controlled, (b) has an automated data transfer, and (c) can be built to be grid-independent. Hence, the system is truly independent of a direct operator at the field site and can be stationed in areas that are difficult to access.

There are several components required to upgrade the standard passive DTS to an autonomous DTS system. Additional to the passive DTS instrument, consisting of (i) a DTS instrument, (ii) a PC, (iii) one or more fiber-optic cables, and (iv) several water baths as temperature references, the autonomous DTS system is equipped with (v) a control box for the automated heating of the fiber-optic cable, (vi) a remote connector, such as a 3G modem, and software for automated data transfer, and (vii) a grid-independent power supply. The grid-independent power supply is the issue most difficult to solve, as power consumption of the heated DTS application is rather high and challenging when exclusively provided with grid-independent power supplies, such as solar panels.

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3.4 Supporting information

Following the field installation of the ADTS system the system was adapted to match the environmental conditions. Adaptations included (i) the removal of the calibrations baths, (ii) the installation of additional software to automatically start the internet connection simultaneously with the computer, forcing it to stay open, (iii) the writing of a script restarting the computer once per day, and (iv) the installation of a low-power cooling system.

Adaptation (i) was necessary, as it was impossible to maintain calibration baths with a temperature difference of 20 K for long-term measurements in the field. The reference baths were substituted with a 40 m long coil of unheated fibre-optic cable stored in the ADTS system and supplemented by a temperature reference probe. This is not as accurate as two reference baths with a temperature difference of 20 K. However, laboratory experiments have shown that the accuracy of the DTS instrument is sufficiently high to use the DTS data without post-measurement calibration.

Adaptations (ii) and (iii) were required for a stable internet connection and thus regular data transfer. Without the software automatically starting the internet connection simultaneously with the computer and without forcing the internet connection to continuously stay live the data transfer did not run smoothly.

Adaptation (iv) was essential to prevent the ADTS system and its components, particularly the hard disk in the computer, from overheating in summer. In winter the emission of heat from the computer should be sufficient to prevent the temperatures in the ADTS system to drop below 0 °C. Nevertheless, it might be advisable to employ the ADTS system in temperatures above -20 °C, as the warmth from the computer might not suffice to keep the temperature in the ADTS system above 0 °C.

Figure 3.2 shows a photograph of the ADTS system currently employed at the Chriesbach.

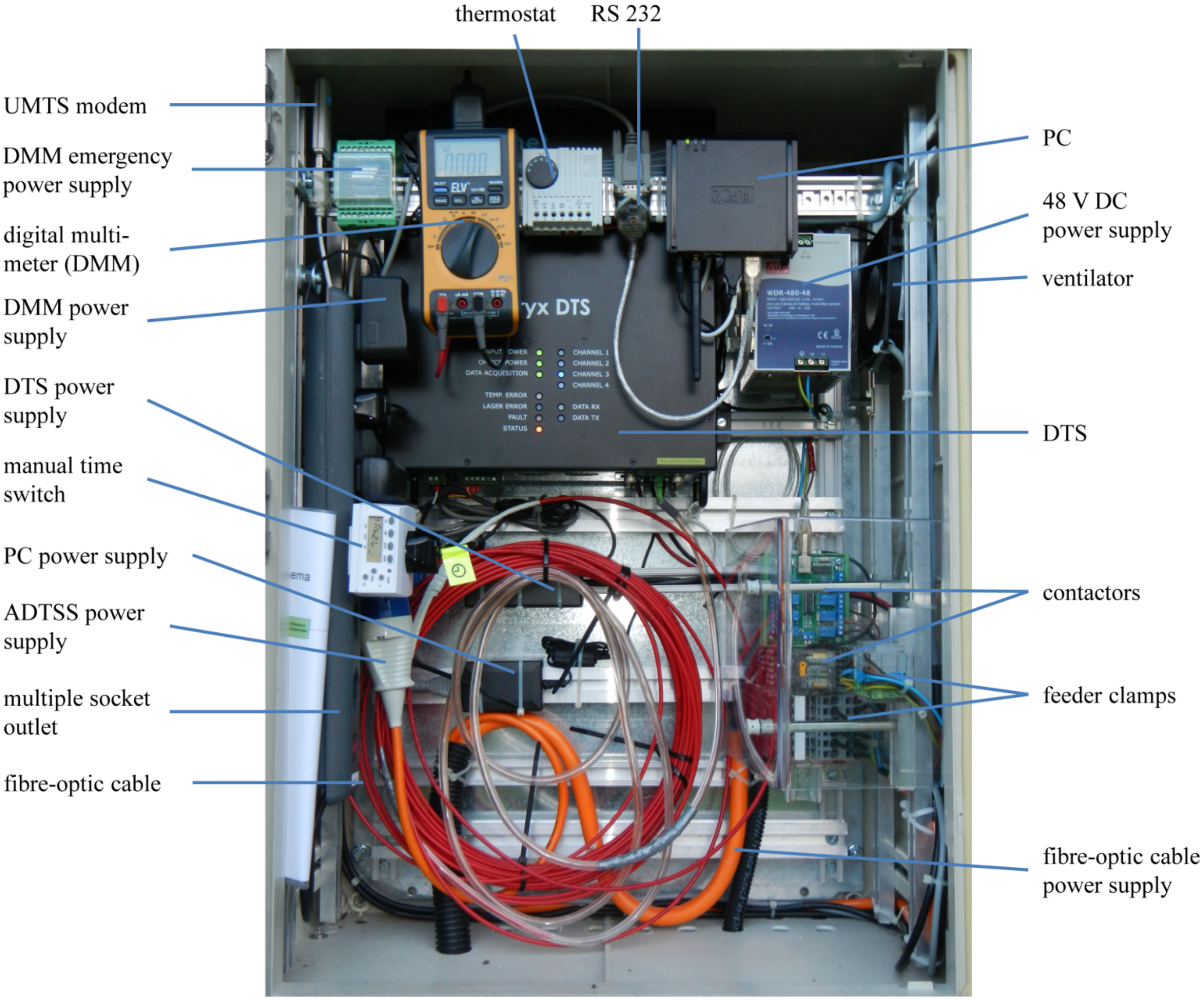

Figure 3.2. The ADTS system and its components.

The ADTS system now in use operates as follows: the DTS instrument sends a laser pulse into the glass fibre. The backscattered light is then analysed and the temperature of the glass fibre calculated in the DTS instrument. The DTS instrument is connected to the computer via an RS-232 serial interface. Via this connection the DTS software on the PC requests the data from the DTS instrument after every measurement and saves it to a folder connected to an online file-hosting server. From there the data is automatically downloaded to the file-hosting server after each measurement. This setting could be changed to a once or twice daily schedule to save power. For this purpose the DTS data would be saved to a folder unconnected to the online file-hosting server. A batch script could then save the data to the folder connected to the online file-hosting server once or twice a day, from where it would be downloaded.

The current settings require the internet connection to be constantly active. As the UMTS modem deactivates itself after a specific time a software is required to keep the internet connection constantly active. This was achieved with a software that forces the internet connection to stay active and, additionally, automatically restarts the internet connection after a power outage or a computer restart. A computer restart, forced by a task scheduler, is necessary twice a day, as the internet provider automatically disconnects the internet connection after 23 hours. By restarting the computer a new IP address is allocated after each restart and the internet connection can stay constantly active.

Computer restarts do not affect the data storage, as DTS data collected while the computer restarts is buffered on the DTS instrument. All software running on the computer is set to automatically restart after each computer restart. All ADTS system components, with exception of the DMM, automatically restart after a power outage as well.

The major asset of the ADTS system is the automatic heating of the fibre-optic cable. This is achieved by the DMM software, which controls the smaller of the two contactors, starting or stopping the current flowing through the fibre-optic cable. As the smaller contactor does not withstand high current load, as second, more rugged, contactor is controlled by the smaller contactor. This device is connected to the power supply for the fibre-optic cable, which reduces the voltage from 230 V to permissible 48 V. The predefined amperage, here 10 A, is then circulated through the metal components of the fibre-optic cable. The power output is constantly measured by the DMM and the data saved to a folder on the computer. A batch file transforms the data from .txt-format into a csv-file and saves it into the folder connected to the online file-hosting server. The manual time switch for the heating was installed in the initial phase of the ADTS system, but does not have a function any more.

The temperature inside the ADTS system is controlled by a thermostat and a ventilator, to prevent overheating of the system, in particular the hard disk of the computer. In winter, the lost heat from the computer should suffice to keeping the ADTS system above 0 °C.

Software for remote control allows access to the ADTS system and its components from anywhere with an active internet connection, rendering the system completely independent of a direct operator. No drive-by for data collection is necessary, and after service interruption the system automatically restarts.

Fuses and ground-fault circuit-interrupters reduce electrical hazards by accidental touching of the live wire. However, as the fibre-optic cable is protected by two insulation layers following the standards for electrical cables, the most likely risk is by rodents eating into the plastic protective layers of the short section of the unburied fibre-optic cable, thereby exposing the metal wires. A protective casing around the unburied cable minimises the risk for rodent interruption or accidental touching of the live wires.

The risk by accidental exposure to laser light is minimal as well, as the bare glass fibres at the fibre-optic cable/DTS interface are protected by plastic tubing and accidental breaking of the glass fibres is unlikely. Furthermore, the section of the fibre-optic cable with the exposed glass fibres is inside the ADTS system, which is contained within a locked encasing.

Chapter 4

The PAB approach for investigations of groundwater-surface water interactions with Distributed Temperature Sensing in gaining and losing conditions

Paper in preparation

Kurth, A.-M., Selker, J.S., and Schirmer, M., in preparation. The PAB approach for investigations of groundwater-surface water interactions with Distributed Temperature Sensing in gaining and losing conditions.

Abstract

Investigations of groundwater-surface water interactions are prerequisites for numerous research activities, such as groundwater recharge studies or the evaluation of the hydrogeological success of river restorations. So far, these investigations were either point-measurements or, in case of distributed measurements, only possible under gaining stream conditions. However, groundwater-surface water interactions are equally interesting under losing stream conditions. Hence, the authors developed a novel approach for the investigation of groundwater-surface water interactions under gaining and losing conditions with Distributed Temperature Sensing (DTS). This fibre-optic technology allows temperature measurements over long distances and thus is ideal for the investigation of groundwater-surface water interactions in streams. The new methodology described in this publication combines passive (P) and active (A) DTS elements with a buried (B) fibre-optic cable (PAB approach). The PAB approach enables investigations of groundwater-surface water interactions under gaining and losing stream conditions. It was tested in a losing stream situated in the Swiss Plateau in north-eastern Switzerland. It could be shown, that the methodology is suitable for the determination of the time shift and dampening of temperature signals in the subsurface and the qualitative identification of groundwater-surface water interactions. This novel approach opens windows on groundwater recharge studies, investigations on contaminant flow paths or investigations on the hydrogeological success of river restorations.

Keywords

Distributed Temperature Sensing (DTS), groundwater-surface water interactions, losing stream, river restoration, PAB approach

4.1 Introduction

Human activities have led to a gradual degradation of riverine ecosystems over the last 150 years (Mill. Ecosyst. Assess. 2005). However, as the value of ecosystem integrity became increasingly apparent (Zeh Weissmann et al. 2009) more and more river restorations were implemented worldwide (Wortley et al. 2013). Nonetheless, the ecological success of river restoration is constantly being questioned (e.g. Higgs 1997; Bernhardt and Palmer 2011; Haase et al. 2013). Possible explanations for the apparent failure of (ecological) success include differing expectations towards and definitions of a successful river restoration (Higgs 1997; Wortley et al. 2013), and the flawed attempt to reverse catchment-scale degradation by restoring only short stretches of streams (Bernhardt and Palmer 2011). Further explanations may be a lack of investigations into the reasons for river ecosystem degradation (Woolsey et al. 2011), or the impossibility to reverse human interference, due to the channelling, lowering of the streambed and diffuse pollution in urban settings. Additionally, it is often overlooked that a lack of groundwater-surface water interactions might have a significant impact on water temperature (Bencala 2005; Hannah et al. 2009; Norman and Cardenas 2014) and quality (Boulton et al. 1998; Findlay 1995; Fuller and Harvey 2000), and hence on ecosystem health (Bardini et al. 2002; Wondzell 2011). In this context, we define groundwater-surface water interactions as the exchange of groundwater and surface water in the hyporheic zone, both under gaining as well as losing conditions. Pre-restoration investigations of the extent of groundwater-surface water interactions might help to elucidate possible reasons for degraded ecosystem health and functioning, which would then allow evaluating whether the restoration of ecosystem health is feasible at all. A holistic approach would thereby include investigations of the water quality, defined by both the chemical content and the water temperature, as well. Raman-based Distributed Temperature Sensing (DTS) enables this investigation of groundwater-surface water interactions in streams (Briggs et al. 2012; Selker et al. 2006 b; Slater et al. 2010). Raman-based DTS is a fibre-optical technology for simultaneous temperature measurements along glass fibres of several kilometres length (e.g. Selker et al. 2006 a). So far, these measurements have been employed, amongst others, in streams (Briggs et al. 2012; Selker et al. 2006 b; Slater et al. 2010) and lakes (Selker et al. 2006a; Tyler et al. 2009) but then exclusively under gaining conditions. As groundwater-surface water interactions are likely to be equally crucial under losing conditions, we developed a DTS-method for the investigation of groundwater-surface water interactions that may be employed both under gaining and losing conditions. In this paper, we describe this novel approach and present data obtained from a newly restored stream in north-eastern Switzerland.

4.2 Methods

4.2.1 *Study Site*

Groundwater-surface water interactions were investigated in the Chriesbach, which is situated in Canton Zurich, north-eastern Switzerland. The Chriesbach is a perennial stream of the Swiss Plateau, flowing through an industrial and residential area. In the investigated area it has losing conditions, the groundwater head being about 0.2 m below the streambed, and a mean annual discharge of 0.51 ± 0.21 m^3/s (Kaenel and Uehlinger 1999). Streambed sediments consist of fine sand and clay, which may cause clogging of the streambed. This is further aggravated by the large number of macrophytes growing on the streambed. The formerly meandering Chriesbach suffered severe degradation due to lowering and channelization in the late 20th century, but was restored between 2006 and 2014. In the framework of this restoration, a glass fibre-optic cable was installed in the streambed at about 0.4 m depth (Fig. 4.1) and passive and active DTS temperature measurements were performed after restoration work had been completed.

4.2.2 *Passive and Active DTS*

As mentioned in the Introduction, Raman-based DTS is a fibre-optical method for temperature investigations along a glass fibre. For each measurement, the DTS instrument injects a laser light pulse into the glass fibre. In the glass fibre the light beam's photons

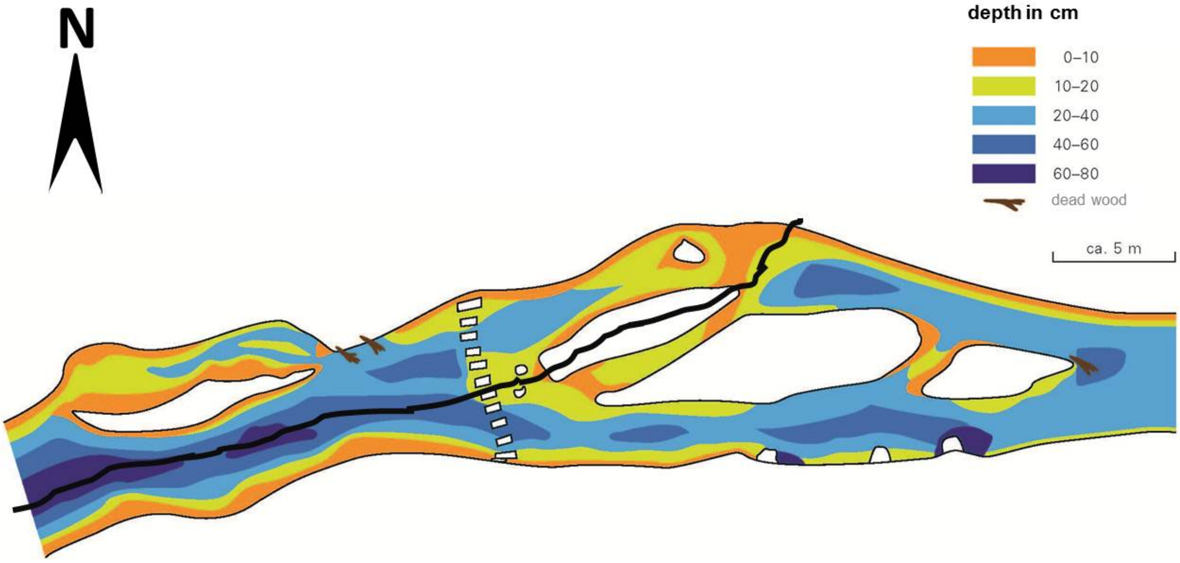

Figure 4.1. Approximate position of the lower section of the fibre-optic cable installed in the streambed of the Chriesbach at about 0.4 m depth. © Eawag

collide with the glass molecules and either gain, lose or conserve their energy, depending on the energy level of the glass molecules. Some of the thus backscattered photons arrive in the detector of the DTS instrument, where they are analysed for their energy and time of arrival. Thereby, only those photons which lost or gained energy are of importance, forming the Stokes and Anti-Stokes signal, respectively. Both signals are temperature dependent. However, as the Anti-Stokes signal is more temperature dependent than the Stokes signal, they may be used to calculate the temperature of the glass fibre-optic cable. The time of arrival of the respective signals thereby allows an allocation of each temperature signal to the fibre section where it originated, thus providing a simultaneously measured temperature profile along the total length of the glass fibre.

This kind of measurement with DTS is termed passive (Steele-Dunne et al. 2010), as no changes are made to the measurement technique. However, there is also an active employment of DTS technology, in which the glass fibre-optic cable is heated by resistive heating, induced by an electrical current being sent through the metal components of the glass fibre-optic cable (Read et al. 2014). While the passive method provides temperature measurements, the active method additionally provides information on the heating and cooling behaviour of the glass fibre-optic cable and thus possibly on the groundwater-surface water interactions. Hence, we employed both the active and passive methods in our study, so as to be able to elucidate whether either of the methods is more suitable to investigate groundwater-surface water interactions in streams.

4.2.3 *Autonomous DTS System*

The advantages of DTS temperature determinations in hydrological sciences are obvious: simultaneous temperature measurements along entire stretches of streams, lakes etc. provide insight into hydrogeological patterns that would otherwise be concealed. However, there are disadvantages as well, such as the required presence of an operator. Therefore, we developed an autonomous DTS system, which is independent of a direct operator. The autonomous DTS system (ADTS system) is remote-controlled and, if equipped with solar panels, grid-independent. Hence, the system may be installed in the field and only requires the direct presence of an operator in case of system failure or yearly maintenance. The system may be set-up, started or stopped from anywhere in the world, provided an internet connection is available. The data is automatically uploaded to a web-based file-hosting service after each measurement, from where all researchers involved may download the data any time.

Additionally, the ADTS system automatically heats the metal components of the glass fibre-optic cable at set intervals and measures the electrical current employed. This data is also automatically sent to the web-based file-hosting service at pre-defined time intervals. The ADTS system enables research in remote areas, where long-term measurements would be impeded by time-consuming journeys to and from the research site. A detailed description of the ADTS system may be read in Kurth et al. (2013) (Chapter 3).

4.2.4 *The PAB approach*

Apart from employing an ADTS system with both passive (P) and active (A) DTS, we tried a novel approach for the investigation of groundwater-surface water interactions by burying (B) the glass fibre-optic cable about 0.4 m below the streambed (PAB approach). As it is impossible to manually insert the glass fibre-optic cable at this depth, we employed a plough specifically designed to insert cables into the subsurface. The plough was mounted on a small vehicle with balloon tyres and pulled by a tractor (Fig. 4.2). This method is quick and minimally-invasive, reducing disturbances to aquatic organisms to a slight turbidity of sediments in the water, which cleared after a few minutes. This method is suitable for streams and small rivers with fine to coarse sediment, the only requirement being free access to the water's edge for the tractor pulling the plough.

Figure 4.2. Tractor-pulled plough employed for the installation of the fibre-optic cable in the streambed of the Chriesbach.

Data was obtained with a Sensornet Oryx® instrument with a sampling resolution of 1 m, a spatial resolution of 1.5 m, and a temporal resolution of 15 minutes, before 17 July 2014, and 5 minutes thereafter.

4.3 Results

Surface water temperature and streambed temperatures along the fibre-optic cable were measured in July 2014. A selection of these results, based on the discharge of the stream, is presented in the following. Figure 4.3 displays the data from 21.07.2014 during low-flow conditions. The left side of Figure 4.3 represents the surface water temperature in [°C], the right side the temperature of the glass fibre-optic cable, buried at about 0.4 m depth, in [°C]. Thereby, one line along the x-axis shows the data from one temperature measurement along the glass fibre-optic cable. It is assumed that the temperature of the glass fibre-optic cable equals the temperature of the surrounding streambed media, as the glass fibre-optic cable rapidly adapts to temperature changes. Water temperature ranged between 16.0 °C and 16.9 °C (Fig. 4.3, right side), surface water temperature between 16.2 °C and 16.6 °C (Fig. 4.3, left side). Groundwater temperature, measured at about 3 m below ground in a nearby piezometer, was at a constant 15.0 °C during the experiment.

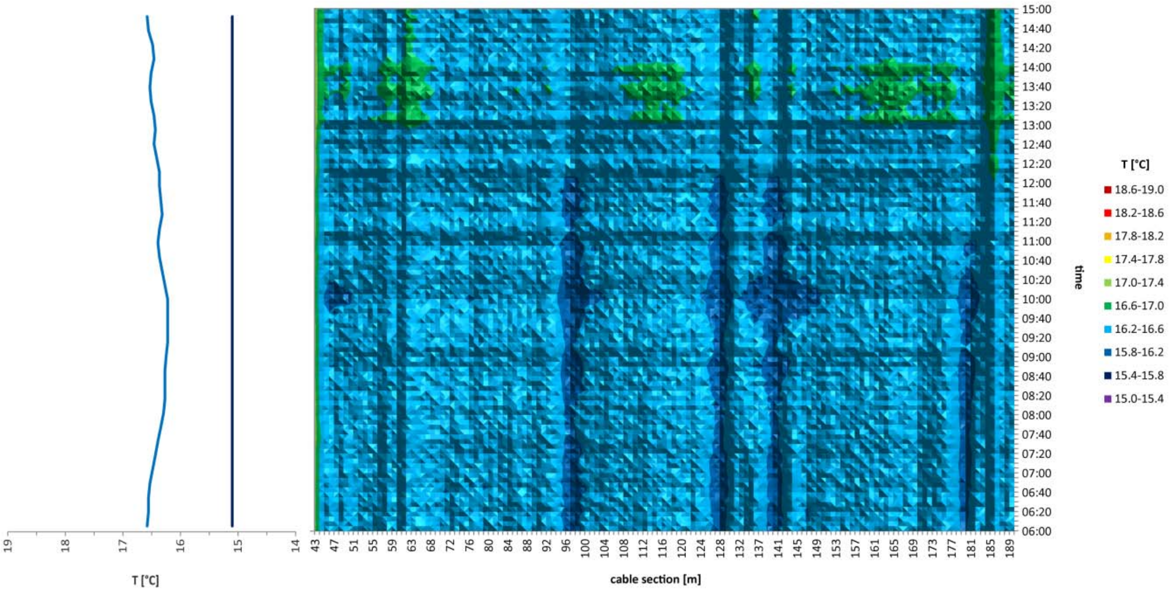

Figure 4.3. Surface water, groundwater and streambed temperatures on 21.07.2014 during low flow. The diagram on the left side displays surface water (light blue) and groundwater (dark blue) temperatures in [°C], the colour plot on the right hand side the streambed temperatures about 0.4 m below the stream in [°C]. The legend provides the colour key to the water temperatures, e.g. light blue represents a temperature range of 16.2 °C to 16.6 °C.

Between 06.00 h and 12.00 h on 21.07.2014 streambed temperatures at the fibre-optic cable depth (~0.4 m) were uniformly equal to or slightly below the surface water temperature, with exceptions of the cable sections at e.g. 96 m, 128 m, or 141 m, in which streambed temperatures were below the surface water temperature. These lower streambed temperatures reflect the surface water temperature signal seen about 6 hours earlier. Towards the end of the experiment around 13.00 h the surface water temperature was rising, causing the simultaneous appearance of zones in which the streambed temperature was higher than in the surrounding cable sections, e.g. at 61 m, 114 m, or 187 m. These elevated streambed temperatures reflect the surface water temperature seen 16 hours earlier. Around 14.00 h these zones simultaneously disappeared again, with the exception of cable sections at 61 m and 187 m.

The data for Figure 4.4 was obtained on 11.07.2014 and 12.07.2014, spanning a low flow, peak flow and decreasing discharge period. Streambed temperatures at ~0.4 m depth ranged between 15.0 °C and 17.5 °C. Surface water temperatures reached 15.0 °C in the early morning and 17.6 °C in the late afternoon. At the time of the experiment groundwater temperature, measured 3 m below the ground, was at a constant 15.0 °C. In the first half of the experiment between 18.00 h on 11.07.2014 and 09.00 h on 12.07.2014 during low flow conditions streambed temperatures were close to the groundwater temperature. However, in

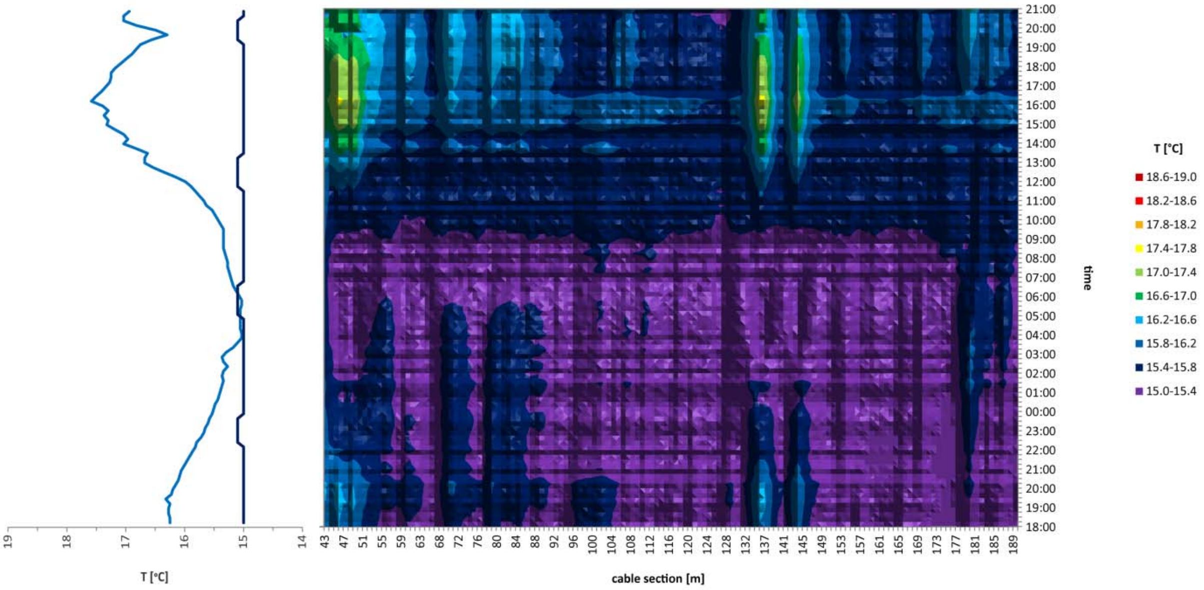

Figure 4.4. Surface water, groundwater and streambed temperatures on 11.07.2014 and 12.07.2014 during low flow and rising discharge. The diagram on the left side displays surface water (light blue) and groundwater (dark blue) temperatures in [°C], the colour plot on the right hand side the streambed temperatures at a cable depth of about 0.4 m in [°C]. The legend provides the colour key to the streambed temperatures, e.g. purple represents a temperature range of 15.0 °C to 15.4 °C.

some zones streambed temperatures were equal to or close to the surface water temperature, e.g. around cable sections at 47 m, 71 m, or 187 m.

These cable sections represent three sets of zones: (1) zones in which streambed temperatures were equal to surface water temperatures, and temperature maxima were reached simultaneously with surface water temperature maxima, e.g. at 47 m, 137 m and 145 m; (2) zones in which streambed temperatures were around 0.5 °C below surface water temperature, and maxima were reached about 1.5 hours after the surface water temperature reached its maxima, e.g. at 71 m, 80 m, and 86 m; and (3) zones where streambed temperatures were around 1.0 °C below surface water temperature, and temperature maxima were reached 1.5 hours after surface water temperature maxima, e.g. at 67 m, 104 m and 187 m (Fig. 4.5). As surface water temperature decreased in the early morning on 12.07.2014, streambed temperatures decreased as well. The background streambed temperature in the second part of the experiment, during increasing and then decreasing discharge, was generally above the groundwater temperature, as measured in the piezometer around 3 m below ground, and

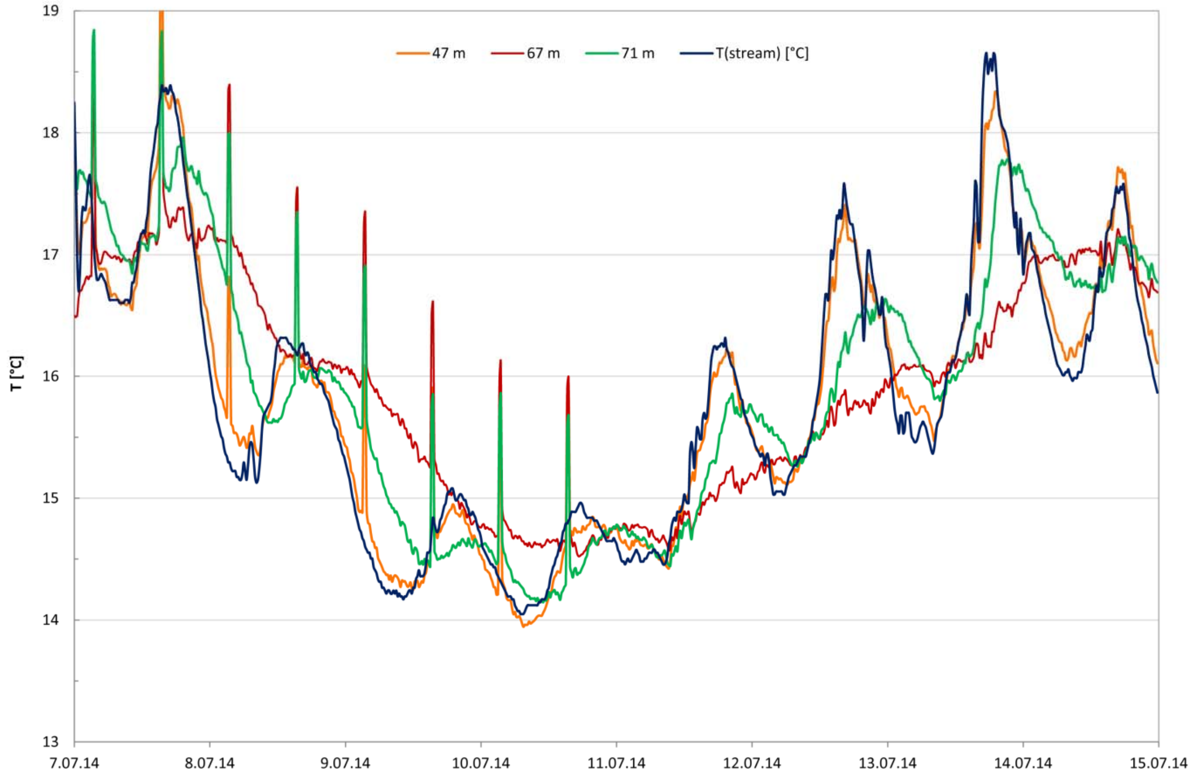

Figure 4.5. Time series analysis of surface water and streambed temperatures at a cable depth of about 0.4 m compared to surface water temperatures between 09.07.2014 and 14.07.2014. The blue line represents the surface water temperature; the orange, red and green line represent cable sections 47 m (zone 1), 71 m (zone 2), and 67 m (zone 3), respectively.

closer to the surface water temperature. Thereby, background streambed temperature describes the streambed temperature in areas without zones of elevated streambed temperatures, e.g. at the cable section at 161 m. Again, there were zones in which streambed temperatures were above the background temperature of around 15.6 °C, correlating with those seen in the first half of the experiment.

Streambed temperature maxima were reached either simultaneously with surface water temperatures, e.g. around cable section 47 m (zone 1), with a time shift of around 7 hours, e.g. at 80 m (zone 2), or with a shift of around 11 hours, e.g. at 67 m (zone 3). The temperature signals were respectively dampened by ~ 0.1 °C (zone 1), 0.9 °C (zone 2), and 1.5 °C (zone 3). The time shift and dampening were determined from one section per zone, i.e. cable section 47 m in zone 1, cable section 71 m in zone 2, and cable section 67 m in zone 3 (Fig. 4.5).

The data in Figure 4.6 was obtained on 13.07.2014 and 14.07.2014. These two days were marked by heavy rainfalls. In the investigated period, streambed temperatures ranged between 15.2 °C and 18.5 °C. Surface water temperatures reached 15.4 °C in the morning and 18.7 °C in the late afternoon. Groundwater temperatures as measured in the nearby piezometer at 3 m below ground fluctuated between 15.0 °C and 15.3 °C. In the first part of the experiment, between 06.00 h and 14.00 h on 13.07.2014 streambed temperatures were above groundwater temperature. As in Figure 4.4 streambed temperatures in some zones closely followed surface water temperature, which at that time was below the background streambed temperature of 16.0 °C, e.g. at around 47 m. In the afternoon of 13.07.2014 these temperature zones became more apparent, e.g. at 47 m, 137 m and 145 m, where streambed temperatures closely followed surface water temperatures, with the streambed reaching temperatures 0.2 °C below surface water temperatures about 15 minutes after the stream reached its maximum temperature. At 71 m, 80 m and 86 m, temperature maxima, 1.0 °C below surface water temperature, were reached about 5 hours after the stream reached its maximum temperature. At 67 m, 104 m and 187 m, maximum streambed temperatures, 1.7 °C below surface water temperature, were reached around 8 hours after the stream reached its maximum temperature (Fig. 4.5). These zones corresponded well with the zones seen on 11.07.2014 and 12.07.2014.

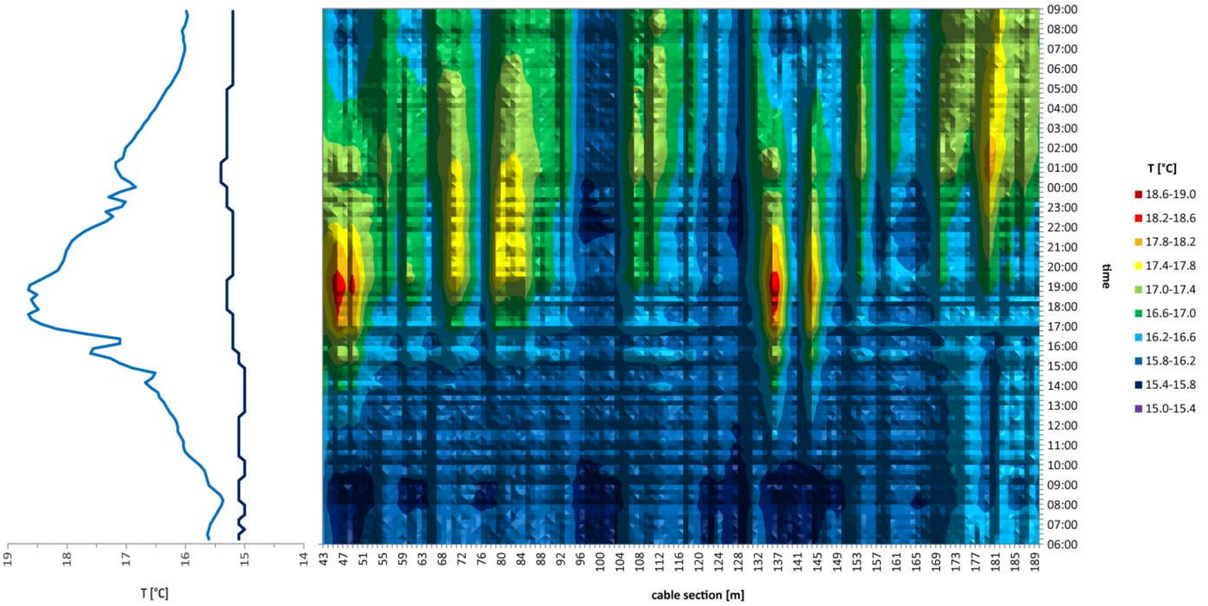

Figure 4.6. Surface water, groundwater and streambed temperatures on 13.07.2014 and 14.07.2014 during peak flow. The diagram on the left side displays surface water (light blue) and groundwater (dark blue) temperatures in [°C], the colour plot on the right hand side the streambed temperatures at a cable depth of about 0.4 m in [°C]. The legend provides the colour key to the streambed temperatures, e.g. dark blue represents a temperature range of 15.4 °C to 16.2 °C.

On 22.07.2014 stream discharge reached a maximum. Surface water temperature reached 17.0 °C in the later morning and 17.7 °C in the afternoon (Fig. 4.7). Streambed temperatures ranged between 16.1 °C and 17.7 °C, groundwater temperatures between 15.4 °C and 15.6 °C. The zonation seen in Figure 4.4 and 4.6 was revealed in Figure 4.7 as well. Streambed temperatures in the first zone were ca. 0.3 °C below surface water temperatures and had a time shift of 1 hour, e.g. around 47 m, 137 m or 145 m (Fig. 4.7 and 4.8). The cable sections 71 m, 80 m or 86 m in the second zone had a time shift of 4.5 hours and temperature signals were dampened by 0.3 °C.

The third zone included cable sections 67 m, 104 m and 187 m, where streambed temperatures were 0.9 °C below the surface water temperature and delayed by 7 hours (Fig. 4.7 and 4.8). Towards the end of the experiment, however, the temperature zonation changed: streambed temperatures were highest in zone 2, followed by zone 3 and zone 1, where water temperatures were above surface water temperature. This time, streambed temperature maxima were reached simultaneously with 0.5 hours delay after the surface water temperature reached its maximum, which was between 0.1 °C and 0.3 °C below the various streambed temperatures (Fig. 4.8).

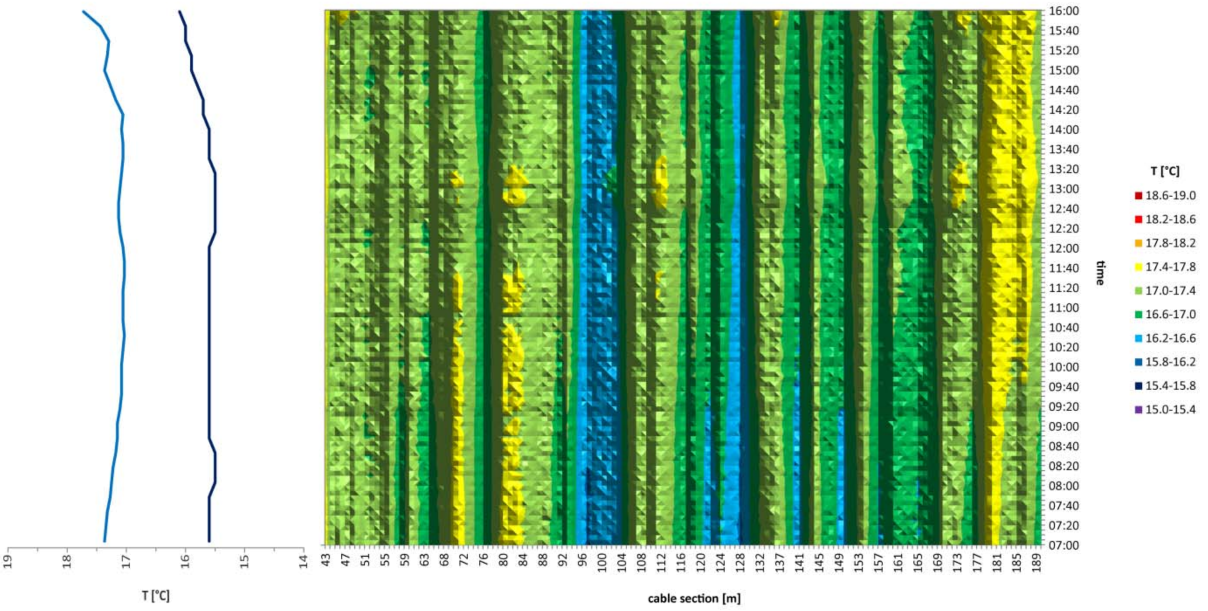

Figure 4.7. Surface water, groundwater and streambed temperatures on 22.07.2014 during maximum peak flow. The diagram on the left side displays surface water (light blue) and groundwater (dark blue) temperatures in [°C], the colour plot on the right hand side the streambed temperatures at a cable depth of about 0.4 m in [°C]. The legend provides the colour key to the streambed temperatures, e.g. light green represents a temperature range of 17.0 °C to 17.4 °C.

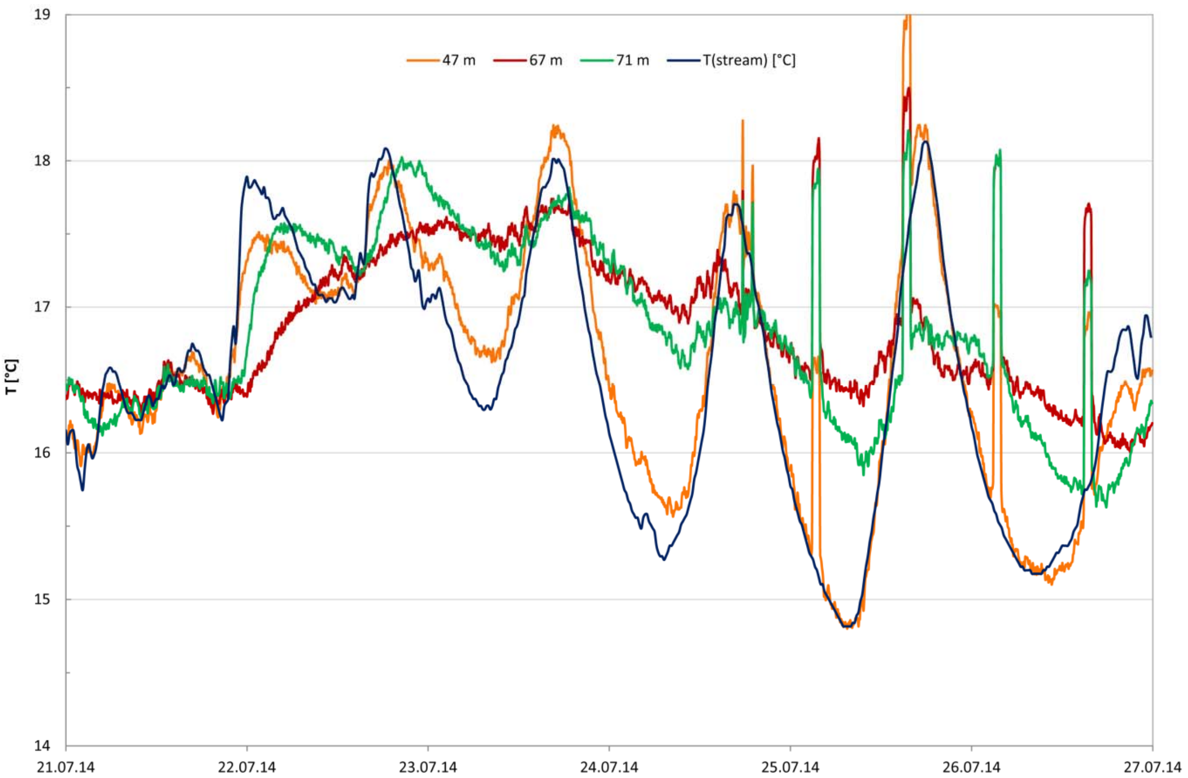

Figure 4.8. Time series analysis of surface water and streambed temperatures in 0.4 m depth compared to surface water temperatures between 21.07.2014 and 25.07.2014. The blue line represents the surface water temperature; the orange, red and green line represent cable sections 47 m (zone 1), 71 m (zone 2), and 67 m (zone 3), respectively.

The data presented in Figures 4.3, 4.4, 4.6 and 4.7 was obtained by passive, unheated DTS. Data from heated, active DTS acquired on 09.07.2014 and 25.07.2014 during peak flow and low flow, respectively, is shown in Figure 4.9. On 09.07.2014 the unheated background streambed temperature ranged between 14.8 °C to 16.2 °C before heating and 14.5 °C to 16.3 °C after heating. Cable temperatures during heating reached 16.0 °C shortly after heating commenced and 17.6 °C at the end of heating. Surface water temperatures were 14.4 °C to 14.8 °C, groundwater temperature was at a constant 15.0 °C. As seen in the passive DTS data there were areas in which streambed temperature maxima were 0.1 °C below surface water temperature maximum and delayed by 1 hour, e.g. at cable sections 47 m, 137 m and 145 m (zone 1); areas in which streambed temperature maxima were around 0.3 °C below the surface water temperature maximum and delayed by 6.5 hours, e.g. at cable sections 71 m, 80 m, and 86 m (zone 2); and areas in which streambed temperature maxima were 0.2 °C below surface water temperature maximum and delayed by 7 hours, e.g. at 67 m, 104 m and 187 m (zone 3) (Fig. 4.8). These zones persisted and were visible during heating. Zones with previously elevated temperatures reached maximum heated cable temperatures, while those zones with previously minimum streambed temperatures reached the minimum of the heated cable temperatures. There was a general trend towards colder streambed temperatures, following the decrease in surface water temperature.

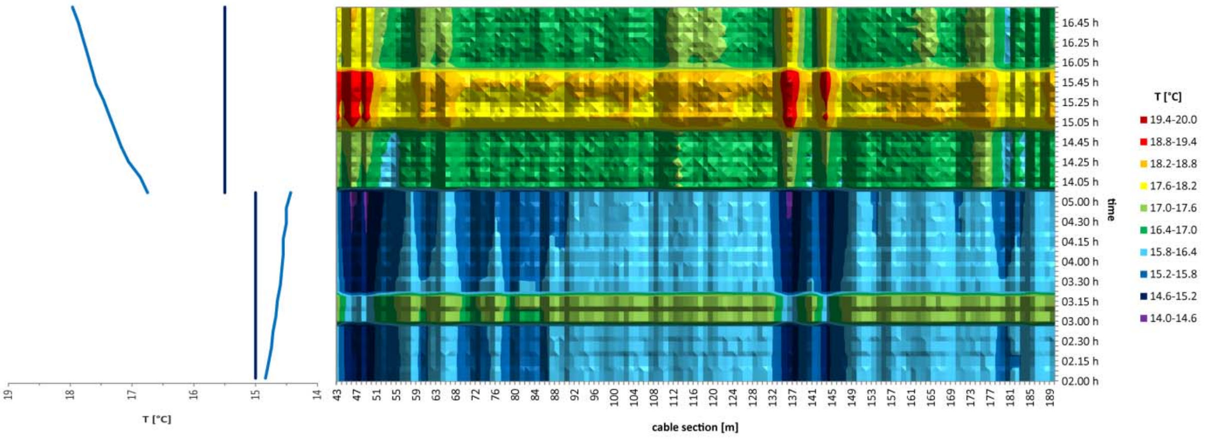

Figure 4.9. Surface water, groundwater and streambed temperatures on 09.07.2014 (02.00 h to 05.00 h) and 25.07.2014 (14.00 h to 17.00 h) before, during and after heating of the glass fibre-optic cable. The diagram on the left side displays surface water (light blue) and groundwater (dark blue) temperatures in [°C], the colour plot on the right hand side the streambed temperatures at a cable depth of about 0.4 m in [°C]. The legend provides the colour key to the streambed temperatures, e.g. dark blue represents a temperature range of 14.6 °C to 15.2 °C.

On 25.07.2014, the unheated background streambed temperature ranged between 16.2 °C and 17.7 °C before heating and between 16.4 °C and 18.5 °C after heating. Heated cable temperatures ranged between 16.5 °C shortly after heating commenced and 19.5 °C at the end of the heated period. Surface water temperature was 16.8 °C at the beginning of the measurement and 18.0 °C towards the end (Fig. 4.9), while the groundwater temperature was at a constant 15.2 °C.

In this experiment, the previously seen zonation was visible as well. This time, however, temperature signals differed after the heating was stopped: the surface water temperature was 0.3 °C below the maximum temperature of cable section 47 m in zone 1; maximum temperatures in zone 3 at 67 m were above those in zone 2 at 71 m; and zone 3 reached its temperature maximum around 1 hour before the stream, followed by zones 2 and 1 (Fig. 4.8). As mentioned above, those zones with previously elevated temperatures reached maximum temperatures during heating, while those with minimal temperatures before heating reached the lowest heated temperatures.

In order to see whether the change in streambed temperature during heating was different in the various parts of the stream, three areas of the previously described three zones were

Table 4.1. Parameters describing the heating and cooling behaviour of the fibre-optic cable. T_{ini} represents the background cable temperature before heating commenced in [°C], T_{max} the highest cable temperature reached during heating in [°C], and ΔT the difference between background cable temperature and maximum cable temperature during heating in [°C]. $(\Delta T/t)_{heat}$ and $(\Delta T/t)_{cool}$ highlight the temperature change per minute during heating in [°C/min].

cable section [m]	T_{ini} [°C]	T_{max} [°C]	ΔT [°C]	$(\Delta T/t)_{heat}$ [°C/min]	$(\Delta T/t)_{cool}$ [°C/min]
			09.07.2014		
47	14.9	16.1	1.2	0.078	0.079
71	15.6	16.9	1.3	0.083	0.083
187	16.0	17.4	1.4	0.083	0.080
			25.07.2014		
47	17.1	19.3	2.3	0.094	0.083
71	16.6	18.2	1.7	0.089	0.092
187	16.4	17.9	1.5	0.085	0.090

selected. Cable section 47 m as part of zone 1, in which streambed temperatures closely followed surface water temperatures; cable section 71 m of zone 2, where streambed temperatures were delayed and dampened; and the cable section 187 m of zone 3, where streambed temperature maxima were delayed and dampened even more than in zone 2.

The temperature differences between the initial streambed temperature before heating and the maximum streambed temperature shortly before heating was stopped may be seen in Table 4.1. As the major temperature change from background temperature to heated temperatures occurred within the first 5 minutes, the temperature change per minute was calculated for the first five minutes after heating, so as to see whether differences in the heating behaviour indicate different grades of groundwater-surface water interactions. The cooling rate was calculated accordingly.

On 09.07.2014 the difference between unheated and heated streambed temperatures was maximum with 1.4 °C at cable section 187 m, belonging to zone 3, where the temperature signal was most dampened and delayed. ΔT at 71 m, part of zone 2, was slightly smaller with 1.3 °C, followed by a ΔT of 1.2 °C at cable section 47 m of zone 1. On 25.07.2014 the pattern of ΔT was the opposite, with a maximum ΔT of 2.3 °C at 47 m (zone 1), and a minimum ΔT of 1.5 °C at 187 m (zone 3). These patterns were mirrored in the temperature change per minute, $(\Delta T/t)_{heat}$, as well: the smallest temperature change had the smallest $(\Delta T/t)_{heat}$, the largest temperature change the largest $(\Delta T/t)_{heat}$. This pattern, however, was not repeated in the cooling rate: the fastest cooling, and therefore the largest $(\Delta T/t)_{cool}$, was always seen at cable section 71 m (zone 2), followed by zones 3 and 1.

Summarizing the results from above it could be seen that (1) some areas followed a specific temperature pattern, which could be separated into three zones: zone 1, where streambed temperatures were dampened by a maximum of 0.2 °C and delayed no longer than 0.5 hours compared to the surface water temperature; zone 2, where streambed temperatures were delayed 1.5 – 7 hours and dampened by a maximum of 1.0 °C; and zone 3, where streambed temperatures were dampened by a maximum of 1.7 °C and delayed by 1.5 - 16 hours; (2) the delay and dampening of the temperature signal was more pronounced during low-flow conditions than during peak flow; (3) groundwater temperatures only changed during major flood events; (4) the heating of the glass fibre-optic cable was most effective in its warmest areas and least effective in the coldest areas; and (5) the heated glass fibre-optic cable always cooled down fastest in the areas belonging to zone 2, followed by zone 3 and zone 1.

4.4 Discussion

These results may indicate the following: in areas with low temperature dampening and small time shifts, the rate of surface water infiltration into the aquifer is high. In areas with high temperature dampening and longer time shifts only little or no surface water infiltration occurs. This implies that the highest surface water infiltration rate, and therefore the highest rate of groundwater-surface water interactions, occurred in the areas belonging to zone 1. Here, the maximum streambed temperatures occurred shortly after the surface water temperature reached its maximum, and streambed temperatures were only slightly below surface water temperatures. The infiltration rate in areas belonging to zone 2 was lower, as the time shift and dampening of the maximum surface water temperature signal were significantly larger than in zone 1. The infiltration rate in zone 3, however, was the lowest, with maximum time shift and dampening of the maximum surface water temperature signal.

Hence, in areas with high infiltration rates, advective processes dominate, preserving the temperature signal and causing only minor time shifts and temperature dampening. In areas with low infiltration rates, conductive processes dominate, inducing high temperature dampening and longer time shifts. This assumption is confirmed by Constanz (2008) and Molina-Giraldo et al. (2011).

During low flow conditions, the temperature dampening and time shifts were generally higher than during peak flow, which would indicate a lower rate of surface water infiltration under low flow conditions. This might be explained by the higher pressure gradient during flood events, forcing more surface water into the underlying aquifer (Cloutier et al. 2014). These processes account well for the temperature pattern seen at around 0.4 m below the stream. However, the glass fibre-optic cable cooled down fastest in areas belonging to zone 2. Hence, it appears that the rate of infiltrating surface water is not as expected, i.e. highest in zone 1 and lowest in zone 3, but highest in zone 2, followed by zones 3 and 1.

A comparison of the cooling behaviour in the month of July indicated that zones 2 and 3 had a very similar cooling behaviour, while the cooling rate in the areas belonging to zone 1 was generally lower than in the other two zones. These results are contradictive, unless the fibre-optic cable is not, as originally assumed, exactly at a depth of 0.4 m, but shallower in zone 1, followed by zones 2 and 3. Different depths of the glass fibre-optic cable would induce different lengths of the flow paths and therefore shorter or longer time shifts and a weaker or stronger temperature dampening. As the plough blade is always the same distance from the wheels, but the streambed is uneven, e.g. V-shaped, the plough might have been inserted into the streambed at slightly different depths. Consequently, the glass fibre-optic cable would be installed in different depths as well. Unfortunately, the exact position of the cable cannot be verified. However, it is most likely that the cable was not installed at exactly 0.4 m depth due to the morphology of the streambed.

This would unite the two data interpretations: the cable in areas belonging to zone 1 was installed at a shallower depth than in zone 2 and zone 3, and the rate of infiltrating surface water was highest in zones 2 and 3. This would explain the short time shift between the streambed and the surface water temperatures reaching their maximum, as well as the limited dampening of the maximum temperature signal in the streambed. It would also hold true for conductive and advective processes during low flow and flood events, respectively.

The higher rate of infiltration in zones 2 and 3 might be induced by a higher permeability of the sediments in these areas or by structures, such as riffles and pools. As there are few in-stream structures, such as riffles and pools, presumably the permeability of the sediment gave rise to the different infiltration rates. This might be confirmed by the similarity of the cooling rates at 71 m and 67 m of zones 2 and 3, respectively, which were only 4 m apart and thus might have a similar sediment profile. Variations in the conduction current, and therefore the heating intensity, are possible, but unlikely, as the heating intensity would decrease uniformly along the glass fibre-optic cable, and not increase and decrease depending on the initial temperature of the glass fibre-optic cable.

4.5 Conclusions

The passive element of the PAB approach is suitable for the identification of time shifts and temperature dampening and would be applicable for the determination of travel times in the subsurface. However, this would require knowledge of the exact depths of the glass fibre-optic cable. These measurements, of course, might be achieved with easier and cheaper methods, albeit only as point-measurements rather than distributed analyses.

The active DTS method is convenient for the qualitative determination of infiltration rates under losing stream conditions. Again, there are cheaper and easier methods for point-measurements of the infiltration rate. However, the unique advantage of the DTS technology is the simultaneous investigation of temperature, time shifts, temperature dampening, and cooling rates along entire stretches of streams in a single measurement under gaining and losing stream conditions. The only disadvantages of the PAB approach described above are the high costs of acquisition and installation and the high power consumption during heating, which requires direct access to a power source or a costly and elaborate set-up with solar panels, wind turbines or other grid-independent devices.

With the methodology described above, it is e.g. possible to investigate whether river restoration enhances groundwater-surface water interactions. This could be simultaneously investigated along the total length of the restored section plus in unrestored stretches and on a long-term basis, without the risk of equipment being lost during flood events, as would be the case with point-measurements. In this way, long-term effects of structural changes to stream morphology might be investigated.

Additionally, the formation and removal of clogging layers after restoration or during and after flood events may be investigated, as well as the zonation of groundwater and surface water up- and down-welling, which are prerequisites for the understanding of underlying issues in ecosystem health. Furthermore, possible pathways of contamination and pollution entering vulnerable aquifers or streams might be identified or large-scale groundwater recharge from surface water infiltration can be investigated. Further research should focus on developing methods for the determination of the exact depth of the glass fibre-optic cable and on the quantification of the groundwater-surface water interactions.

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4.6 Supporting information

This chapter is the second draft of a manuscript describing the PAB approach. However, the results and their interpretation presented therein focus too strongly on the varying depth of the fibre-optic cable, omitting the interpretation of the results regarding the qualitative analysis of surface water downwelling. The actual PAB approach is not described in sufficient detail. Hence, the interpretation method described in Chapter 5 will be applied to the data described in this chapter and the PAB approach be integrated in more detail. The manuscript will be adapted accordingly.

Chapter 5

How effective is river restoration in re-establishing groundwater-surface water interactions? - A case study

Paper submitted to *Hydrology and Earth System Sciences*

Kurth, A.-M., Weber, C., and Schirmer, M., submitted. How effective is river restoration in re-establishing groundwater-surface water interactions? – A case study

Abstract

In this study we investigated whether river restoration was successful in re-establishing vertical connectivity and, thereby, groundwater-surface water interactions, in a degraded urban stream. Well-tried passive Distributed Temperature Sensing (DTS) and novel active and passive DTS approaches were employed to study groundwater-surface water interactions in an experimental reach of an urban stream before and after its restoration and in two (near-) natural reference streams. Results were validated with Radon-222 analyses. Our results indicated that river restoration at the study site was indeed successful in increasing groundwater-surface water interactions. Increased surface water downwelling occurred locally at the tip of a gravel island created during river restoration. Hence, the installation of in-stream structures increased the vertical connectivity and thus groundwater-surface water interactions. With the methods presented in this publication it would be possible to routinely investigate the success of river restorations in re-establishing vertical connectivity, thereby gaining insight into the effectiveness of specific restoration measures. This, in turn, would enable the optimization of future river restoration projects, rendering them more cost-effective and successful.

Keywords

Distributed Temperature Sensing (DTS), groundwater-surface water interactions, river restoration, groundwater upwelling, surface water downwelling,

5.1 Introduction

In recent years, significant efforts have been taken worldwide to restore degraded rivers and streams (Filoso and Palmer 2011; Gilvear et al. 2012; Haase et al. 2013) in order to protect ecosystem health, incorporate sustainable flood protection, and preserve valuable water resources (Andrea et al. 2012; Palmer et al. 2005; Wortley et al. 2013).

The aim of river restoration is often stated as achieving the highest possible ecological status or re-establishing the natural function of streams to a pre-degraded state (EU WFD 2000; Maher et al. 2001; Swiss Water Protection Act 814.20). This includes the recreation of a natural river morphology, the provision of habitats for native flora and fauna, and re-establishing groundwater-surface water interactions.

The latter, in particular, is of paramount importance with regard to the natural functioning of streams: the interaction between groundwater and surface water controls the availability of nutrients in the hyporheic zone (Fuller and Harvey 2000; Gooseff et al. 2002; Butturini et al. 2003), impacts water temperature (Bencala 2005; Hannah et al. 2009; Norman and Cardenas 2014) and quality (Boulton et al. 1998; Findlay 1995; Fuller and Harvey 2000), and thus influences ecosystem functioning (Boulton et al. 1998; Malard et al. 2002; Thorp et al. 2006) and health (Bardini et al. 2012; Wondzell 2011).

Many river restoration efforts worldwide focus on the re-establishment of longitudinal and lateral connectivity and appearance, rather than increasing hyporheic exchange (Mendiondo 2008; Filoso and Palmer 2011; Sudduth et al. 2011; Kurth and Schirmer 2014), a fact that might explain the often cited failure of river restoration with respect to ecosystem functioning (Louhi et al. 2011; Sudduth et al. 2011; Violin et al. 2011). Clearly, it is not sufficient to change the appearance of a short stretch of a stream to restore the complex interplay of riverine ecosystems and their surroundings. Hence, more and more projects take a more holistic approach to river restoration (Kurth and Schirmer 2014).

The success of these river restorations may be evaluated with respect to abiotic parameters, such as hydromorphological characteristics, biotic parameters, such as biodiversity, or socioeconomic aspects, e.g. the recreational value (Jähnig et al. 2011). Most river restoration success evaluations, however, seem to focus on biotic parameters (Wortley et al. 2013). Reports regarding the success in re-establishing the vertical connectivity in streams could not be found.

We were therefore interested in evaluating the hydrogeological success of a restoration project which had been planned by a multidisciplinary team of biologists, chemists, civil engineers, ecologists, hydraulic engineers, hydrogeologists, physicists, and social scientists.

We define hydrogeological success as an increase in hyporheic exchange along the restored site of the stream, indicated by increased groundwater-surface water interactions.

In this paper we discuss the results gained from investigations with Distributed Temperature Sensing (DTS), a fibre-optical method for temperature measurements along a glass fibre (Kurth et al. 2013; Selker et al. 2006 a, b). Fibre-optic cables were either installed directly on top or in ca. 0.4 m depths of the streambed. This enabled us to determine the groundwater-surface water interactions under gaining and losing stream conditions. Additionally, hydrogeological conditions in the area surrounding the study site at the restored stream were examined and Radon-222 measurements were performed to verify the DTS data. Apart from investigating a stream before and after its restoration, experiments were performed in natural and near-natural reference streams. “Natural” and “near-natural” thereby refer to the condition of the stream bed as being unaffected or only mildly affected by anthropogenic alterations. Thus, we tested the hypothesis that the vertical connectivity, and therefore groundwater-surface water interactions, indeed improves after river restoration. We conclude with an outlook and recommendations for restoration practise based on our insights.

5.2 Material and Methods

5.2.1 *Study site*s

In our study we evaluated three perennial Swiss streams: the Chriesbach, the Röthenbach and the Urbach (Fig. 5.1). Apart from similarities in their dimensions and discharge, they vary in their state of morphological degradation: while the Urbach is a natural alpine stream, the Röthenbach and the Chriesbach are mildly to severely degraded streams of the Swiss Plateau in rural and urban areas, respectively. Flowing between gentle-sloped meadows and steep rock walls, the Urbach is a braided stream with various main and side channels and in-stream islands (Doering et al. 2012). Its sediment is composed of fine sand and clay in the side channel to coarse gravel and small rocks in the main channel. In spite of upstream hydropower production and the installation of stone crib walls as flood protection measures in the meadows, the Urbach has maintained its natural river morphology and thus was selected as a reference for presumably natural groundwater-surface water interactions. Although being lowered and straightened led to a rather uniform stream width, the Röthenbach still has a naturally varying water depth and flow velocities. The streambed sediment is composed of coarse gravel to fine sand, depending on the flow velocity of the water. The stream is

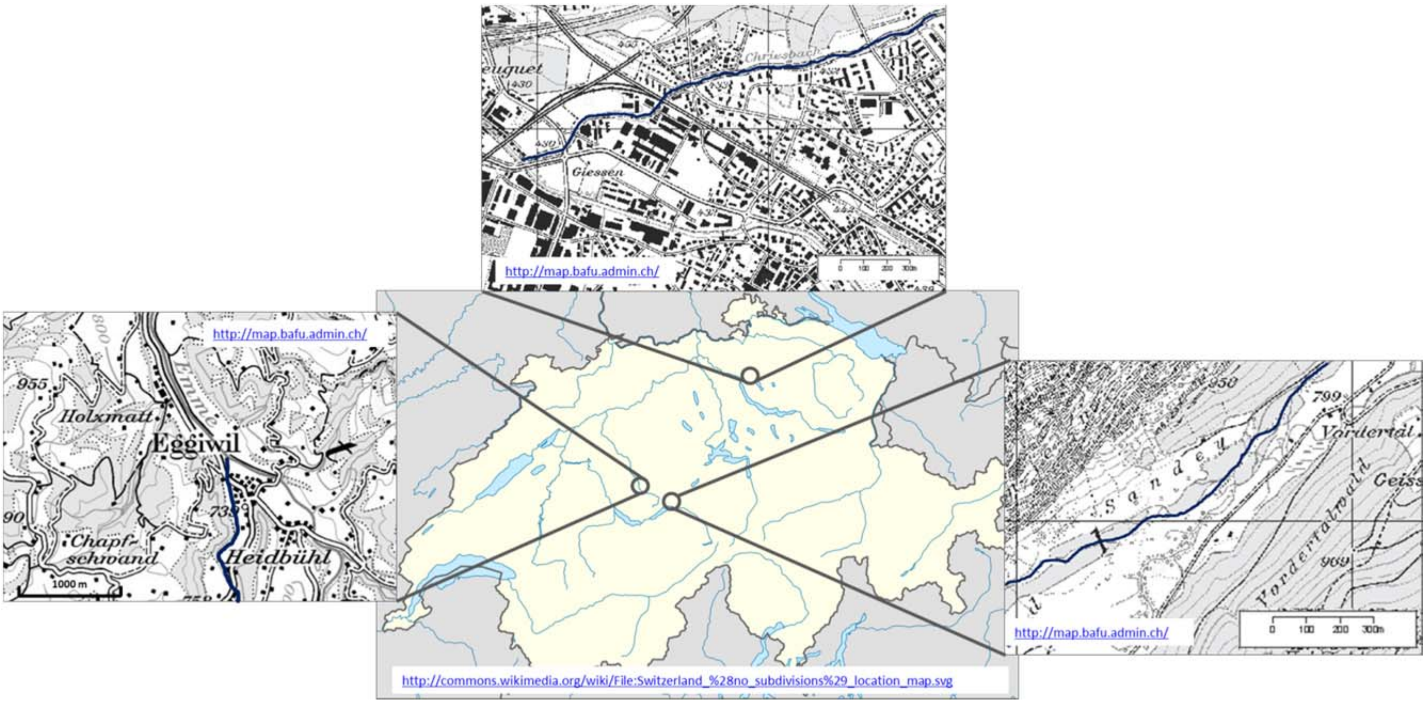

Figure 5.1. Locations of the Chriesbach (top), the Röthenbach (left) and the Urbach (right) in Switzerland.

impacted by diffuse manure inflow into the stream, by discharge of warm water from power production in a nearby sawmill and by a significant drawdown due to water abstraction in the surrounding areas. Nevertheless, the stream bed was still considered to be near-natural and thus used as reference for near-natural hydrogeological conditions. Originally a meandering stream with a streambed composed of fine sand and clay, the Chriesbach was lowered and channelized in the 1910s and 1970s, leading to a loss of in-stream structures and habitats, and causing severe degradation. Hence, between 2006 and 2014, 900 m of the Chriesbach were restored: the channel was widened, the shores levelled, and the water depth and width varied. In-stream gravel islands and ponds were created and a site-specific riparian vegetation planted. Even though these measures hardly reverse the severe effect of channelization and lowering, the Chriesbach now has a more natural river morphology.

5.2.2 *Water temperature measurements with Distributed Temperature Sensing (DTS)*

Raman-based DTS is a fibre-optic method for temperature measurements along a glass fibre into which laser light pulses are injected (Selker et al. 2006 a; Tyler et al. 2009). Inside the glass fibre, the laser light's photons are backscattered either inelastically or elastically, i.e. with or without a change in their energy, depending on the temperature-sensitive energy level of the glass molecules with which the photons interact. The DTS instrument then analyses the energy and the time of arrival of the elastically and inelastically backscattered photons, the so called Stokes and Anti-Stokes signal, respectively, and calculates the temperature for each section, e.g. every meter, of the glass fibre. Thus, the temperature of the entire length of the glass fibre is measured simultaneously. Careful calibration of the DTS instrument with reference baths thereby improves the accuracy of the measurement. It is generally assumed that the temperature of the fibre-optic cable equals the surrounding temperature, e.g. the surface water temperature.

DTS technology is very convenient in hydrogeology, as the temperature of long stretches of streams can be determined simultaneously or groundwater upwelling into streams can be monitored due to differences in their temperatures (Anderson 2005; Briggs et al. 2012; Tyler et al. 2009). DTS measurements may be performed as passive and active measurements. Passive measurements are standard temperature measurements along the glass fibre (Steele-Dunne et al. 2010). In active measurements, on the other hand, the metal components of the fibre-optic cable, e.g. copper or steel wires, are heated by sending an electrical current through them (Read et al. 2014). This allows retrieving information on the cooling behaviour of the fibre-optic cable, indicating areas with lower or higher rates of water flow over the cable. The cooling rate of the fibre-optic cable was calculated as a temperature change per minute. To avoid possible correlations between the temperature of the fibre-optic cable and the cooling rate of the fibre-optic cable, the cooling rate was investigated in the temperature range of 15.9 °C to 16.1 °C. Thereby, the temperature resolution was 0.1 °C. This temperature range was selected as it had the highest number of measurement points.

5.2.3 *Radon-222 measurements*

Radon-222 is a product of the decay of Radium-226 in the decay chain of Uranium-238 to Lead-206. As decaying Uranium-238 is present in the subsurface, groundwater is generally enriched in Radon-222. Surface water, on the other hand, has lower Radon-222 levels due to rapid degassing of Radon-222. Hence, Radon-222 is an ideal tracer for groundwater upwelling in surface waters (e.g. Cartwright et al. 2014; Cook 2013; Hoehn et al. 1992).

5.2.4 *Experimental set-up in the field*

DTS measurements were performed with an Agilent DTS N4386A and a Sensornet Oryx® DTS, with a sampling interval of 1 m, and a spatial resolution of 1.5 m, respectively. We employed a heatable multimode BRUsens fibre-optic cable (BRUGG AG, Switzerland) with copper and steel wires for heatability. As it was impossible to maintain a temperature reference bath in the field, a 200 m section of the cable exposed to air was used as reference and the cable temperature determined with Hobo TidbiTs® temperature probes. Two additional temperature probes were installed in the water at the beginning and the end of the fibre-optic cable submerged in the streams. The temperature probe at the end of the investigated stream section were included as reference in the diagrams (Fig. 5.2 – Fig. 5.6), as were groundwater temperatures where available (Fig. 5.2, 5.3 and 5.6). Measurements were performed on days with low flow and no precipitation, on the coldest days in winter (Chriesbach, Röthenbach) and a moderately warm day in summer (Urbach). DTS measurements at the Urbach could not be performed in winter, as the valley is closed during winter due to an elevated risk of avalanches.

All measurements in the Urbach and the Röthenbach were passive measurements. At the Chriesbach site, measurements were passive before restoration and active and passive after restoration. For passive measurements at the Urbach, the Röthenbach and the Chriesbach prior to its restoration, the fibre-optic cables were fixed on the streambed; for passive (P) and active (A) measurements at the Chriesbach after restoration, the fibre-optic cable was buried (B) with a plough at a depth of about 0.4 m within the streambed (PAB approach). These measurements could not be performed prior to restoration, as the inserted fibre-optic cable would have been damaged by the mechanical diggers remodelling the streambed during river restoration. During active measurements, the metal components of the fibre-optic cable were heated with a current of 10 A for 30 minutes twice a day.

Measurements in the Urbach were performed with the fibre-optic cable being passed through three areas: a side channel (cable sections 140 m to 188 m), a drainage ditch draining the surrounding meadows (cable sections 194 m to 266 m), and the main channel of the Urbach (cable sections 269 m to 327 m). The drainage ditch was measured to provide insight into the local groundwater temperature, as it was assumed that it was solely fed by groundwater that day.

At the Chriesbach site, groundwater temperature and the groundwater level were measured every 15 minutes with an STS logger situated in around 3 m depth of a piezometer situated next to the investigated reach of the stream.

Radon-222 measurements for the detection of groundwater inflow into the Chriesbach were performed after river restoration with a RAD7 instrument (Niton-Durridge, USA). Water samples were taken shortly before analysis from surface water and groundwater in the restored site and from an unrestored reference site further upstream. Groundwater samples were also taken from piezometers at the restored site. The piezometers were flushed for 15 minutes and water samples taken from 6 m depths. All sample bottles were triple-washed and samples taken without air inclusion. Comparative measurements with the Urbach and Röthenbach sites were not possible due to unavailability of the Radon-222 detector.

5.3 Results

5.3.1 *Passive DTS water temperature measurements*

The surface water temperature profile of the Chriesbach was investigated before (Fig. 5.2) and after river restoration (Fig. 5.3). During the data collection before river restoration, the air temperature varied between -5.3 °C and 8.8 °C (Fig. 5.2, left side). The surface water temperature (Fig. 5.2, right side) closely followed the air temperature, varying between 6.4 °C and 9.9 °C. Groundwater temperatures ranged between 11.3 °C and 11.4 °C during the investigated period. Apart from two cable sections with elevated surface water temperatures at 372 m and 379 m, the surface water temperature distribution in the Chriesbach was relatively uniform, decreasing after sunset and increasing again in the morning.

The data collected after the restoration of the Chriesbach appeared to be rather different (Fig. 5.3). Here, air temperatures varied between 0.5 °C and 4.9 °C and surface water temperatures

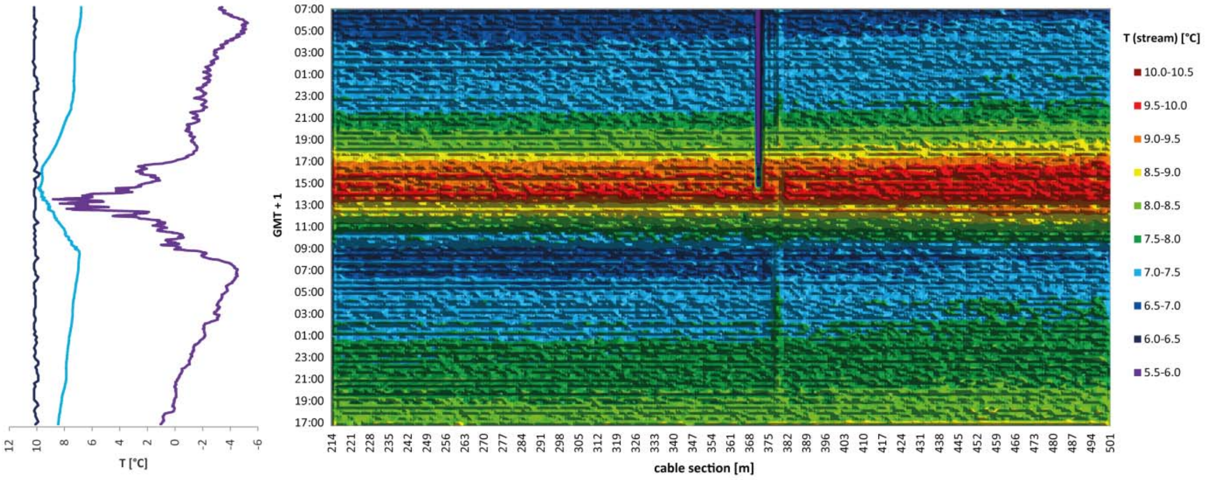

Figure 5.2. Air (purple), stream (light blue) and groundwater (dark blue) temperature (line diagram, left side) and surface water temperatures (colour plot, right side) of the Chriesbach before river restoration, on 13. – 15. March 2013. The x-axis of the colour plot shows the sections of the fibre-optic cable in meters, the colours represent the surface water temperatures in °C. Thereby, each coloured line on the x-axis, from cable section 214 m to 501 m, represents one measurement. The y-axis states the time of the measurements.

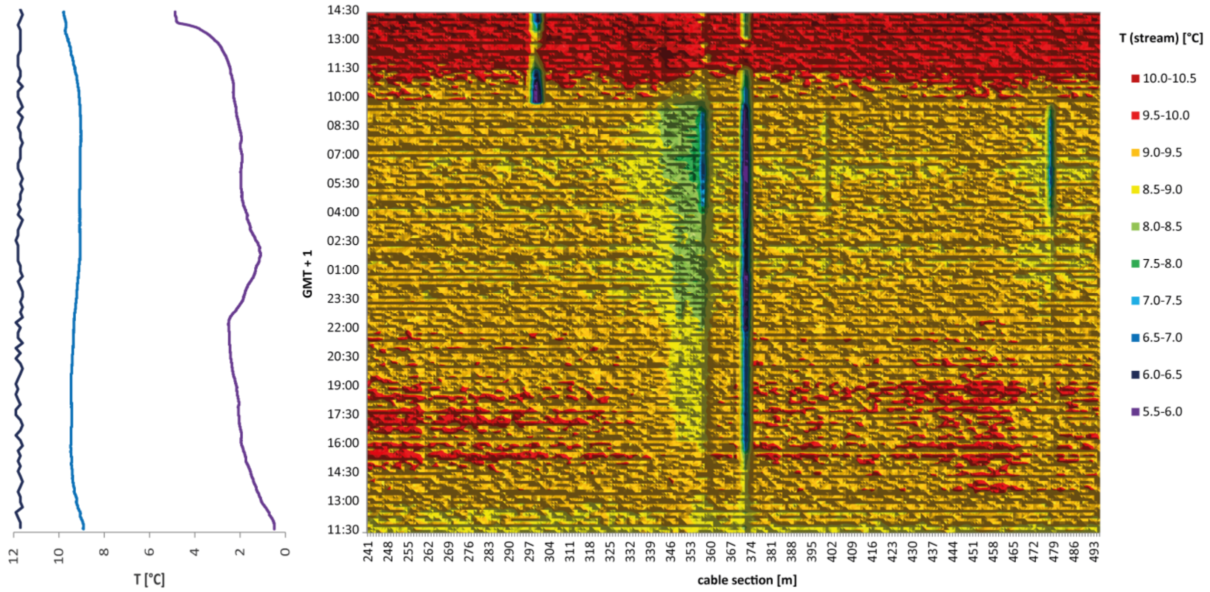

Figure 5.3. Air (purple), stream (light blue) and groundwater (dark blue) temperature (line diagram, left side) and surface water temperatures (colour plot, right side) of the Chriesbach after river restoration, on 28. – 29. November 2013. The x-axis of the colour plot shows the sections of the fibre-optic cable in meters, the colours represent the surface water temperatures in °C. Each coloured line on the x-axis, from cable section 241 m to 493 m, represents one measurement. The y-axis states the time of the measurements.

ranged between 8.6 °C and 10.3 °C. The surface water temperature reached its minimum and maximum in the morning and afternoon, respectively. However, the pattern is less distinct than in the pre-restoration data set. Surface water temperature anomalies were to be found around cable sections 299 m, 357 m, 372 m, and 478 m.

The surface water temperature data from the Urbach, the natural reference site, was very diverse (Fig. 5.4). The air temperature ranged between 18.6 °C in the late morning and 23.6 °C in the afternoon. The surface water temperature in the side channel (cable sections 140 m to 188 m) closely followed the air temperature, ranging between 9.4 °C and 12.3 °C, as the fibre-optic cable was installed in a shallow part of the stream, which was exposed to the sun throughout the measurement. Surface water temperatures in the drainage ditch (cable sections 194 m to 266 m) ranged between 7.8 °C in the late afternoon and 10.6 °C around noon. Thereby, the 7.8 °C are assumed to represent the groundwater temperature in that area. The drainage ditch was partially exposed to sunlight between the morning and the early afternoon and completely shaded afterwards. The higher temperatures at cable section 247 m at the beginning of the measurement were caused by the fibre-optic cable being exposed to air. The surface water in the main channel (cable sections 269 m to 327 m) had water temperatures

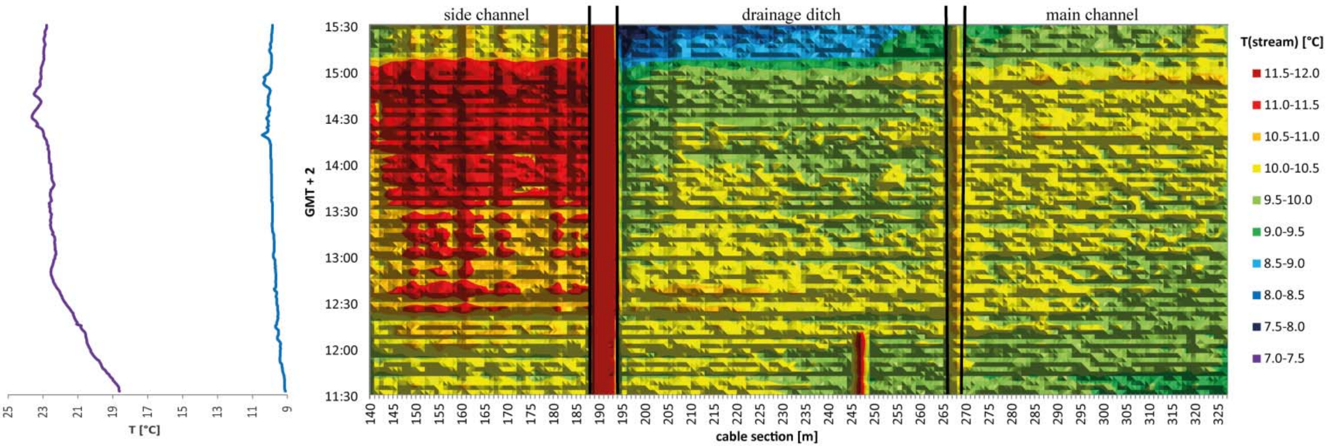

Figure 5.4. Air (purple) and stream (light blue) temperature (line diagram, left side) and surface water temperatures (colour plot, right side) of the Urbach on 03 September 2013. The x-axis of the colour plot shows the sections of the fibre-optic cable in meters, the colours represent the surface water temperatures in °C. Thereby, each coloured line on the x-axis, from cable section 140 m to 327 m, represents one measurement. The y-axis states the time of the measurements.

similar to the drainage ditch, ranging from 9.0 °C in the morning to 10.7 °C in the early afternoon. The stream was completely exposed to sunlight throughout the measurement period.

The data from the near-natural reference site, the Röthenbach (Fig. 5.5), differed strongly from the previously seen natural reference of the Urbach. Air temperatures ranged between -4.5 °C and 13.1 °C. Surface water temperatures closely followed the diurnal variations in air temperature, with the surface water temperature ranging from 1.2 °C in the morning to a maximum of 7.6 °C. However, this maximum water temperature occurred exclusively around cable section 199 m and was constant throughout the measurement period. Around cable section 273 m the surface water temperature was elevated as well, but less pronounced and not as constant as around cable section 199 m. With the exception of these two sections, the surface water temperature in the Röthenbach was very uniform. It decreased after sun-set and increased around noon, following the air temperature with a delay of a few hours. This delay was due to the Röthenbach being in shadow until noon.

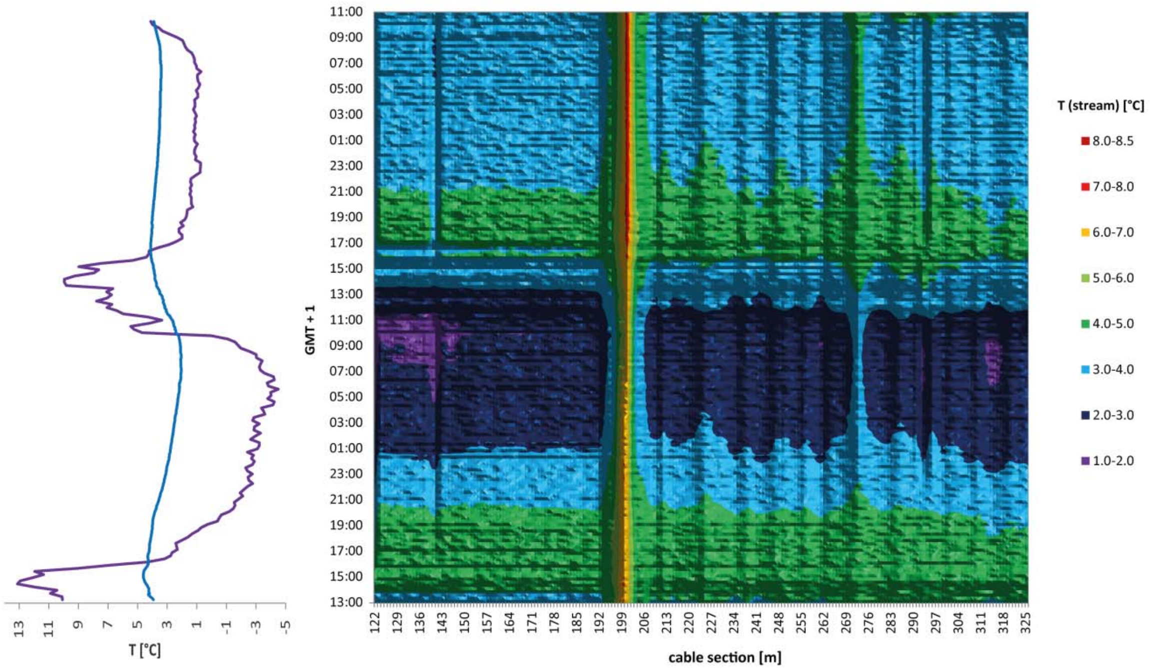

Figure 5.5. Air (purple) and stream (light blue) temperature (line diagram, left side) and surface water temperatures (colour plot, right side) of the Röthenbach on 17. – 19. February 2014. The x-axis of the colour plot shows the sections of the fibre-optic cable in meters, the colours represent the surface water temperatures in °C. Thereby, each coloured line on the x-axis, from cable section 140 m to 325 m, represents one measurement. The y-axis states the time of the measurements.

5.3.2 *Active and passive DTS measurements with the buried fibre-optic cable*

During active and passive DTS data acquisition with the buried fibre-optic cable (PAB approach), surface water temperatures varied between 14.3 °C and 19.2 °C (Fig. 5.6). The streambed temperatures, on the other hand, varied more strongly, ranging between 14.3 °C and 29.6 °C. The streambed temperature distribution, however, was not uniform. Maximum streambed temperatures occurred around cable sections 205 m and 240 m. Elevated and minimum streambed temperatures appeared around cable sections 45 m, 135 m and 143 m, but also, less pronounced, around cable sections 60 m, 70 m, 79 m and 180 m. In the other sections of the fibre-optic cable, streambed temperatures changed less throughout the day and night, varying only slightly between 15.4 °C and 16.5 °C, except during periods in which the fibre-optic cable was heated. The heating of the fibre-optic cable caused a rise in cable temperatures of between 1.3 °C and 1.6 °C, depending on the initial temperature of the cable. In the section of maximum streambed temperatures, heating was more rapid and led to a slightly higher temperature difference (ΔT 1.6 °C), than in the other sections (ΔT 1.3 °C).

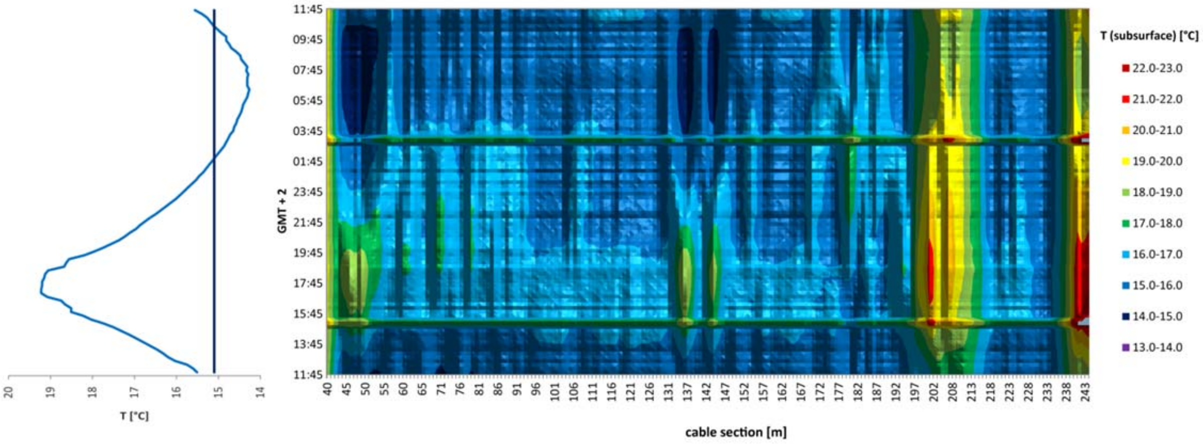

Figure 5.6. Surface water (light blue) and groundwater (dark blue) temperature (line diagram, left side) and streambed temperatures (colour plot, right side) in the Chriesbach streambed at about 0.4 m depth, as measured with a fibre-optic cable installed after river restoration on 03. – 04. July 2014. The x-axis of the colour plot shows the section of the fibre-optic cable in meters, the colours represent the streambed temperatures in °C. Thereby, each coloured line on the x-axis, from cable section 40 m to 243 m, represents one measurement. The y-axis states the time of the measurements.

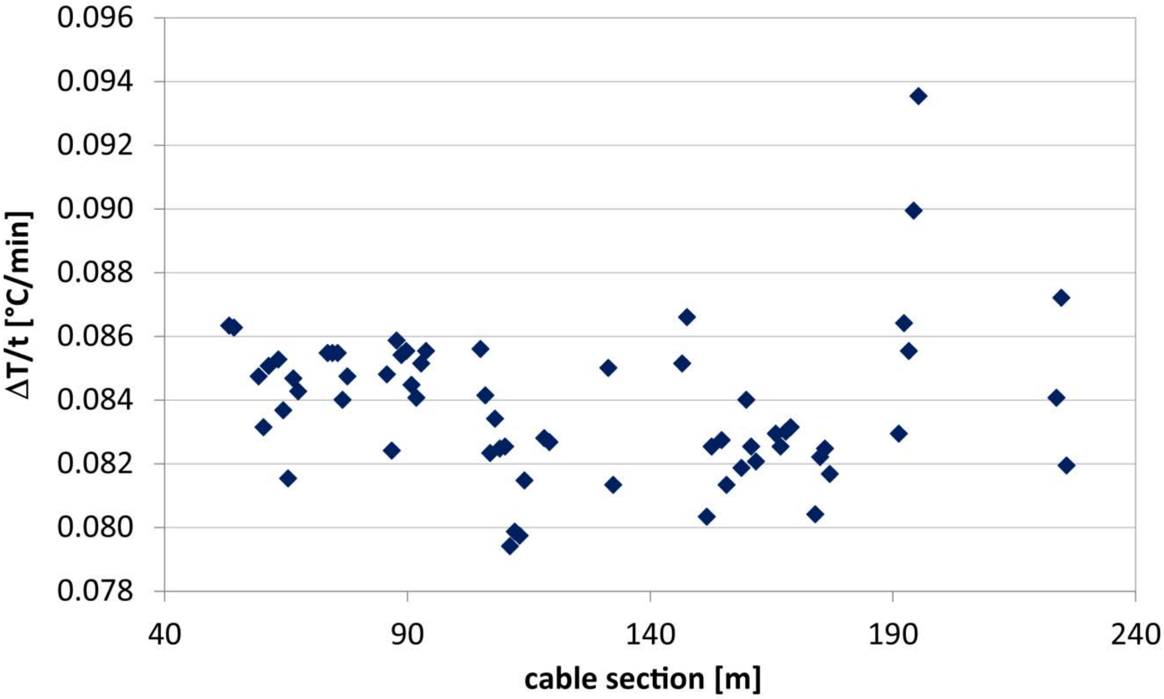

Figure 5.7. Cooling rates of cable sections with a temperature between 15.9 °C and 16.1 °C determined at 3 am on 04 July 2014 in [°C/min].

The lowest cooling rate was seen at cable sections 111 m (Fig. 5.7) in a shallow part of the stream with stagnant water, the highest cooling rate was seen at cable section 195 m at the tip of a gravel island. About 80 % of cooling rates ranged between 0.082 °C/min and 0.086 °C/min.

5.3.3 *Radon-222 measurements*

The Radon-222 activity in the surface water samples of the Chriesbach, obtained after its restoration, was very low (Table 5.1). However, sample 5.1 had a higher Radon-222 activity, which was not seen during the second sampling campaign. The Radon-222 activity in the groundwater samples was significantly higher than in the surface water samples, and increased with increasing distance from the stream.

5.4 Discussion

In this study we investigated whether river restoration in an urban setting indeed enhanced the vertical connectivity in the stream and thus created conditions in which the ecosystem can, under given conditions, unfold its full potential.

Table 5.1. Radon-222 activities in Bq/m^3 in groundwater and surface water samples from the Chriesbach. Samples 4.2 and 5.2 are replicates of samples 4.1 and 5.1, taken 39 days after the first sampling event.

#	sample location	type	Radon-222 activity [Bq/m^3]
1	restored section, close to stream	groundwater	3482 +/- 627
2	restored section, close to piezometers	surface water	517 +/- 246
3	restored section, further away from stream	groundwater	5037 +/- 563
4.1	restored section, 0.4 km upstream of investigated area	surface water	411 +/- 169
4.2			90 +/- 104
5.1	unrestored section, ca. 0.5 km upstream of investigated section	surface water	1103 +/- 243
5.2			47 +/- 94
6	unrestored section, ca. 0.55 km upstream of investigated section	surface water	0 +/- 0

The surface water temperature profile of the unrestored Chriesbach was very uniform along the investigated section of the stream. However, there were two cable sections at 372 m and 379 m with slightly elevated surface water temperatures. The purple line visible after 3 pm on 14 March 2013, around cable section 372 m (Fig. 5.2), was caused by a sharp bend in the cable, a defect that was visible in the post-restoration data as well (Fig. 5.3). The slightly elevated surface water temperatures around cable section 379 m (Fig. 5.2) were due to algae and debris accumulating at this section of the fibre-optic cable, possibly acting as a temperature buffer.

A similarly uniform surface water temperature profile was seen in the Urbach. The drainage ditch was groundwater-fed on the day of the experiment. The surface water temperature profile in the main channel was very similar to the drainage ditch, indicating that the main channel was mainly groundwater-fed in the investigated section of the stream. The slightly elevated surface water temperatures in the main channel were caused by the channel being fully exposed to the sunlight throughout the experiment, while the drainage ditch was shaded in the afternoon. Robinson and Doering (2013) observed a similar pattern of groundwater upwelling in the investigated section of the Urbach’s main channel and groundwater-fed tributaries on the eastern side of the stream. Presumably groundwater upwelling occurred uniformly and on a large scale, as no localised regions of groundwater temperatures were observed in the main channel or the drainage ditch.

Localized groundwater upwelling, however, was observed in the Röthenbach. Here, groundwater upwelling occurred in discrete zones, in which surface water temperatures were constant or elevated throughout the experiment. In the zones with constant surface water temperatures, significant amounts of groundwater were infiltrating into the stream. Similar observations were made e.g. by Unland et al. (2013). In this context, *significant* means a groundwater inflow rate sufficient to maintain surface water temperature at a constant value equalling the groundwater temperature. In the zones with elevated surface water temperatures, groundwater was infiltrating, albeit not in significant volumes.

In case of the Chriesbach, these results would indicate that there was either groundwater upwelling on a large scale or no groundwater upwelling at all. The surface water temperature of the Chriesbach was ca. 2 K below the groundwater temperature and strongly varied with the daily temperature fluctuations, indicating that there was no significant groundwater upwelling in the investigated section of the stream. The surface water temperature profile of the Chriesbach after restoration was equally uniform in space as prior to its restoration, with four exceptions. The lower surface water temperatures around cable section 372 m were caused by the defect in the fibre-optic cable already seen in the data of the unrestored Chriesbach. The surface water temperature anomalies around cable sections 299 m and 478 m were due to the fibre-optic cable being exposed to the air. The lower surface water temperatures around cable section 357 m, on the other hand, were induced by the fibre-optic cable resting in a section of the stream with stagnant and very shallow water, which cooled down more rapidly than the rest of the stream.

Apart from these anomalies, the surface water temperature profile was very uniform in space. However, it was very uniform in time as well. There are several explanations for this behaviour: either the amount of groundwater infiltrating from further upstream increased due to river restoration or the significantly lower variation in air temperature (14.1 °C before restoration, 4.4 °C after restoration) induced a much smaller change in the surface water temperature. Hydrogeological investigations at that time indicated that the Chriesbach was a losing stream in the investigated section, which confirmed that the homogeneous surface water temperature profile was caused by the lower air temperature variations.

Radon-222 measurements in the restored Chriesbach and an unrestored reference section of the Chriesbach further upstream confirmed the losing conditions of the Chriesbach in the investigated section and indicated that no groundwater upwelling occurred upstream either.

The active DTS data with the fibre-optic cable buried at about 0.4 m depth indicated that most surface water downwelling occurred at cable section 195 m, the tip of a gravel island newly created during restoration of the Chriesbach. Research by Shope et al. (2012) confirm this observation. The lowest downwelling was seen at cable section 111 m, a section of the cable buried in a shallow pool of stagnant water at the side of the stream. Cooling rates in the other cable sections were rather uniform, which might be explained by the homogeneous sediment composition and a lack of in-stream structures in these stream sections.

5.5 Conclusions

Even though success evaluations in river restoration are increasingly being employed to test whether restoration measures were successful in improving conditions for the ecosystem, hydrogeological success, which influences ecological success as well, is not routinely investigated. We therefore, for the first time, examined hydrogeological success, i.e.

groundwater-surface water interactions, before and after the restoration of an urban stream and compared results to streams in natural and near-natural conditions. Results indicated that in the Chriesbach, groundwater-surface water interactions after restoration significantly increased due to the installation of gravel islands. Although our results were site specific, it may be assumed that the installation of gravel islands, riffle-pool sequences and other in-stream structures generally improve groundwater-surface water interactions.

Future research should focus on investigating, amongst others, the hydrogeological success of river restorations. Suitable methods for investigating the hydrogeological success in gaining and losing conditions is the PAB approach which applies passive (P) and active (A) Distributed Temperature Sensing (DTS) to a buried (B) fibre-optic cable. Admittedly, it would be impossible to install a fibre-optic cable in or on the streambed of every restored stream. However, an installation in the streambed would only be necessary under losing conditions; in gaining streams a simple installation on the streambed would suffice. These methods could then be employed only in selected case studies to help elucidate which restoration measures improved hydrogeological conditions and under which circumstances. In this way, future restoration projects could be optimized towards cost-effectiveness and efficiency in re-establishing vertical connectivity, which would help to increase the overall effectiveness of river restorations.

Acknowledgements

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Chapter 6

Conclusions and Outlook

6.1 *Conclusions*

The main contribution of this Ph.D. thesis is the development and application of a Distributed Temperature Sensing (DTS) method for the investigation of groundwater-surface water interactions under gaining and losing conditions with special attention to the effects of river restoration on vertical connectivity. This is achieved by (1) the development of an autonomous DTS system (ADTS system), (2) by the further development of existing and the development of novel DTS methods, and (3) the application of these DTS methods to answering questions regarding the effects of river restoration on vertical connectivity. In order to understand the latter, however, it was (4) necessary to review the restoration methods employed in Switzerland. In the following, the conclusions for each of the objectives are discussed.

6.1.1 *Autonomous Distributed Temperature Sensing System (ADTS system)*

Following initial difficulties with system failures, the ADTS system now runs stable. The remote control enables changes to the system, and monitoring of data, from any computer with a working internet connection. The ADTS system has been simplified and is easy to operate. Collected data is automatically sent to a web-based file hosting service, from where all parties involved have access to the data. The heating of the fibre-optic cable is automated and runs steadily, and the power consumption of the heating is automatically logged. In case of power failure, the ADTS system automatically restarts, while in the event of computer failure the DTS data is buffered on the DTS instrument. Computer failures were reduced with regular forced restarts and the installation of a cooling system for the ADTS system. Power consumption was reduced by installing power-optimised system components and by evaluating the optimal heating moment and duration. Even though the ADTS system is connected to the power grid, a grid-independent power supply would be an option.

Combining these assets, the ADTS system enables time-saving research in remote areas, the only requirement being access to an internet connection once a day. The ADTS system provides research opportunities in areas that would otherwise be unavailable for long-term investigations due to expenditure of time or remoteness, such as mountainous regions or desert surroundings. Additionally, the Raman-based DTS instrument in the ADTS system could be exchanged or supplemented with Brillouin- or Rayleigh-based DTS instruments. This would allow the ADTS system to be used not only for temperature investigations (Raman-based DTS), but also for pressure measurements (Brillouin-/Rayleigh-based DTS).

6.1.2 *PAB approach for DTS measurements under gaining and losing conditions*

The well-established passive DTS method has been shown suitable for investigating groundwater upwelling in brooks and small streams. However, investigations of groundwater upwelling in larger streams and rivers, and surface water downwelling in similar settings are of equal interest. Hence, this Ph.D. thesis aims at developing a method that will enable research in all water courses, independent of their sizes or their hydrological conditions.

The novel approach of combining passive (P) and active (A) DTS methods with a buried (B) fibre-optic cable (PAB approach) enables investigations of groundwater-surface water interactions in gaining and losing conditions and even in higher-order streams, provided the terrain is accessible by a tractor and the tractor pulling the plough is sufficiently strong to enter the streambed substrate.

Apart from investigations of groundwater-surface water interactions under gaining and losing conditions, the PAB approach enables the determination of travel times in the subsurface by providing information on dampening and time shifts of temperature signals. Additionally, groundwater upwelling and surface water downwelling rates can be qualitatively estimated. This provides information on “hot spots” (temperature anomalies) of groundwater exfiltration or surface water infiltration into the water course, enabling the sequencing of the complex interplay of up- and downwelling areas and their connection to in-stream structures.

6.1.3 *Effects of river restoration on vertical connectivity in streams*

The above-mentioned PAB approach is suitable for the investigation of the effects of river restoration on vertical connectivity within streambeds, i.e. groundwater-surface water interactions, as the latter can be examined before and after the restoration of a water course and results compared thereafter. In this Ph.D. thesis, an urban stream, the Chriesbach, was surveyed before and after its restoration with passive DTS (before restoration) and the PAB approach (after restoration). The PAB approach could not be employed prior to restoration, as the buried cable would have been damaged due to the extensive remodelling of the streambed during restoration. Hence, the passive DTS method was employed and results compared to reference streams in natural and near-natural settings.

The results indicate that, after restoration, an increase in surface water downwelling was inferred at the tip of a newly installed gravel island. In no other section of the Chriesbach was such a high surface water downwelling observed. Unfortunately, there are no comparative data from pre-restoration conditions. However, as the highest surface water downwelling occurred specifically at the newly created gravel island, it is reasonably concluded that the rate of surface water downwelling indeed increased due to river restoration. In the investigated section of the Chriesbach, three gravel islands were installed, two of which were not investigated with the PAB approach. Presumably, vertical connectivity in these structures is equally distinctive. It is thus also concluded that the installation of in-stream structures, such as gravel islands, gravel bars, riffle-pool sequences and meanders, are suitable measures for the enhancement of vertical connectivity in degraded streams.

6.1.4 *River restoration efforts in Switzerland*

River restoration projects have been undertaken in Switzerland since 1979. A nation-wide survey found no correlation between the number of restoration projects and the size of the canton, its population density, political orientation or financial status. However, there was a geographical trend in the type of implemented restoration measures. Western Switzerland preferred a more holistic approach to restoration, combining various restoration measures, such as water quality improvements, habitat provisions and removal of shore-stabilising structures, to support a natural (re-)development of surface waters. Cantons in central and eastern Switzerland preferred direct mechanical intervention, namely the remodelling of the terrain. This might be due to restorations being implemented in predominantly rural areas in western Switzerland, where (agricultural) pollution might be an issue. In central and eastern Switzerland, more restorations were performed in urban areas with a high occurrence of covered streams, which required direct mechanical intervention, i.e. uncovering and re-creation of natural streambeds.

Most restoration projects did not record any data regarding success evaluations, either because they had not been performed or because they had been outsourced to private companies and no data were available. For those projects which included success evaluations, they were predominantly assessed as being successful. However, success evaluations often did not, as proposed e.g. by the EU Water Framework Directive (2000/60), evaluate the state of species defined as representative for ecosystem health and functioning, but rather focussed on flagship species, such as the number of salmonids passing a specific section of the stream. The goal of river restoration in Switzerland as defined by the Swiss Water Protection Act (814.20) is the re-establishment of a naturally functioning ecosystem, which thus would be difficult to evaluate.

6.2 *Recommendations*

In the following we provide a decision tree to assist in the application of the ADTS system and the PAB approach (Fig. 6.1).

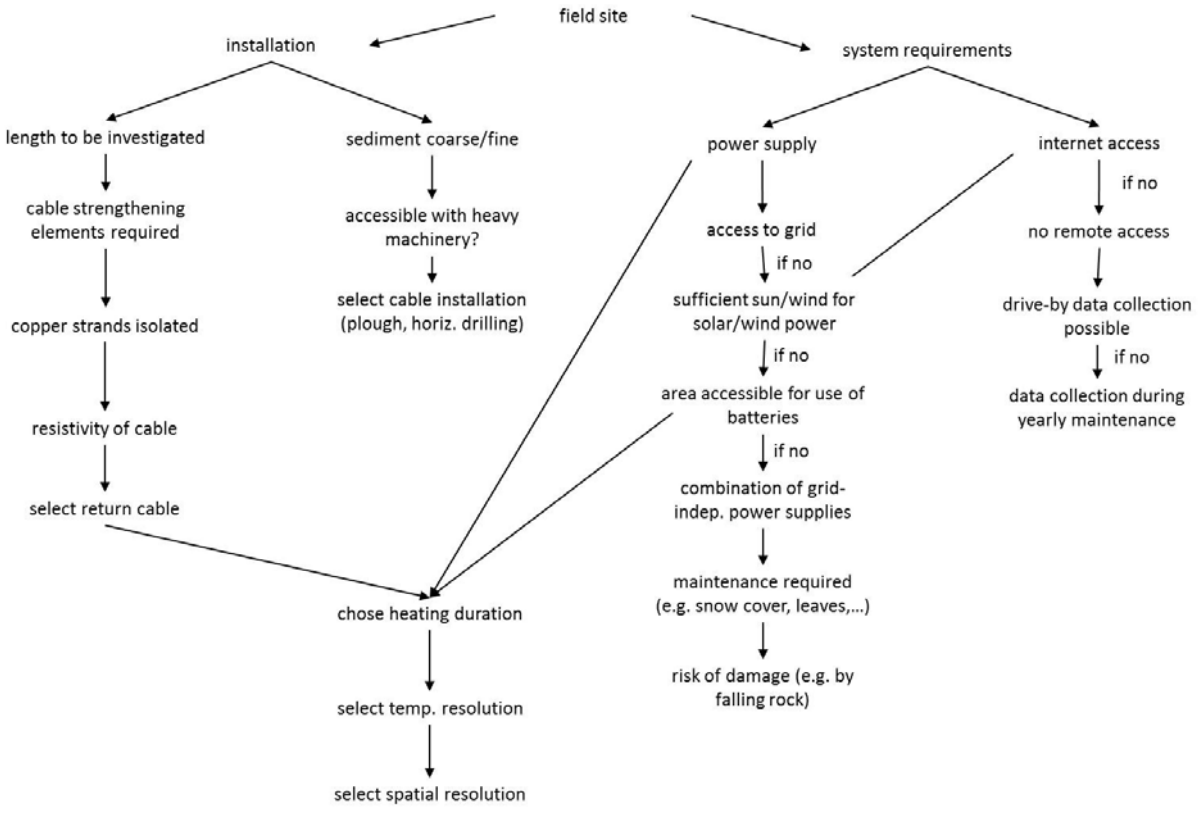

Figure 6.1: Decision tree for the application of the ADTS system and the PAB approach.

In the case of the application of the ADTS system and the PAB approach at the Chriesbach field site in north-eastern Switzerland the decision tree was as follows (from right to left):

- field site
    - system requirements
        - internet connection: available via mobile phone network
        - power supply: available via the power grid on site
    - fibre-optic cable installation
        - sediment: fine
            - Chriesbach accessible for heavy machinery
        - length to be investigated: 200 m
            - strengthening elements in cable required: yes
                - copper strands isolated in fibre-optic cable: no
                - resistivity of fibre-optic cable: 4.8 Ohm
                - return cable properties: copper, cross section 30 mm^2
    - heating duration: 30 min
        - temporal resolution: 5 min
            - spatial resolution: 1 m

The large cross-section of the copper return cable had to be selected as the maximum resistivity of the total heating installation, i.e. the fibre-optic cable plus the return cable required to close the circuit, was 5 Ohm. This value resulted from the required amperage of 10 A necessary to heat the fibre-optic cable sufficiently and the maximal allowed voltage of 48 V. The heating duration was selected in laboratory investigations prior to the field installation. In these experiments the fibre-optic cable reached its maximum temperature after 5 minutes. Allowing for another 5 minutes of heating for the calculation of the cooling rate a total heating duration of 10 minutes would have sufficed. In order to resolve the heating and cooling behaviour adequately a temporal resolution of 5 minutes was selected. A longer temporal resolution of maximal 10 minutes would have been possible as well. A shorter temporal resolution would have significantly lowered the signal-to-noise ratio and therefore data quality. The spatial resolution was set to the lowest possible value of 1 m as the highest possible spatial resolution was preferred. Higher spatial resolutions, such as 0.1 m, would have been interesting. However, they were not possible with the employed DTS instrument.

Independent of the field site and the resulting requirements, it is highly recommend to testing the system, as it is to be installed in the field, in the laboratory prior to field installation.

6.3 *Outlook*

This Ph.D. thesis has yielded insights into various aspects of groundwater-surface water interactions and Swiss river restoration practice, and has provided numerous opportunities for further research.

The ADTS system opens windows on new investigations in geographically remote areas. Prerequisites for successful application of the ADTS system, however, are a stable internet connection and, most importantly, a grid-independent power supply. In a few years time, stable internet connections may be available worldwide. Additionally, new technologies might provide efficient and environmentally friendly grid-independent power sources, which are small, require low maintenance and are independent of the weather. This would facilitate research applications in remote areas, which is currently difficult or impossible due to a lack of internet connection or insufficient solar radiation for power production.

Combined with the PAB approach, the ADTS system enables research investigating not only contaminant inflow into streams, but also from streams into aquifers. Additionally, complex patterns of up- and downwelling in various in-stream structures, such as riffle-and-pool sequences, can be sequenced or the effects of streambed clogging on the vertical connectivity in streams can be surveyed. Large-scale investigations of groundwater recharge could be performed, or effects of drastically lowered groundwater levels, e.g. due to seasonal variations in groundwater levels or due to excessive groundwater pumping, could be examined.

Another focus of attention could be the continuing investigation of groundwater-surface water interactions in water courses before and after their restoration. Here, further research could address the question of quantifying groundwater upwelling and surface water downwelling, e.g. by aid of thermal transport models. Thus, the effects of specific structural changes to river morphology could be studied. As a consequence, the effects of specific river restoration measures on vertical connectivity could be investigated. Optimal restoration techniques for re-establishing near-natural groundwater-surface water interactions might be also be identified for various settings, thus optimising the restoration process. As natural aquatic ecosystems depend on groundwater-surface water interactions (Bardini et al. 2002; Wondzell 2011;

Boulton et al. 1998; Malard et al. 2002; Thorp et al. 2006), establishing these interactions should be an integral part of future river restoration projects. The result will be a naturally functioning water course.

However, it would be advisable to make success evaluations an obligatory element of river restoration projects, using, for example, a specifically-reserved proportion of the budget. This would require detailed pre-restoration investigations, ideally better exposing the underlying causes of degradation, which would enable better definitions of appropriate restoration targets. The achievement of these pre-defined goals could then, post restoration, be tested in success evaluations. It would be advisable to create a code of practice for river restoration success evaluations, which would have to be followed in all restoration projects. The results of these nationally-comparable success evaluations, including the restoration aims and measures, should be entered into a nationwide restoration database and made available to the public. This would then better enable identifying suitable restoration measures under various different settings, e.g. in urban or mountain streams, making river restoration more efficient. As 4000 km of degraded water courses are to be restored over the course of the next 80 years (BAFU 2011), it would be sensible to render the restorations as efficient as possible in re-establishing a natural functioning of water courses and their ecosystems. A first step could be the routine investigation of groundwater-surface water interactions in degraded streams before and after their restoration by aid of the ADTS system and the PAB approach.

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