Summary of Thesis

Understanding groundwater-surface water connectivity of heavily modified rivers, County Durham, UK

Rebecca Smith – August 2019

Abstract

Groundwater and surface-water systems have long been considered fragmentally, lacking a holistic integrated understanding that is considered essential for sustainable catchment management. The high heterogeneity of local systems and the influence on water quality is typically unaccounted due to limited monitoring of hydrologic and hydraulic variables, particularly of minor aquifers. Thus, impacting on the wider catchment management of freshwater systems due to the dearth of understandings of the system characteristics. This thesis focuses specifically on water bodies in County Durham that are heavy modified attributing to their industrial past, with the current water quality being compromised by a multitude of historic and contemporary pressures. The research employs a combination of desk- and field-based approaches to investigate flow and solute patterns and processes operating at the groundwater-surface water interface.

The research demonstrates that through the collation of spatial data it is possible to assess the stream-aquifer connectivity by evaluating simple patterns in the landscape characteristics. In-turn challenging the local-scale connections and leading to subsequent investigations of the groundwater-surface water controls on water quality. Field-based investigations of the local systems highlight the integral role of near-stream sediments on the fate of flow and solutes from the surface and subsurface. Through the application of numerical modelling, flow pathways have been further interpreted, assessing the spatial and temporal interactions at the stream-aquifer interface in response to changing hydrological conditions. Findings indicate the likely role of the shallow groundwater having a detrimental effect on the cycling of flow, with dynamic responses reflecting variations in stream levels, thus highlighting the need to consider processes at the stream-aquifer interface that are typically overlooked. The findings of this research challenge the predominant targeted reductionist approaches to water management in systems of this sort, where the influence of the multitude of pressures pathways and their relation to the contemporary water quality has been overlooked. There is a need for practitioners to consider the freshwater systems over multiple dimensions and time to achieve sustainable water management.

1. Background and motivation

There is a need to address water-quality issues, both in the present and in the foreseeable future (Wallace and Gregory 2002), considering the ever-increasing human and ecological demands for freshwater resources (Muller 2017). To meet such demands, it is imperative that water is of good quality. However, the quality of water, both at the surface and subsurface is increasingly threatened by pollution from historic industry (Younger *et al.* 2002, Potter *et al.* 2004, Gandy *et al.* 2007) as well as contemporary sources (Wheater and Evans 2009, Hering *et al.* 2015). The accumulation of pollutants and contaminants across the surface-water (SW) and groundwater (GW) systems consequently results in a multitude of threats to freshwater resources attributing to the interactions and exchanges in flow and solutes across the streambed (Sophocleous 2002, Yu *et al.* 2006, Baldock *et al.* 2009, Kløve *et al.* 2011, Deb 2014, Harvey and Gooseff 2015, Johnson and Hallberg 2015).

Traditionally the monitoring and management of water quality has been broadly segregated between hydrologists and hydrogeologists, individually focusing on the SW and GW systems respectively (Macleod *et al.* 2007, Staes *et al.* 2008, Muller 2017). The understanding and management of pollution and contamination has typically been prioritised at the source or point of impact as part of a reductionist or '*command and control*' approach (Macleod *et al.* 2007, Staes *et al.* 2008, Heathwaite 2010, Li *et al.* 2016) overlooking the pathways and interactions from the source to receptor. Instead, addressing issues with a '*black-box*' or '*pipe-system*' focus (Figure 1-1) in either the surface or subsurface regardless of the exchanges within and between the systems (Bencala 1993, Bencala *et al.* 2011, Harvey and Gooseff 2015, Magliozzi *et al.* 2017). Consequently, the segregated understanding of water resources has, and most often remains to be resulting in conflicting management and solutions with priorities and procedures to address issues being dispersed amongst organisations and stakeholders (McDonnell 2008). The fragmented arrangement and subsequent mismanagement is despite the likely coupling and connectivity between the systems, whereby the deterioration or improvement of the SW having the potential to impact on the GW body, and vice-versa (Baldock *et al.* 2009, Kløve *et al.* 2011, Figure 1-1). The stream needs to be considered as an integral part of the catchment system, as a conduit of inputs from the landscape with transport via flow paths downstream and across the streambed (Bencala 1993, Bencala *et al.* 2011, Figure 1-1).

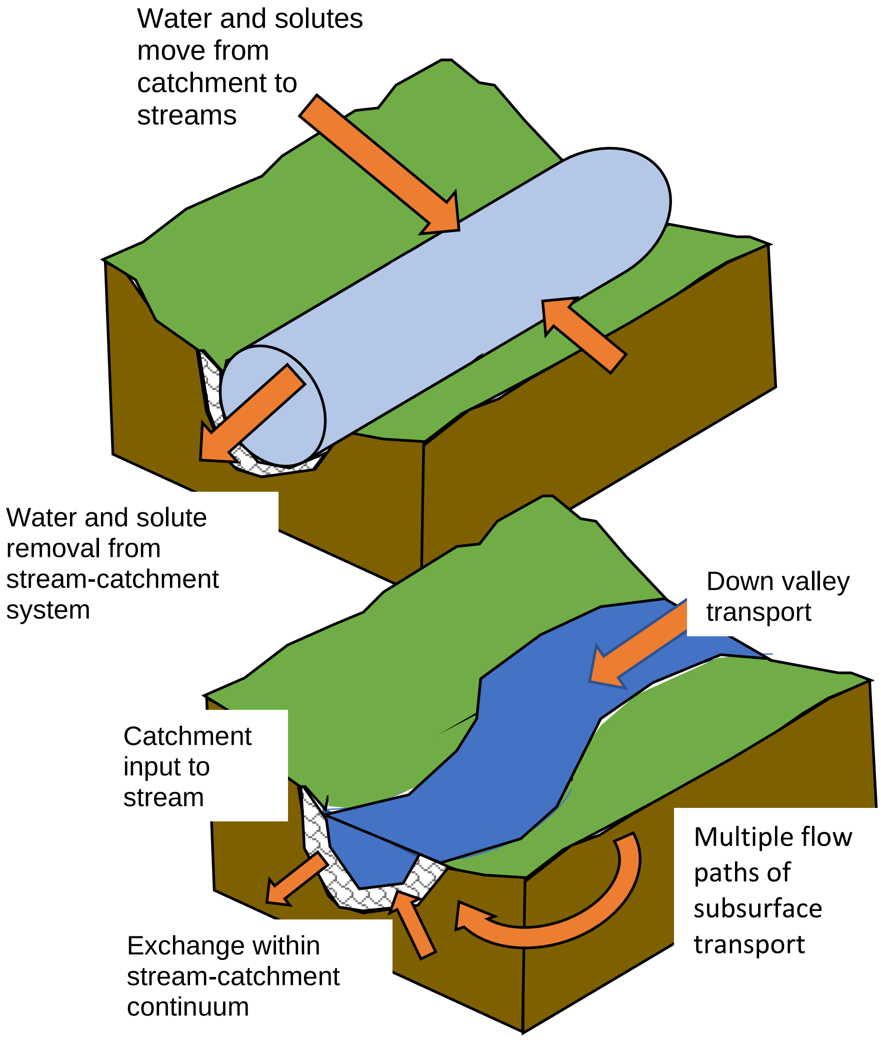

Figure 1-1: (A) The stream's function in a catchment considered as a pipe; (B) A contrasting view where the stream is an integral part of the catchment system (Source: adapted from Bencala 1993).

GW/SW interactions are widely acknowledged in research (Cardenas 2015). A continually growing body of literature are looking at the GW/SW exchanges and the myriad of processes spanning hydrological to ecological disciplines with the mixing of GW and SW within the streambed interface referred to as the hyporheic zone (Winter *et al.* 1998, Sophocleous 2002, Buss *et al.* 2009, Cardenas 2015, Figure 1-2). The hyporheic zone is characterised by the mixing of GW and SW, as well as biogeochemical activity attributing to fluxes in oxygen (O_2), nutrients or organic carbon (Brunke and Gonser 1997, Bencala 2000, Hannah *et al.* 2009, Wondzell 2011). The high reactivity of the near-stream sediments (Smith and Lerner 2008) with the mixing of GW and SW and biogeochemical activity creates potential environmental hotspots (McClain *et al.* 2003, Lautz and Fanelli 2008). Within these hotspots, the cycling and fate of dissolved nutrients and contaminants of GW or SW origin are potentially enhanced by hydrochemical or biogeochemical processes (Ibrahim 2012). The GW/SW interactions result in a mosaic of pathways operating across the surface-subsurface interface and are dependent on a range of spatial and temporal controls, namely the geomorphic and hydrogeologic features of a catchment, as well as hydrometeorology and geomorphology dynamics operating over short- to long-term scales (Tetzlaff et al 2007).

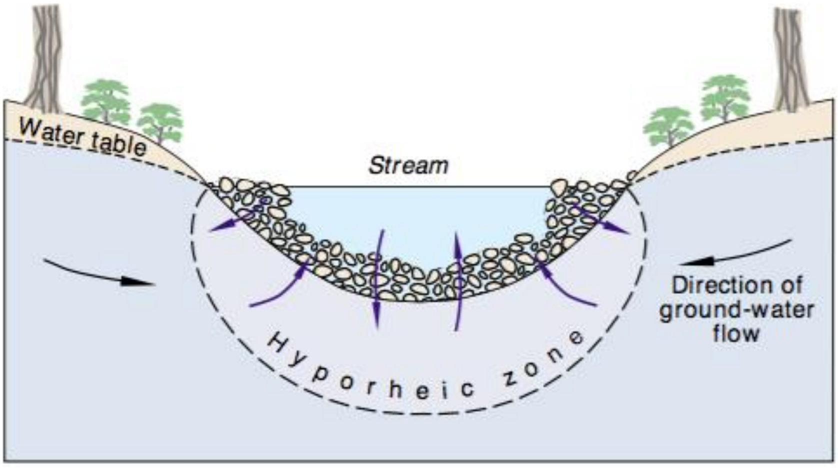

Figure 1-2: Hydrological interfaces: the stream, GW and hyporheic zone (Source: adapted from Winter et al. 1998).

Within academia there is a strong understanding of the GW/SW processes, and it is generally well documented that systems interact, with several comprehensive reviews on the stream-aquifer interactions (Cardenas 2015, Tanner and Hughes 2015). However, there is often a lack of direct data to quantify the individual processes or structural geological information to establish GW/SW connections of local systems (Tanner and Hughes 2015). There is growing emphasis to develop an understanding of such processes operating at the local scale and integrate these understandings into the larger scale patterns of GW/SW interactions and hyporheic pathways within the catchment boundaries (Harvey and Wagner 2000, Woessner 2000, Poole *et al.* 2008, Magliozzi *et al.* 2017). For effective water management there is a need to develop an understanding of the local-scale processes and link these understandings to the wider catchment, rather than assessing and managing the catchments broadly as closed systems with targeted efforts on specific pressures. The integrative understanding across the catchment is particularly relevant to the framing of recent legislative policy, including the European Union Water Framework Directive (2000/60/EC, CEC 2000, Wheater and Peach 2004, Skeffington *et al.* 2015). The intended holistic and integrated management of water resources at the catchment scale according to the WFD requires an improved assessment of the GW/SW interactions operating within catchments (Smith 2005).

1.1. Aim and objectives

The aim of this thesis is to investigate the way in which GW/SW are connected and interact based on the application of a multi-method approach to assess the movement and fate of flow and solutes within, and between GW and SW systems in heavily modified streams of tributary catchments in the lower River Wear, County Durham. Throughout the thesis, the goal is to explore the use of novel approaches to conceptualise and characterise the connectivity and interactions between the GW and SW systems in situations where there is a fragmented understanding and thus subsequent decoupled management of the systems attributing the inadequacy of hydrologic and hydraulic data representative of the GW and SW systems.

To achieve this aim, the thesis has the following objectives:

Objective 1 – to assess the threats to GW and SW quality, identifying historic and contemporary sources through the application of desk- and field-based approaches, to give a primary assessment on the connectivity making use of reconnaissance walkover surveys and discussions with local water organisations and stakeholders.

Objective 2 - to assess the likely controls on the water movement, testing the feasibility of utilising existing data to conceptualise the characteristics and linkages between the GW and SW systems to provide an understanding of the connectivity when baseline monitoring is lacking. In-turn, this will involve reviewing existing integrated assessment approaches and understanding what is missing. They will result in a proposed framework/tool to facilitate an integrated assessment of the GW/SW system connectivity is to be recommended and introduced with the application to case study areas facing a multitude of on-going water quality threats.

Objective 3 – to undertake field sampling to determine the fluxes of flow and solutes within the stream water and across the streambed, to further test the understanding of the GW/SW connectivity following on from the initial conceptualisation. By doing so, it is with the intention to assess the role of GW in the potential attenuation and release of flow and solutes and the likely consequent impact on the water quality of the overlying stream in systems which are currently viewed to be disconnected due to the neglected assessment of the superficial systems between the stream and major aquifers.

Objective 4 – to apply numerical modelling techniques to explore the system responses to changing hydrological conditions, interpreting the flow and solute patterns beyond the local-scale. Thereby extending the scope of the study and understanding beyond the spatial and temporal constraints of field sampling, upscaling the point-based understanding into the dynamics and processes operating in the wider systems.

Objective 5 – to make recommendations of how the management of GW and SW systems could be improved in working practice to enhance the water quality and fitting into the wider catchment priorities.

2. Integrated River Evaluation for Management (IREM)

IREM is proposed as a simple, first-order approach to provide an approximation of the characteristics and connectivity within catchments, providing a basis to then assess the likely GW/SW exchange pathways operating at the local reach and sub-reach scales. The novelty of IREM is that the approach is developed to utilise existing, freely available data, to assess the structural and functional connectivity within catchments, considering multiple spatial dimensions and time. The framework allows for the state of connectivity to be determined where intensive and simultaneous monitoring of the GW and SW has not been performed. As acknowledged previously, there is a range of existing data that can provide useful information about surface and subsurface environments, and here I explore the collation of this data to develop a conceptual understanding of the systems. In practice these data, for instance, surface runoff and superficial deposit thickness are not typically brought together to investigate and conceptualise problems within catchments, instead there is typically a dependence on metric-based estimates, which offer limited insight, particularly when interested in smaller scale variations accounting to localised issues.

IREM allows for a holistic assessment of the system behaviour and connections required to deal with contemporary fluvial challenges, a key priority, moving beyond the fragmented view of the systems (Staes *et al.* 2008) to bring together data that helps to understand interactions between SW and GW that influence water quality (Figure 1-3). Where there are multiple threats to the water quality, a point-source attribution is inappropriate, as the threats themselves and the pathways intertwine resulting in diffuse pollution from a multitude of sources (Heathwaite 2010). Previously, attempts have just focused on the threats and local-scale assets, failing to demonstrate the ICM principles, which overlooks the multiple stressors affecting the water quality. There is a need to develop an understanding of the local links, moving towards understanding the processes and pathways likely operating within catchments to then challenge the current management of water-quality issues with a holistic and integrated focus.

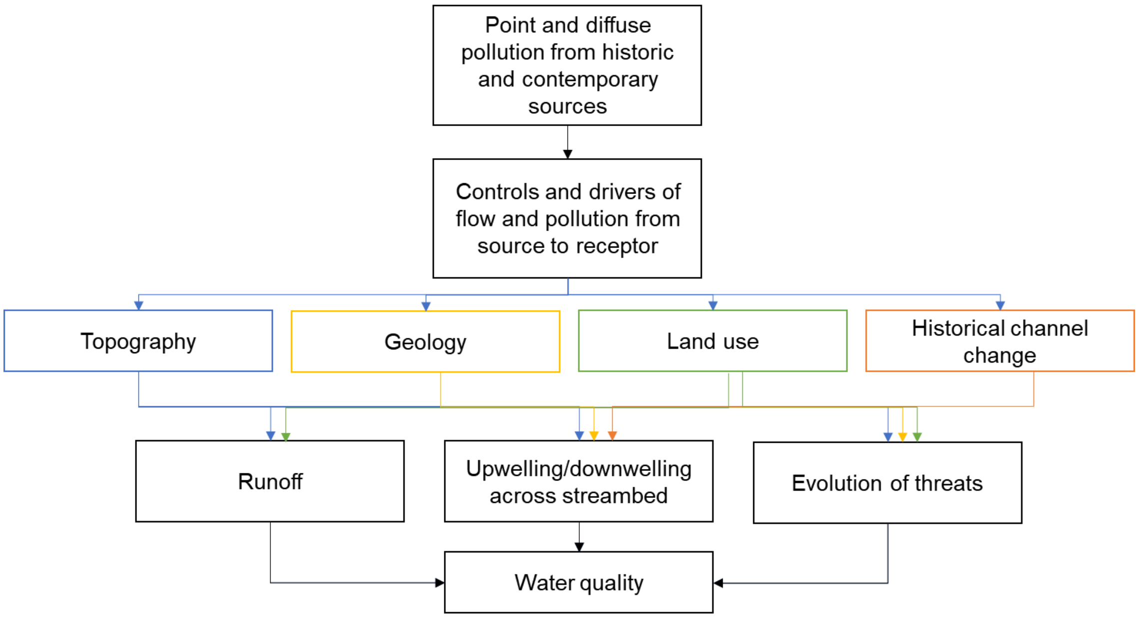

Figure 1-3: Data use in IREM, illustrating the links between elements/factors to derive patterns and pathways accounting to the overall conceptualisation of the catchment systems and resulting water quality.

2.1. Evaluating the IREM approach

The results of this study demonstrate the potential use of secondary spatial data as a way of exploring and developing a preliminary understanding of the connections between the terrestrial and aquatic systems where a paucity of monitoring data deters alternative approaches. By assessing the connections then allowed for thoughts to lead to the factors controlling and driving the evolution of water quality threats, which ultimately need to be better understood to facilitate more effective and sustainable management of water resources (Ivkovic *et al.* 2009, Bracken *et al.* 2013).

The application of IREM allows for a relatively simple, first-order approximation of the characteristics and connectivity compared to alternative, more technical and intensive approaches, as outlined e.g. by Oyarzún *et al.* (2014). IREM offers a useful insight into the system links and pathways, looking at simple patterns, such as those associated with the superficial deposits that may have the potential to support downwelling stream water, and links these observations with other factors, e.g. the thickness of the potential perching material. From such simple patterns, there is the opportunity to start informing how multiple threats impact on the water quality, above and below the streambed, complying a more complex picture from simple links between pressures and drivers (Harris 2007, Kluger 2008).

Recognising the links between controlling factors is essential element when working towards the ICM principles (Macleod *et al.* 2007, Kanndorp *et al.* 2018). Until now, the understanding has been that the stream environments have been closed to the GW, however, looking at the longitudinal, lateral and vertical, and temporal dimensions where relevant, and subsequent discussion with practitioners are indicative that the system connectivity is inherently complex and variable, requiring further investigations. Previously, such understandings of the connectivity having been omitted with high resolution screening studies (Wainwright *et al.* 2011). Applying IREM to the Herrington and Twizell catchments has proven insightful in terms of the next steps with management and research respectively.

The application of IREM has challenges the fragmented views of two heavily modified systems, faced with the complex water-quality issues attributing to a multitude of pressures. Decoupled views of the systems have hindered the understanding and thus likely the improvement of the water quality with procedures focusing on the end-point monitoring and dealing with the consequences rather than looking at the heterogeneity of the systems, accounting to four dimensions over space and time. While it is tempting to assume that systems are homogenous, which effectively simplifies the way the water movement and interactions, this is simplification is at the cost of mismanaging the issues the environment faces at the cost of putting stress on the water resources for humans, ecology and the environment. There is a need to recognise the complexity of systems. In both case studies it is evident that the systems are likely to be variably connected as a function of the catchment characteristics, for example, the geology and the permeability of sedimentary deposits. The understanding requires an insight based on several pieces of data to derive useful information, essentially by removing one could significantly alter the findings.

2.2. Further work

The GW/SW connectivity in the Herrington is complex and inherently important to consider in dealing with the drinking water abstractions. The findings of the application of IREM have led to the discounting of the original hypothesis that the source of nitrate at the borehole was from the stream environment. Consequently, leading to investigating and interrogating the drainage system, however, it was also discounted, given the relatively low nitrate levels compared to those sampled in the borehole. Most recently, at the time of writing, investigations to look at the borehole fabric continue, with no definitive source having yet been found. Without the application of an integrated approach such as IREM, the investigations were arguably lacking coordination due to the missing of vital information, requiring the collaboration of data to make sense of a very complex system.

In the case of the Twizell, the GW/SW system is more intricate in that the managed rebounding GW and shallow GW of the superficial systems is likely acting as a buffer and/or propagator to the pollution arising from coal mining and contemporary sources, e.g. effluent releases, thus requires further investigation. Dissimilar to the Herrington which is receiving targeted efforts as part of on-going work on behalf of Northumbrian Water, the Twizell remains somewhat of a black-box system, with scattered efforts to address water quality at various points throughout the catchment, looking at asset failure, for example (Personal communication with Northumbrian Water). However, there is no wider scope to look at accounting the impacts of industry with the contemporary threats, thus leading for the thesis to carry forward looking specifically at the superficial system of the Twizell.

The primary investigations carried out in this chapter subsequently lead onto Chapter 3 – to look at the functional connectivity along the Twizell. In response to the changing hydrological conditions, the thesis investigates specifically the role of local scale processes of minor aquifers in the buffering/propagation potential of overlying streams, with the need to better understand local processes in the wide catchment understanding.

2.3. Conclusions

To summarise, using the existing spatial datasets has allowed for a more holistic understanding of the systems to be developed. Ultimately, IREM allows for a first-order insight when there are no other data available, such as the possibility of intensive field campaigns, which are costly and may ultimately target the wrong areas to address the challenges. IREM also encourages discussion between practitioners to support collaborative management, something which has traditionally been lacking in management decisions (Downs *et al.* 1991). However, while IREM allows a first-order approximation of the connectivity to be conceptualised, for it to be rolled out in practice further refinements are required, including the use of temporal data, such as flow and rainfall records to allow for changes over time to be factored into the understanding generated.

As demonstrated throughout this chapter, we need to start thinking about the catchment systems in a different way, not just as that the pollution enters at points, but from this, how the system is and interacts with the landscape and other features around it. Moving beyond the mismanagement of water resources requires a holistic and integrated understanding, and this is unachievable under the current protocol and procedures by which we currently attempt to understand the systems. Over recent years, the movement towards collating data to derive information and infer understandings to illustrate the GW/SW connectivity has grown. There is now the need to then look at what is happening in specific catchments of interest where water challenges prevail. Thus, adding to the multi-dimensional focus by starting to establish the movements in flow and solutes and what such processes attribute to the way in which they deal with pollutants and contaminants.

3. Developing an integrated perspective on water chemistry between the stream and subsurface

The work presented in Chapter 3 builds on the findings of Chapter 2, which has led to consider the processes operating at the reach-scale GW/SW interface, with the focus on the role of the minor aquifer system acting as a potential buffer and/or propagator to pollutants resulting from the historic coal mining, besides contemporary effluent wastes. Moving beyond the initial assessment of the GW/SW water connectivity, this chapter seeks to explore the mechanisms by which water moves across the streambed, in-turn assessing the interactions and exchanges in flow and solutes attributing to the dynamics and processes operating at the reach-scale within the Twizell Burn catchment.

The regulation of water quality has traditionally been undertaken from either a surface or subsurface perspective, with separate prioritisations and fragmented frameworks for managing each (Macleod *et al.* 2007, Staes *et al.* 2008, Li *et al.* 2016). Now deemed unsustainable, there is a growing focus on the need for integrative and adaptive solutions (Watson and Howe 2006, Staes *et al.* 2008, Schoeman *et al.* 2014). A key driver of integrative management is the WFD (CEC 2000), a novel approach based on policy, focusing on understanding and integrating all aspects of the water environment at the catchment-scale (Teodosiu *et al.* 2003, Voulvoulis *et al.* 2017, Varli *et al.* 2018). Promoting the protection and enhancement of SW and GW bodies, the aim of the WFD is to achieve the objective of ‘*good*’ status for all water bodies originally by 2015, and now 2027 (DETR 2001, Schmedtje and Kremer 2011). An integral element to the holistic integrated management is developing an understanding of the interactions between the water bodies. There is emphasis on the local-scale processes operating within the boundaries of the catchments, and thus developing a more complete understanding, leading to an improved whole-systems approach to water management.

GW/SW connectivity varies spatially and temporally in response to geomorphic and hydrogeologic features (Tetzlaff *et al.* 2007, Banks *et al.* 2011), including the geology, topography, climate, and the position of the stream-water body and water table with exchanges of the GW and SW occurring at the interface known as the hyporheic zone (Winter *et al.* 1998, Sophocleous 2002, Buss *et al.* 2009). Hyporheic flow paths are important drivers supporting the interconnection of surface and subsurface waters at certain locations (Malard *et al.* 2002, Tetzlaff *et al.* 2007), driving the exchanges and interactions of flow and solutes between the subsurface and stream-water systems with the mixing of stream water with deep GW and shallow GW of underlying aquifers.

Minor aquifers which form in the permeable superficial layers underlying the surface are often capable of supporting water supplies at the local scale, in some cases forming an important source of base flow to rivers (Environment Agency 2013). The vertical hydraulic conductivity of unconsolidated strata permits the loss and gain of stream-water and GW to and from the subsurface (Rains *et al.* 2006). Assessing GW/SW interactions with minor aquifers is challenging, notably because of the heterogeneity along the bed and banks, and complex flows and hydrochemistry associated with these settings, but monitoring is much less intensive in comparison to more productive formations (Jones *et al.* 2000, Ibrahim *et al.* 2010, Abbott *et al.* 2017). As a result, interconnections between the SW and shallow GW are often poorly understood (Niswonger and Fogg 2008, Conant *et al.* 2019), regardless of the contribution to the quality and quantity of water resources of the overlying stream-water, for example, through the provision of baseflow (Soulsby *et al.* 2001, Ivkovic *et al.* 2009, Lerner and Zheng 2011, Lee *et al.* 2018).

Emerging research has focussed on investigating the role and impact of minor aquifers on stream-water mainly using nested hierarchical approaches, often focusing on small scale, point features, such as riffles, pools and meanders (e.g. Soulsby *et al.* 2001, Malcolm *et al.* 2005, Käser *et al.* 2013), and nutrient dynamics (e.g. Dudley-Southern and Binley 2015). Yet in practice, despite the multiple threats to water quality, particularly in heavily modified tributary systems, the focus remains segmented, overlooking this stream-subsurface connectivity (McDonnell 2008). Most often the fragmented view of the SW and GW systems attributes to is a result of the lack of baseline studies and that there is no protocol to address and manage the minor superficial systems given that there is no provision of drinking water, for example, thus lack of need to prioritise from a management priority, hence lack of monitoring. However, as the GW/SW systems are likely connected, it is necessary to account to what is happening, given that a deteriorating GW system could impact greatly on the SW (Kløve *et al.* 2011), Therefore potentially impacting on the water quality of the stream, as also elsewhere in the catchment, or neighbouring water bodies. There is a need to challenge the mismanagement, especially where multiple threats are acting on the GW and SW systems. There is the need to understand the processes operating locally within catchments and link these to the wider catchment understanding to facilitate a holistic and integrated focus to water management.

Monitoring was conducted to acquire spatial and temporal insights into the water quality response. A network of sampling sites enabled the collection of flow and solute measurements (Figure 1-4), comprising SW and shallow GW sampling.

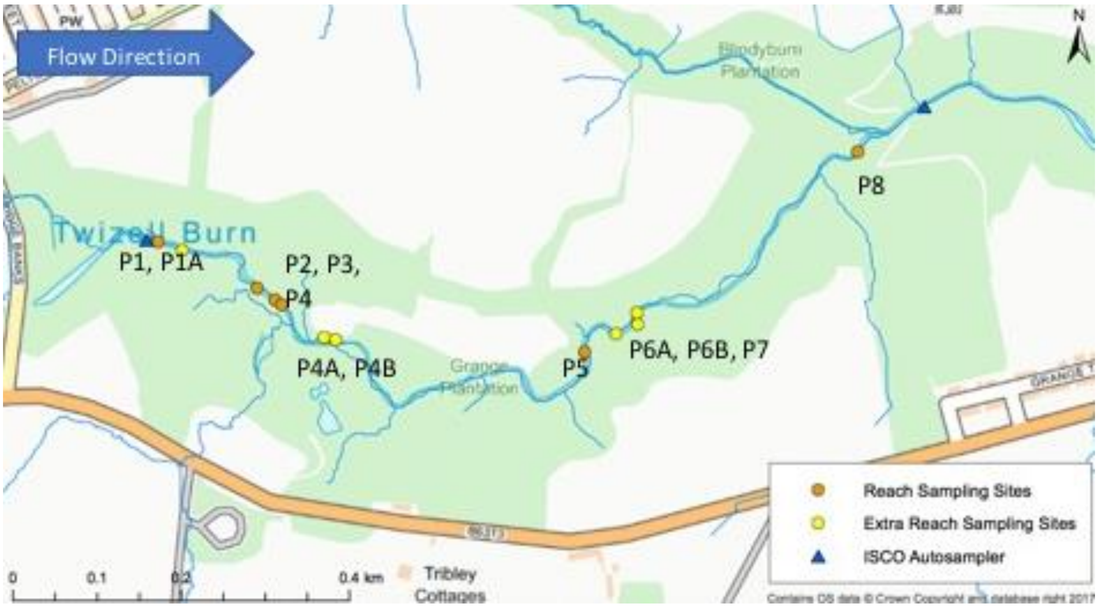

Figure 1-4: Reach sampling locations, showing the sites of piezometers and ISCO-3700 auto-samplers.

3.1. Shallow hyporheic zone

In this unconstrained reach, flow and solute exchanges are evident across the streambed and are complex, operating as a function of the stream flow and vertical hydraulic gradients, with inputs from historic and contemporary sources. VHGs typically ranged between +30 and -20 %, indicative of upwelling and downwelling between the stream and unconsolidated deposits. Ratios of the solute concentrations between the stream and subsurface water confirm that enrichment and depletion is occurring, and it is proposed that the source of this water is most likely that from the stream, rather than solutes rising from the deep GW. Analysis of the research results has led to the working hypothesis that downwelling SW mixes with stagnant or low-flow water in the interface of the surface hyporheic zone (perched), as observed previously in the upper Wear catchment at Rookhope Burn by (Palumbo-Roe and Dearden 2013). The composition of water in the hyporheic zone is dominated by SW and the temporal changes of the pore-water thus reflect those of the SW (Benner *et al.* 1995, Palumbo-Roe and Dearden 2013), with hot-spots of enriched species, such as SO_4^{2-} and Mn occurring under changing conditions.

3.1.1. Monitoring implications for management

Following the monitoring of the flow and solute patterns, an initial insight into the system dynamics suggests that the minor aquifer in the vicinity of the stream is acting as a source and sink of flow and solutes, associated with effluent and mine-water discharges. Whilst results reflect the sampling events throughout the sampling campaign, the study has allowed an insight beyond that of the one-dimension of the stream-water, instead looking across spatial and temporal scales. Whereas previous regulatory sampling has been restrictive, with limited spatial and temporal sampling points, this study has evolved the understanding of the contemporary flows and chemistry to include GW/SW interactions. It is proposed that the spatial proximity to threats and variable stream-flow are key factors in controlling the SW quality. The role of the streambed then adds complexity and it appears that the hyporheic zone acts as a source and sink for pollutants, whereby they are attenuated, resulting in the enrichment of the pore-water, or degraded, occurring as a function of several processes, including the flow direction, oxidation-reduction potential, for example. Hence conceptualising the reach as a black box where the inputs and outputs in chemistry are a function of the flow along the stream alone is incorrect and not appropriate. The findings emphasise that local processes are key to evaluate when considering the larger, catchment-scale water movements, further supporting the need for hierarchal approaches as outlined by Magliozzi *et al.* (2017).

3.1.2. Further investigations

The findings from this study have provided a foundation for several areas of further exploration, which leads onto the next chapter in this thesis. The intention of Chapter 4 is to extend the understanding the reach scale results monitoring through the application of modelling. Specifically, looking at the likely responses to changes in stage, including flood conditions, which were not possible to sample and to further explore the spatial and temporal responses over the study reach, upscaling from point-sampling to further interpret flow patterns.

3.2. Conclusions

From the sampling it is evident that historic and contemporary threats negatively impact on the stream-water quality. To better understand and manage the impacts requires an investigation beyond the standard measurements, e.g. the WFD, assessing both spatial and temporal variations and likely drivers and controls, both above and below the streambed. The streambed interactions are complex, and not just a function of the hydraulic conductivity, or the upwelling/downwelling across the streambed, and here I have provided an insight from selected sites, which show the response to a limited, however, insightful range of events allowing for an investigation into the changes in stream flow and solute loadings. From the findings presented in Chapter 3, it is suggested that the streambed plays a key role in the cycling of the water chemistry. This study has relied on the use relatively of low-cost methods to give a first-order insight into the system dynamics, nevertheless demonstrating the importance of looking at the subsurface connectivity, which will be further explored in the next chapter.

4. Using numerical modelling to understand the role and impact of groundwater-surface water interactions on in-stream water quality

4.1. Background and modelling approach

Predominantly there has been a limited understanding of the links between drivers and how processes interact within and between the GW and SW systems, looking at water quality problems with a one-dimensional focus at limited points of the stream-water and subsurface environments. There is a need to better understand the connectivity and exchanges to enable more sustainable water management particularly in heavily modified tributary catchments, which are typically structurally heterogeneous, with modifications to the channel planform and deposition of man-made materials. Developing an integrated focus is not trivial, and as demonstrated in preceding chapters, in which utilising the existing data to derive information and linking it with field data is one way of achieving an understanding of the links within and between these relatively unexplored systems. In this chapter I remain focussed on the 1.3 km reach of Twizell Burn, and specifically consider the interactions and exchanges between the stream and shallow GW comprising a discontinuous minor aquifer with variably saturated unconsolidated superficial (drift) deposits (see Figure 1-5). The purpose of this chapter is to apply the understanding from the field sampling conducted in this research and upscale the insight beyond point measurements. The aim is to further challenge the understanding of the system behaviour over spatial dimensions and time, upscaling point-based system sampling of the hydrochemistry and hydraulics to investigate the flow and solute pathways, patterns and processes between the SW and GW systems.

Field sampling over an intensive three-month campaign (March-July 2017) indicates that the shallow GW system is interacting with the stream water, with the subsurface thought to be acting as a source and sink of flow and solutes, with attenuation in the near-stream sediment. Given the large vertical extent of the unsaturated zone of the fractured and faulted bedrock extending below the superficial system, connection of the stream with the deeper GW is thought to be unlikely, leading this research to scale the focus entirely on the shallow GW, near-stream pathways within a shallow hyporheic zone interactions attributing to the loss and return of stream water along the reach (Figure 1-6). The impacts of the stream and shallow GW system variability is reflected through the physio-chemical characteristics of the stream and shallow pore water, with the chemistry appearing responsive to the stream stage at the time of sampling and the bed geomorphology, with hydraulic head changes and subsequent variations in the flow and solutes. However, the insight into the system dynamics and processes operating within and across the streambed are restricted both spatially and temporally to specific sampling events and points along the reach. To extend the understanding, looking at the system behaviour in response to changing hydrological conditions, one such approach is through the application of numerical modelling to derive estimates of the hydraulic heads in the aquifer based on the data and information collated throughout this research to better inform and thus understand the system behaviour, further interpreting the flow patterns observed (Gooseff *et al.* 2006, Magliozzi *et al.* 2017). The research presented in this chapter is driven with the need to understand GW/SW connections and processes with the intention of better understanding and managing the water resources of a local scale, and how they fit into the wider system processes.

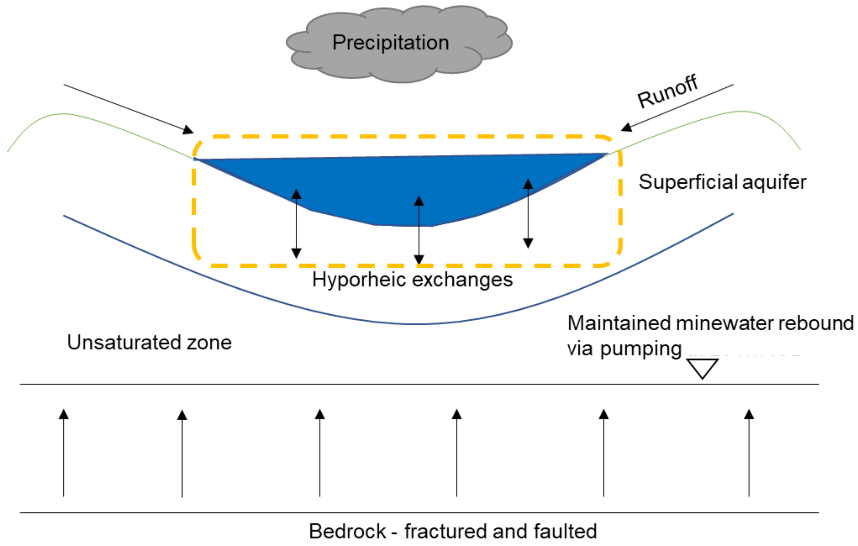

Figure 1-6: Conceptual cross-section of the Twizell Burn GW/SW systems, highlighting direct inputs into the systems and the shallow hyporheic exchanges within the minor aquifer.

The setting up and testing of a first-order numerical model, which has been implemented using the available spatial data (Figure 1-7), as well as primary field data collected in the spring-summer 2017 field sampling campaign will be used as an exercise to provide an upscaled understanding of the reach system. The intention is to investigate the system response to varying hydrological conditions, testing the response to observed events where it was not possible to sample, and scenario-based test simulations, such as with the onset of flooding as well as the likely extreme conditions with future climate change.

From the field sampling I have two main questions which require further investigation:

1. How do the hydraulic gradients across the streambed respond to changing hydrological conditions over space and time?

It is typical that with studies of this sort the nature of the sampling is at periodic intervals of weeks, or months. As a result, the sampling is demonstrative of a snapshot in time during which the samples are obtained, nevertheless this leaves a gap in the understanding between sampling events. Without the implementation of *in-situ* sampling apparatus, the ability to capture the hydrological response and associated chemical changes are not possible. Extending the insight into the system behaviour thus requires an extrapolation of the current understanding, which can be achieved through numerical modelling approaches (Gooseff *et al.* 2006). Modelling facilitates the possibility of estimating/representing the conditions, e.g. before and after storm events, looking at the trends over the reach and with time.

2. Are there any return fluxes (i.e. upwelling of GW/return of SW) along the reach, and if so, are they likely associated with the presence of iron-ochre flushes and staining as observed from the walkover surveys and sampling?

The possibility of sampling along the reach entirety would have required an extremely costly approach. The ability to identify return flows, however, requires the insight of the system at a higher spatial resolution than that achieved through the relatively small number of piezometers installed. Without continuous monitoring of the system, the system response is limited to the sites sampled, therefore, further upwelling and downwelling of GW/SW is likely missed. By upscaling the understanding from the piezometric measurements via numerical modelling offers a potential of identifying return flows based on the estimation of the hydraulic properties of the streambed material.

The research presented in this chapter:

1. Demonstrates the use of existing secondary data and field data to implement a numerical model approach representing the reach-scale system, with emphasis on linking together data and methods (see Magliozzi *et al.* 2017);
2. Tests the response and role of the near-surface, minor aquifer system in the cycling of water and solutes in response to changing hydrological conditions under observed and scenario-based events.

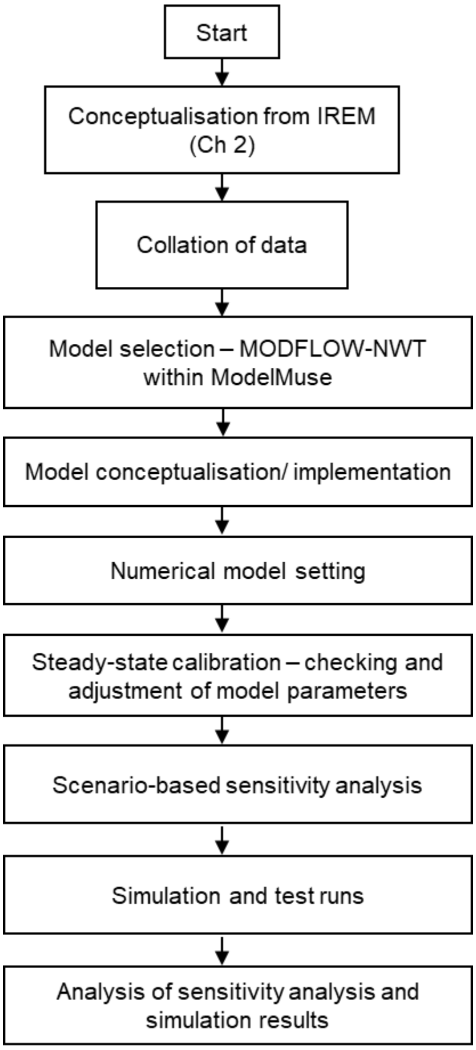

Figure 1-7: Steps taken to develop a numerical model representing the Twizell Burn reach using MODFLOW-NWT.

4.2. Concluding remarks: Challenging the current GW assumptions

The implementation of a numerical modelling approach has allowed an upscaled understanding of the general processes operating across time and space between the GW and SW systems. Hydraulic head changes are responsive to the changes in stage, with the extent of upwelling and downwelling operating as a function of the location and degree of change in stage. The simulated system responses are not without large uncertainties; however, they are insightful, particularly when thinking about the system response following the onset of large rainfall events which were impossible to sample the piezometers throughout the field sampling campaign. Returning to the two original research questions, the hydraulic gradients are responsive to changing hydrological conditions, and the iron-ochre flushes are likely attributing to return flows, although further testing, e.g. via isotopic analysis would be required to confirm this source.

Under average, baseflow conditions, the gains and losses to and from the stream are inherently variable along the reach likely owing to the bed characteristics. Gains and losses to the stream are supportive of the patterns observed in Chapter 3. Increasing discharge through the system attributes to the enhancement in the downwelling and associated loss of stream water to the subsurface, resulting in solute enrichment, e.g. manganese. Implying the understanding from the modelling to how we have otherwise understood this system. While it is evident that under baseflow conditions, the stream is impacted by the mining-derived solutes, which are lost from the subsurface. Meanwhile, during storm events, the subsurface becomes effectively cut-off from the stream with reduced vertical upwelling, and as a result solute concentration are likely to become enriched.

The Twizell is nevertheless a complex system, with dynamic changes in the water fluxes and chemistry. Traditionally assumed disconnected to the subsurface, this is unlikely to be the case, particularly here with reference to the shallow, near stream GW/SW system. It is important to consider and challenge how we look at these systems, as without coordinated joined-up understandings and management, the impacts can be further detrimental. For instance, as observed post-storm events throughout field sampling, the sulphide and metals are highly enriched in the streambed. If after a storm this is true, then when the upwelling of these enriched waters rises, coinciding with phosphate-rich waters from upstream could potentially result in the mobilisation of the entrained phosphate (Smolders and Roelofs 1993), leading to significant issues downstream. Such a concern has been pointed-out by Northumbrian Water; however, this is the first time that we have looked at the role of the streambed in having an attenuating and release potential.

Ultimately, the modelling is a useful exercise for challenging how the way we look at and think about the GW systems and the interaction with stream-water across various spatial and temporal scales. Modelling suggests that the hydraulic heads of the superficial system are responsive to changes in stream stage, with various patterns and dynamic changes in the upwelling and downwelling as a function of the bed geomorphology, but also the conditions. In this chapter I have looked at the response of the system to changing hydrological conditions as a result of periodic releases from the sewage treatment works and rainfall events of various orders of magnitude. With reference to the Twizell, where field sampling only provided a snapshot of the dynamics and processes, modelling has facilitated an assessment beyond these constraints. Without the application of modelling as a tool to better understand these systems, the prevalent understanding of the cycling and exchanges in flow and solutes would be continued from a one-dimensional focus, with a reliance on limited monitoring. Ultimately, there is a need to look beyond such limits and gain a fuller understanding of the system dynamics and processes, linking together the local- and larger-scale processes (Magliozzi *et al.* 2017).

5. Principal conclusions from the research

The research has found that:

1. Despite a shift in policy and frameworks to assess and shape how we manage water quality at the catchment scale, we need to start thinking about the systems in a different way, not just as that the pollution enters the stream channel via point and diffuse sources, but also how the GW and SW systems interact with the landscape and other features around it. Moving beyond the mismanagement of water resources requires a holistic and integrated understanding, and this is unachievable under the current protocol and procedures by which we currently attempt to understand the systems. Sustainable GW/SW management requires considering the connections between drivers and factors likely influencing the movement of flow and solutes. Considering subsurface connectivity as well as landscape connectivity is vital in making advancements in the addressing of water quality. Looking beyond the focus of the stream system, however, requires the integration of data and information, to then step beyond and target efforts to investigate the sources which threaten the water quality. It is then about taking this knowledge and disseminating it to stakeholders who can then make re-informed decisions on ways to manage the water quality.

2. From the sampling conducted in this research it is evident that historic and contemporary threats impact on the stream-water quality. To better evaluate the impacts requires an investigation beyond the routine measurements, assessing both spatial and temporal variations and likely drivers and controls, both above and below the streambed. Do-make evaluations simply ignore the historic dimensions in favour of instrumental data (which are often very limited). Most legislation is based on data that cannot possibly be obtained from instrumental records, and so it is to then question how we better use the available data. In data sparse situations, it is most

feasible to accumulate the existing secondary data and then move forward with empirical investigations, rather than collecting data as done under routine sampling which is not linked to the already existing data.

3. The streambed interactions are complex. A combination of factors adds to the high heterogeneity, with the propagation of factors within the channel, catchment, and beyond, including the likelihood of extreme rainfall events. This study has relied on the use relatively of low-cost methods to give a first-order insight into the system dynamics. Due to the low-cost nature of the techniques applied thus enables for a much greater coverage capturing detail across the wider system, e.g. catchment scale, both spatially and temporally which can be more useful than an expensive approach which then lacks coverage. The replicability of intensive approaches is unfeasible. Nevertheless, demonstrating the importance of looking at the subsurface connectivity, which is partly responsible for the SW quality.

4. Traditionally, decisions as to how water resources are managed are based on a snap-shot insight into the systems. While field sampling is a useful approach to quantifying the water chemistry, it needs to be linked with other approaches, specifically laboratory work, existing data and modelling to extend the understanding providing a generalised understanding of the systems. Customarily, the prevalent understanding of the cycling and exchanges in flow and solutes would be continued from stream-system focus looking at the system at a given time and place, with a reliance on limited monitoring. However, there is a need to look beyond such limits and gain a fuller understanding of the system dynamics and processes and work with the available resources and supplement additional findings to them.

Ultimately, the impact of the fragmented views of the GW and SW systems from stakeholders has resulted in a disparate focus on different issues. Traditionally such an approach was accepted, however, emphasis from international policy, e.g. the WFD seek to move beyond these. Not only is there a lack of cohesion in the holistic investigation of how water and solutes move across the streambed, but it comes also from the lack of disciplinary connectivity. The shift requires coordinated efforts to gain an understanding of the systems, with collaboration between those responsible for managing the resources. Projects such as TOPSOIL are providing a platform to facilitate such a movement, yet it remains particularly challenging to implement, and has some way to go. In practice, through EU projects like

TOPSOIL have been going on for decades, so the question is, why are they not any further forward in addressing the connections between disciplines? It is likely because they are not re-evaluating the systems and attempting to break-down the complexities. As ultimately this has implications for the learning process and understanding.

5.1. What the findings of this research mean for management

The traditional assumption that the GW and SW systems are disconnected has been held for some time. However, over the last 25 years, the shift in research to look at the GW/SW interface has highlighted the potential in changing how we should think about and manage water resources. There is the need to avoid targeted, black-box approaches. To facilitate the development of an integrated understanding is by no-means straight-forward and is associated with high costs if high resolution methods are chosen, for example, the use of *in-situ* recording devices. Regardless of the elaborate nature of selected methods, there is a growing pressure to address the GW/SW interactions, with complex interpretations of the systems possible to derive from simple analysis, as demonstrated in this research. With regards to management, this research has demonstrated that is feasible to look beyond the fragmented views of the SW system, from which it is possible through innovative approaches to start and gain a general understanding of the system dynamics and processes. As demonstrated at the study catchments, the way in which we start and think about how water moves through a system, and where it attenuates, for instance can start and lead to new intentions as to how we should this about issues.

One of the greatest challenges facing the integrated evaluation of water systems is the visualisation of the GW environment, which is difficult due to the lack of data available. However, it is then a matter of how we chose to work around these challenges. Using the available data resources, it is possible to derive information, which then supports subsequent investigations. Despite the lack of baseline water quality data, it is still possible to make links between factors, inferring potential flow routes, which can then be tested.

5.2. What the findings of this research mean for management in the Wear catchment

In the Wear Catchment, the limited insights and assessments of large- and local-scale processes within the catchment boundaries has hindered progress for sustainable management. Stepping aside from approaches that mask the threats to water quality, it is evidently needed that processes and pathways within and between the surface and subsurface systems need to be explored. In-turn looking at the interactions between the pollution pressures, considering both the historic and contemporary effluents. Such explorations require the need to step-back from the complexities of the systems and start by evaluating simple links in the landscape characteristics. Simple patterns and links can then be explored, as done at the Twizell reach, from which it has been demonstrated as to how the local processes likely fit into the wider system. The accumulation of threats in the Twizell appeared to intertwine, however, required an insight across the spatial and temporal dimensions to develop a greater understanding as to how water-quality issues are impacting on the system.

5.3. Summary

The findings of this research support that GW/SW systems need to be considered holistically to allow for more sustainable management of water resources, with evidence of the interactions of flow and solutes across the streambed. They will support management within County Durham, within the Wear Catchment, and inform of how we should conceptualise and better derive information from available data resources to support in the decision-making process in other tributary catchments. The ability to make such assessments and monitor water quality beyond limited points in the catchment is reliant on the collaborations and workings of stakeholders responsible for managing the water resources, with scientific findings informing working practice.

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