

## The impact of geological control on flow accretion in lowland permeable catchments

S. Arnott, J. Hilton and B. W. Webb

### ABSTRACT

The results of two comprehensive catchment-scale flow accretion surveys that were conducted in the lowland permeable catchments of the Rivers Frome and Piddle in Dorset, UK are presented. The surveys, undertaken as part of the NERC lowland catchment and research (LOCAR) program, were conducted under baseflow conditions during the summer of 2005. Results were adjusted for seasonal variation, the occurrence of intense precipitation events and anthropogenic inputs. A number of significant groundwater–surface water interactions related to various geological formations and boundaries were identified in this study. These included inputs of groundwater associated with the Greensand/Chalk ( $18\text{--}51\text{ L s}^{-1}\text{ km}^{-1}$ ) and Chalk/Palaeogene ( $68\text{--}152\text{ L s}^{-1}\text{ km}^{-1}$ ) boundaries and the Oakdale Clay Member ( $52\text{--}79\text{ L s}^{-1}\text{ km}^{-1}$ ), as well as substantial surface water losses associated with the Broadstone Sand Formation ( $158\text{--}171\text{ L s}^{-1}\text{ km}^{-1}$ ). The study suggests that it may be possible to predict groundwater–surface water interactions from basic information on solid geology, which would be of considerable benefit to the implementation of the Water Framework Directive in England and Wales.

**Key words** | catchment-scale, flow accretion, Frome, groundwater–surface water interactions, lowland permeable catchments, Piddle

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### INTRODUCTION

Water resources throughout lowland permeable catchments are affected by numerous problems including groundwater abstraction that can affect baseflow regimes (Winter *et al.* 1998), intensive agricultural pressures that may lead to the long-term pollution of drinking water supplies (Wheater & Peach 2004) and climate change that could dry out headwater streams during the summer and create groundwater flooding during the winter (Griffiths *et al.* 2006). A greater understanding of these problems in relation to catchment-scale hydrological and hydrogeological processes may assist the future management of these fragile habitats (Stevens 1999). Research at a catchment scale may greatly aid the understanding of the complex mechanisms that control groundwater and surface water systems as well as the exchanges that occur between them, which are

commonly referred to as groundwater–surface water interactions (Sophocleous 2002).

The United Kingdom Technical Advisory Group (UKTAG) (2004) stated that the confident identification of groundwater–surface water interactions is the first step to defining and then protecting Groundwater Dependant Terrestrial Ecosystems (GWDTEs) such as wetlands, mires, blanket bogs and alluvial woodland throughout the UK (Griffiths *et al.* 2006). However, it is also widely accepted that the geological controls which influence groundwater–surface interactions in GWDTEs are poorly understood. Increased knowledge of these interactions would help protect GWDTEs, which is a major objective of the Water Framework Directive (WFD) in England and Wales (Griffiths *et al.* 2006). It would also improve our

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understanding of chemical and nutrient exchanges (Valett *et al.* 1990; Castro & Hornberger 1991; Bencala 1993; Ghiorse & Wilson 1998; Jarvie *et al.* 2006), the supply of baseflow (Hynes 1983; Brunke & Gonser 1997), preferential flow paths of contaminated groundwater and surface water (Brunke & Gonser 1997; Winter *et al.* 1998; Mayes *et al.* 2008; Mighanetara *et al.* 2009) and the preferred locations in rivers and lakes of some invertebrate (Datry *et al.* 2008) and fish species (Olsen & Young 2009).

In order to appreciate the complexity of these exchange sites, it is important to understand a number of large-scale and small-scale processes that control the location, direction and rate of groundwater–surface water interactions. Large-scale controls are related to groundwater flow systems that contain a nested hierarchy of multiple flow systems that operate over a range of temporal and spatial scales (Sophocleous 2002). Toth (1963) identified three basic groundwater flow systems within a geological region or catchment: (1) local groundwater flow systems that discharge into ponds or streams with a residence time of days to years; (2) regional flow systems with groundwater travelling greater distances to discharge into rivers, lakes and oceans and characterized by a residence time of decades to millennia; and (3) discharges of intermediate groundwater flow systems ranging in scale from local to regional systems that have residence times of years to decades.

Woessner (2000) highlighted a number of small-scale controls that influence groundwater–surface water interactions. These include the permeability of the riverbed, the relationship between stream stage and the adjacent groundwater level and the position of the stream channel in relation to the alluvial plain. Riverbed permeability will influence the rate of seepage flux through the riverbed. Stream stage and adjacent groundwater levels will control the direction of flow, because adjacent groundwater levels are generally greater than stream stage in gaining reaches and lower than stream stage in losing reaches. The orientation of the stream channel to the floodplain will also influence the direction of seepage flux. For example, when the stream channel is parallel to the fluvial plain, gaining and losing reaches will generally arise whereas flow-through reaches occur when the channel is perpendicular to the fluvial plain and groundwater tends to traverse through the surface water system (Huggenberger *et al.* 1998; Woessner 2000).

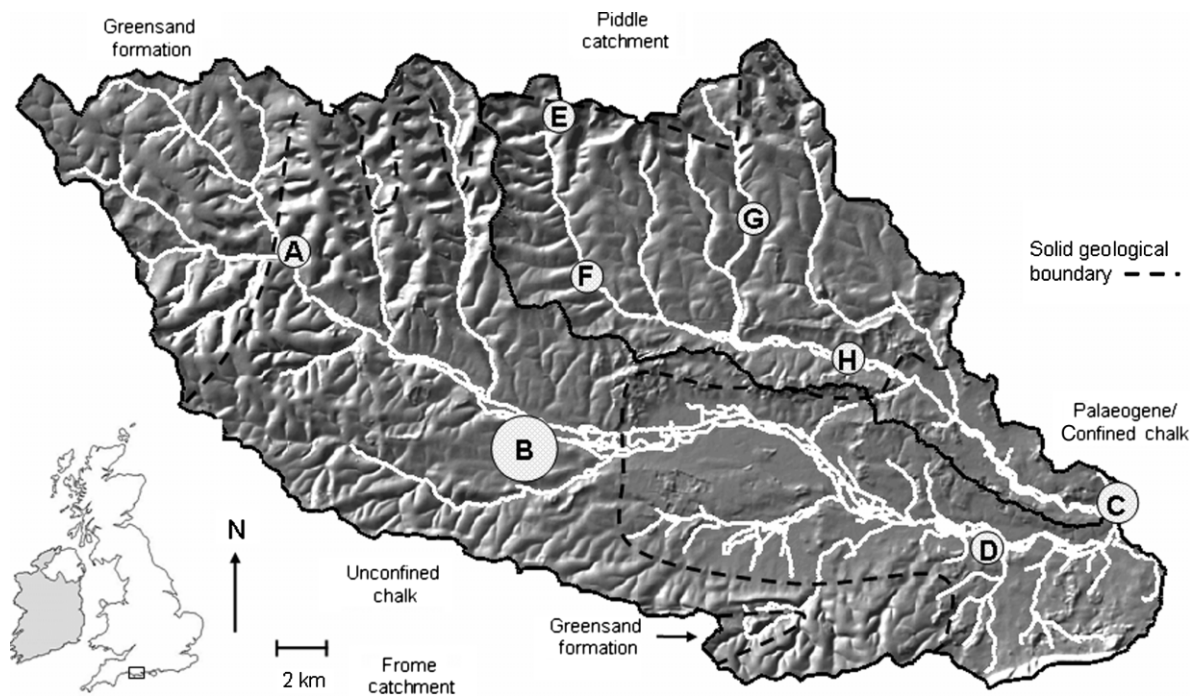
This paper presents the results of two detailed catchment-wide flow accretion surveys in the Rivers Frome and Piddle, Dorset, UK. The main objective of these surveys was to investigate the location of significant groundwater–surface interactions and to relate these to the underlying solid geology. The results of this investigation provide more detailed information on groundwater inflows and surface water losses than previously available in these catchments, and will contribute to the understanding of GWDTes as well as a number of other hydrological and hydrogeological processes, such as aquifer recharge and discharge, groundwater flooding/drought and preferential flow paths.

## STUDY CATCHMENTS

The Frome and Piddle catchments are adjacent to each other and are situated close to the south coast of England in the county of Dorset (Figure 1). Their catchment drainage areas are 463.7 km<sup>2</sup> and 187.5 km<sup>2</sup>, respectively. The main lithologies of the Frome and Piddle catchments are Chalk (*ca.* 65%), sand and sandstone (*ca.* 18%) and argillaceous rocks (*ca.* 11%) (Newell *et al.* 2002). The headwaters of the Frome and Piddle catchments cut into the Greensand Formation, the middle reaches flow across unconfined Chalk and the lower reaches traverse Palaeogene deposits (Newell *et al.* 2002).

The River Frome is 59 km in length. It rises on the Greensand Formation at an elevation of 179 m AOD and flows in a southeast direction to Dorchester (Figure 1B) where it turns east and reaches its mouth in Poole Harbour. In its middle and lower reaches, the River Frome is typically split into multiple channels. The stretch of river downstream of Dorchester has the largest number (five) of channels. The River Frome has seven major tributaries. Over the period 1961–1990, mean annual rainfall values in the range 800–1,000 mm were recorded in the Frome catchment. Throughout 1990–2005, the flow recorded at the Environment Agency (EA) flow-gauging station furthest downstream, at East Stoke (Figure 1D), ranged 2.015–26.850 m<sup>3</sup> s<sup>-1</sup>.

The River Piddle lies to the north of the Frome catchment and is shorter than its neighbour at 37 km. Its major source rises on the Chalk approximately 500 m west



**Figure 1** | Topography and simplified solid geology of the Frome and Piddle catchments (A: Maiden Newton; B: Dorchester; C: Wareham; D: East Stoke; E: Alton Pancras; F: Piddlehinton; G: Dewlish; H: Briantspuddle).

of Alton Pancras (Figure 1E) at an elevation of 127 m AOD. The river flows towards Piddlehinton (Figure 1F) in a southward direction and then turns east, and it also has its mouth in Poole Harbour. Like the River Frome, the middle and lower reaches of the River Piddle tend to split into multiple channels with a maximum number of four separate channels. Historically, the Piddle catchment has been subject to the abstraction of groundwater in the upper and middle reaches resulting in its designation by the EA as a river requiring Alleviation of Low Flows (ALF). In response to this, Wessex Water supplements low flows at Alton Pancras (Figure 1E), Dewlish (Figure 1G) and Briantspuddle (Figure 1H) with abstracted groundwater. A mean annual rainfall of 850–1,000 mm has been measured in the catchment over the period 1961–1990. Discharge at the furthest downstream EA flow-gauging station, at Wareham (Figure 1C), ranged from 0.53–10.2 m<sup>3</sup> s<sup>-1</sup> over the period 1990–2005.

The solid geology of the study catchments ranges in age from the Mid Jurassic (Bathonian-167 million years ago or Mya) to the Palaeogene (Eocene-34 Mya) (Newell *et al.* 2002). The oldest and most extensive geological units that

outcrop in the Frome and Piddle catchments are the Greensand and Gault Formations, which cover 9.42% and 4.26% of their areas, respectively. They are located exclusively within the headwaters of the study site (Figure 1). They were formed during high energy marine conditions of the Aptian (125–112 Mya) and Albian (112–99.6 Mya) stages of the Early Cretaceous period.

The Late Cretaceous Chalk, which succeeds the Greensand Formations, dominates the solid geology (65%) of the Frome and Piddle catchments (Figure 1). The Lower Chalk is made up of Zig Zag Chalk and West Melbury Marly Chalk with outcrops commonly located throughout the north of the study site (Newell *et al.* 2002). The base of the Zig Zag Chalk is defined by an impermeable 1.5 m thick band of Chalk hardground that is commonly referred to as the Chalk Marl (Robins & Lloyd 1975). The Middle Chalk consists of New Pit Chalk and Holywell Nodular Chalk, and the latter has a very hard base of Melbourn Rock consisting of nodular marls and hardgrounds. Minor outcrops of Middle Chalk can be observed in the headwaters of the Frome catchment. The Upper Chalk forms the majority of the unconfined Chalk

observed in the study site, and comprises the Portsdown, Spetisbury, Tarrant, Newhaven, Seaford and Lewes Nodular Chalks. With the exception of the Lewes Nodular Chalk, the Upper Chalk tends to be soft with numerous marl seams and flint bands. The Lewes Nodular Chalk forms the base of the Upper Chalk and is a hard nodular Chalk with an even harder base of Chalk Rock (Allen *et al.* 1997).

The youngest units of the solid geology in the Frome and Piddle catchments were formed during the Eocene epoch (55.8–33.9 Mya) of the Palaeogene period and comprise a succession of marine and non-marine sediments formed as a result of numerous marine transgressions and regressions (Toghill 2002). Within the study site, they are confined to the Wareham Basin but outcrop over an area of 174 km<sup>2</sup> or 26% of the catchments (Figure 1). This heterogeneous mix of sands and clays is sub-divided into the Branksome Sand, Poole and London Clay Formations; the former being a coarse-grained sand outcropping on the high grounds of the study site. The Poole Formation is further separated into the Broadstone Sand

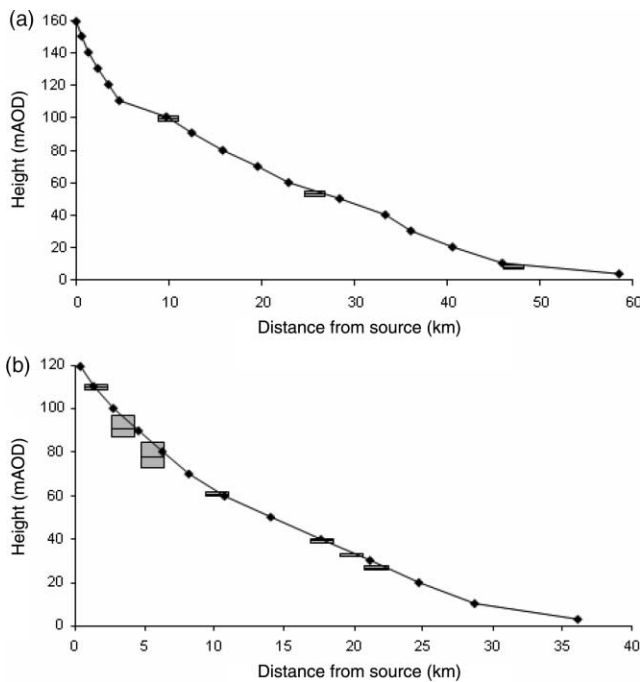
Member, Oakdale Clay Member and Oakdale Sand Member. The West Park Farm Member, also known as the 'Reading Beds', is the lowest layer of the London Clay Formation, which caps the Upper Chalk. The solid geological succession of the study site is summarized in Table 1.

Groundwater flow in the Frome and Piddle catchments tends to be south to south-easterly until the influence of the River Frome becomes dominant and changes the groundwater flow to an easterly course (Peach *et al.* 2004). As a result, the River Piddle is classified as a baseflow dominated river as the groundwater moves perpendicular to the surface stream flow and the River Frome as an underflow dominated river because the groundwater moves in the same direction as the surface stream flow (Larkin & Sharp 1992; Griffiths *et al.* 2006). Paolillo (1969) stated that the Frome and Piddle catchments can be viewed as a single aquifer unit with the same underlying regional and intermediate groundwater flow systems. Groundwater levels measured in LOCAR boreholes along the River Frome (21/12/02–06/11/05) and

**Table 1** | Solid geological succession in the Frome and Piddle catchments (Mya: million years ago)

Period/Epoch	Mya	Member/Formation name			
Palaeogene	65.5–23.0	Poole	Branksome Sand (BrkS)		
			Broadstone Sand (BrtS)		
			Oakdale Clay (OakC)		
			Oakdale Sand (OakS)		
		London Clay	London Clay (LC)		
			West Park Farm (WPF)		
		Late Cretaceous	99.6–65.5	Upper Chalk	Portsdown Chalk (PCK)
					Spetisbury Chalk (SpCK)
					Tarrant Chalk (TCK)
					Newhaven Chalk (NCK)
Seaford Chalk (SCK)					
Lewes Nodular Chalk (LeCK)					
Middle Chalk	New Pit Chalk (NPCK)				
	Holywell Nodular Chalk (HCK)				
Lower Chalk	Zig Zag Chalk (ZCK)				
	West Melbury Marly Chalk (WMCK)				
Early Cretaceous	125–99.6	Green Sands	Upper Greensand (UGS)		
			Gault (G)		
			Lower Greensand (LGS)		





**Figure 2** | The height (mAOD) of riverbed elevation (black line graph) and minimum, average and maximum groundwater levels recorded along the (a) River Frome and (b) River Piddle.

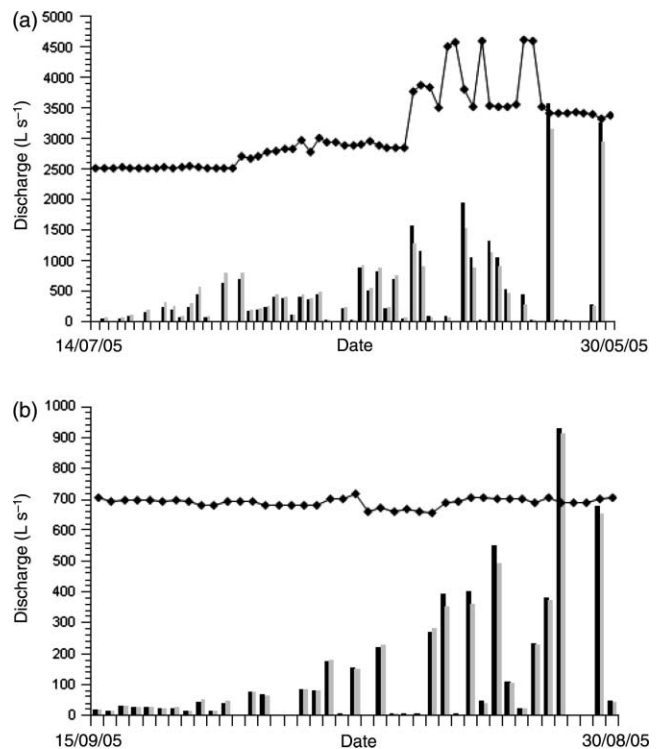
Environment Agency (EA) boreholes along the River Piddle (06/03/90–19/01/09) are very similar to riverbed elevation (Figure 2(a) and (b)).

## METHODS

A flow accretion survey was carried out during baseflow conditions across both river catchments over the periods of 30 May to 28 July 2005 (Frome) and 30 August to 19 September 2005 (Piddle). The river systems were systematically divided into sub-sections of 1–3 km length, the length depending on the proximity of easy access via road bridges, footpaths and bridleways. The flow gauging method used in these surveys involved wading into the river; it was therefore not possible to measure flows in the River Frome downstream of East Stoke because of the channel depth and water velocity. The braided nature of Chalk streams meant that each stretch could require up to eight measurements in order to define all the incoming and outgoing flows. Inputs originating from sewage treatment works and stream support sites were treated as

inflows and integrated into the results of the survey. The difference between the sum(s) of all inflows minus the sum(s) of all outflows was used as an estimate of surface water loss or groundwater inflow for individual study reaches.

A Valeport single-axis electromagnetic flow-meter (Model 801) was used during the surveys. Discharge measurement sites were located on straight reaches with, as far as possible, a rectangular cross-section with no large bed material, no aquatic vegetation and safe access. Discharge estimates were made by measuring a representative mean velocity in each vertical at 0.6 of the water depth from the surface over a 50-second period. The number of verticals depended on the width of the transect (0–2.5 m: 5 or 6 verticals; 2.6–5.0 m: 10 verticals; 5.1–7.5 m: 15 verticals; 7.6–10.0 m: 20 verticals and 1 reading every metre for >10 m wide rivers). At each transect, discharge was measured twice and the two discharge estimates were averaged. The average percentage difference between all the

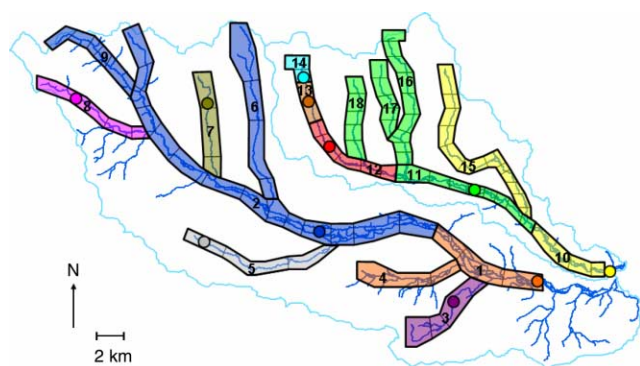


**Figure 3** | The results of the normalization procedure along the (a) River Frome and (b) River Piddle. The discharge (solid line with diamonds) at the East Stoke (R. Frome) and Wareham (R. Piddle) gauging stations during the survey period. The effect of normalization at sites along the major branches of the Frome and Piddle measured on the days indicated can be seen by the difference between the measured (black) and normalized (grey) columns.

duplicated discharge measurements for the Frome and Piddle catchments were 3.8% and 5.9%, respectively, which are within the acceptable range of 3–6% recommended by Sauer & Meyer (1992) for discharge estimates.

The discharge was measured at 99 points along the River Frome and its tributaries, which allowed the definition of 40 flow accretion sub-sections of approximately 2.9 km in length. The Frome flow accretion surveyed 116 km out of a total channel length of 126 km, which represents 92% of total channel along the Frome and its tributaries. The Piddle flow accretion survey measured discharge at 80 points, which led to the definition of 51 flow accretion sub-sections of approximately 1.4 km in length. The Piddle flow accretion survey covered approximately 71 km out of a total channel length of 74 km, which equates to 96% of the surface waters.

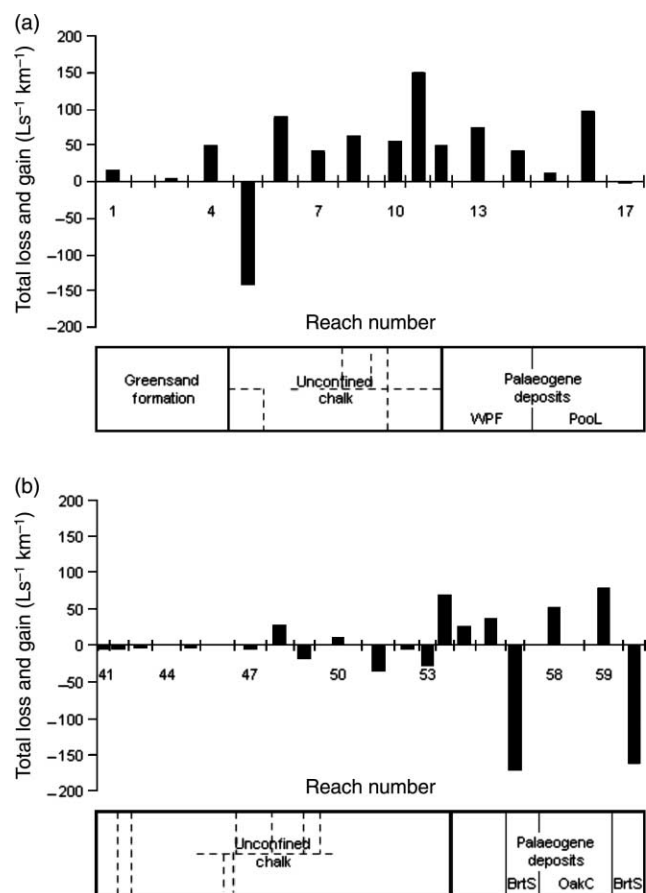
The flow accretion survey took 60 days to complete for the Frome catchment and 21 days for the Piddle, during which time discharge was not constant (Figure 3(a) and (b)). In order to compare discharge at reaches measured on different days, a normalization procedure was used. All survey transects were related to their nearest EA flow gauging station (Figure 4), of which there were 11 situated throughout the Frome and Piddle catchments. Reaches located along the seven tributaries without EA flow gauging stations were related to the closest downstream EA flow gauging station (Figure 4). The discharge measured manually at each survey transect (Figure 3, black columns) was adjusted (Figure 3 grey columns) to the discharge that would have been



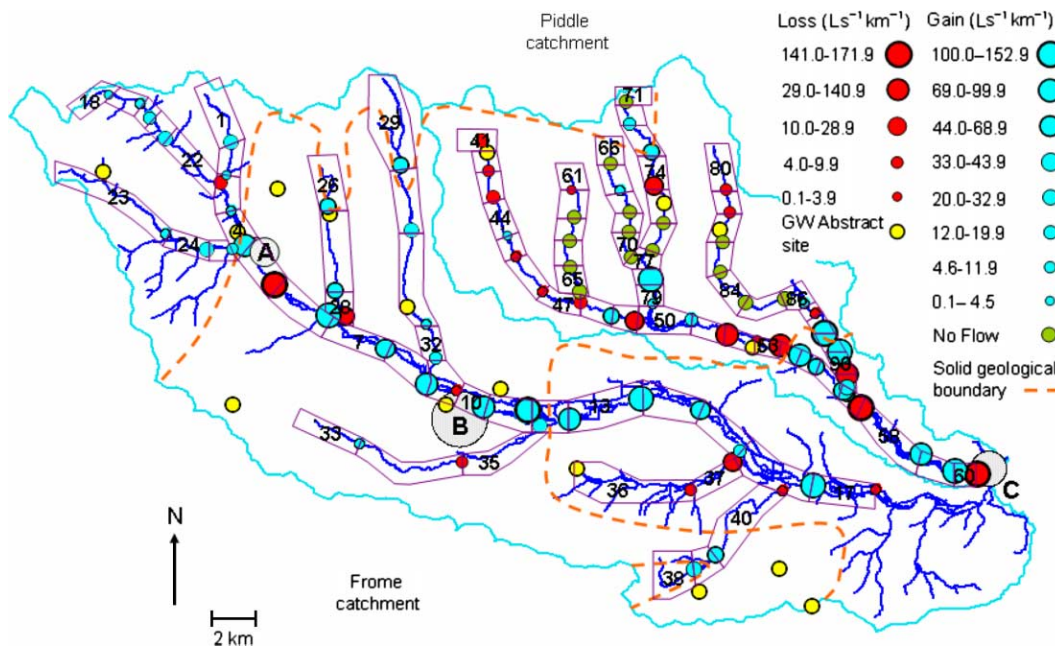
**Figure 4** | The location of the 11 Environment Agency flow gauging stations (dots) which determines the distribution of the 18 reaches used during the normalization process.

measured if the flow had been equivalent to the average flow rate over the whole survey period. This was done by dividing each manually gauged transect flow by the average flow at the relevant gauge (Figure 4) during the hour covering the measurement period, and multiplying by the average over the whole survey period (Frome = 60 d; Piddle = 21 d).

The CEH Intelligent River Network (IRN) facility operating in ArcGIS 9.1 (Dawson *et al.* 2002) linked the survey reaches to the underlying solid geological structures of the study site. The IRN was used to calculate distance to source for both the boundaries of the survey reaches and the solid geological structures. The distance to source measurements were then used to superimpose the survey reaches onto the solid geological structures of the study site,



**Figure 5** | Total losses/gains ( $Ls^{-1} km^{-1}$ ) and solid geological transect along (a) the River Frome and (b) River Piddle (vertical solid lines: solid geological boundaries; WPF: West Park Farm Member; Pool: Poole Formation; BrtS: Broadstone Sand Member; OakC: Oakdale Clay Member; vertical dashed lines: faults crossing under the river channel; and horizontal dashed lines: faults running parallel to the channel). A selection of the survey reaches are numbered.



**Figure 6** | A catchment-scale summary of losses and gains ( $\text{L s}^{-1} \text{km}^{-1}$ ) measured in the surface waters of the Frome and Piddle catchments. A selection of the survey reaches are numbered (A: Maiden Newton; B: Dorchester; C: Wareham).

which provided an accurate representation of surface water losses and groundwater inputs ( $\text{L s}^{-1} \text{km}^{-1}$ ) in relation to the underlying solid geological structures. An example of this methodology is displayed for the major branches of the River Frome and River Piddle in Figure 5 and a catchment-scale summary is depicted in Figure 6.

the Piddle crosses over the Oakdale Clay Member, where two relatively large inputs are observed in reaches 58 and 59. These groundwater–surface water interactions were previously unrecorded and the mechanisms that control

## RESULTS

The survey reaches with the largest rates of gain and loss ( $> 50 \text{ L s}^{-1} \text{km}^{-1}$ ) are listed in Table 2. There are many more reaches with larger gains than losses, but three out of four of the reaches with the highest values ( $> 140 \text{ L s}^{-1} \text{km}^{-1}$ ) exhibited losses.

Because of the high clay content, the Palaeogene deposits in the Frome and Piddle catchments are regarded as being relatively impermeable (Schurch *et al.* 2004) and minimal groundwater and surface water interactions were expected in the area of their outcrop. However, the reaches with the two largest losses were recorded in this region, where the River Piddle flows over the Broadstone Sand Member (reaches 57 and 60, Figures 5 and 6). Between these two outcrops of the Broadstone Sand Member,

**Table 2** | An ordered list of the highest gains and losses for survey reaches in the Frome and Piddle catchments

Order	Gains		Losses	
	Reach number	Flow ( $\text{L s}^{-1} \text{km}^{-1}$ )	Reach number	Flow ( $\text{L s}^{-1} \text{km}^{-1}$ )
1	11	152.2	57	-170.9
2	88	101.2	60	-158.4
3	78	98.2	5	-141.4
4	16	97.5		
5	6	90.2		
6	59	79.0		
7	89	76.3		
8	13	74.4		
9	54	67.8		
10	8	61.2		
11	10	56.4		
12	58	52.2		
13	4	51.0		

these hydrogeological/hydrological processes are, at present, unknown. Two large gains were also observed as the River Frome crossed the Palaeogene West Park Farm Member (reach 13) and the Poole Formation (reach 16), both which comprise medium-to-coarse grained sands and are consistent with the findings of work by Howden (2006).

The largest gain of groundwater to the river,  $152 \text{ L s}^{-1} \text{ km}^{-1}$ , was observed in reach 11 on the River Frome, just upstream of the Chalk/Palaeogene boundary. A number of other high gains from groundwater were also observed in reaches that crossed the Chalk/Palaeogene boundary e.g. in reach 54 on the River Piddle and reaches 88 and 89 on the Bere Stream (Figures 5 and 6). The Chalk/Palaeogene boundary is commonly associated with karstic features, such as fractures, conduits, dolines and caves (Allen *et al.* 1997), which tend to be associated with rapid groundwater flows. These appear to contribute to the overlying surface waters under artesian conditions in these reaches (Buckley 1996). Urbano *et al.* (2006) previously identified groundwater inputs at similar unconfined-confining boundaries which are commonly exploited by a number of anthropogenic, water-based activities throughout the study catchments, such as fish farms and watercress-beds.

A substantial loss from the river of  $141 \text{ L s}^{-1} \text{ km}^{-1}$  was observed in reach 5 as the River Frome flows along the upper section of the Frome Valley Fault and traverses across two hardgrounds of Chalk Marl at the base of the Zig Zag Chalk and Melbourn Rock at the base of the Holywell Nodular Chalk. Parallel fault structures that originally defined the course of the river network (Alexander 1981) may provide a sub-surface conduit for surface water flow (Allen *et al.* 1997; Howden *et al.* 2004). Chalk hardgrounds tend to contain much greater fracture intensities and permeabilities which, through dissolution, can develop into effective preferential flow paths (Price *et al.* 1993). The combination of these numerous geological structures appears to create this substantial surface water loss.

Significant inflows from groundwater, most in excess of  $50 \text{ L s}^{-1} \text{ km}^{-1}$ , occurred in all but one of the reaches along the River Frome that were underlain by Chalk (e.g. 6, 7 ( $43 \text{ L s}^{-1} \text{ km}^{-1}$ ), 8 and 10). The only exception, reach number nine, displayed no significant loss or gain

( $0.4 \text{ L s}^{-1} \text{ km}^{-1}$ , which is not significantly different from zero). Over this reach, the river system meandered through numerous road and rail bridges where the river was artificially modified to form canalized channels with a concrete base, stopping any interaction between the groundwater and surface water.

In contrast, the vast majority of surface water reaches over the unconfined Chalk of the Piddle catchment during the survey were either dry or were losing. Although the modest surface water losses and numerous dry reaches could be attributed to the influence of different underlying groundwater flow regimes (the River Piddle is baseflow dominated and the River Frome is underflow dominated) it is more likely to be due to the considerable abstraction of groundwater in the upper and middle reaches of the Piddle catchment. The groundwater abstraction sites tend to be located adjacent to the surface water systems (Figure 6). The only exceptions were survey reaches 48 ( $28 \text{ L s}^{-1} \text{ km}^{-1}$ ) and 78 ( $98 \text{ L s}^{-1} \text{ km}^{-1}$ ), which both overlie complicated fault structures that appear to form preferential flow paths for inflowing groundwater.

Reach number four which is located in the upper reaches of the River Frome mainly overlays the Greensand Formation. However, as the river crosses over the Greensand/Lower Chalk boundary (which also tends to be within the transition zone of the headwaters and lowland plateau) a large gain to the river of  $51 \text{ L s}^{-1} \text{ km}^{-1}$  was observed (Figures 5 and 6). A number of small gains were also observed in other surface waters as they crossed the same boundary, such as reach 26 on the Sydling Water ( $30 \text{ L s}^{-1} \text{ km}^{-1}$ ), reach 30 on the River Cerne ( $18 \text{ L s}^{-1} \text{ km}^{-1}$ ) and reach 73 on the Devil's Brook ( $23 \text{ L s}^{-1} \text{ km}^{-1}$ ). Reach 66 did not display any gains at this boundary as this survey reach was located above the perennial head of the Cheselbourne Stream, which was dry during the flow accretion survey. In typical Chalk catchments, lateral flowing groundwater tends to contribute to the surface water at the outcrop of the Upper Greensand/Lower Chalk boundary. Although these gains could be attributed to the break in slope increasing the hydraulic gradient between the river and the groundwater (Konrad 2006) they are most likely a result of the impermeable rhythmically bedded grey Marls and very hard Limestone bands of the West Melbury Marly Chalk (Allen *et al.* 1997).



## DISCUSSION

In terms of water resource management within the Frome and Piddle catchments, the results of the present study contributes to the understanding of catchment-scale hydrological and hydrogeological processes in relation to a number of water resource issues, such as the nature of aquifer recharge/discharge, low and high surface water flows, groundwater flooding/drought, preferential flow paths, supply of baseflow and the impact of anthropogenic activities such as groundwater abstraction. For example, the two large losses ( $158 \text{ L s}^{-1} \text{ km}^{-1}$  and  $171 \text{ L s}^{-1} \text{ km}^{-1}$ ) that were observed over the Broadstone Sand Member could be amplified by riparian-based anthropogenic activities. Currently, planning permission is being sought to develop the adjacent riparian land into an open-cast quarry. Dewatering activities may disrupt the unique nature of the groundwater flow paths that are present in this area, which could have an adverse impact on the flow regime of the River Piddle.

There are, however, wider implications of this work. With the exception of one reach (78), for which no explanation can currently be given, the results of the present study suggest that in the Frome and Piddle catchments, when substantial ( $> 50 \text{ L s}^{-1} \text{ km}^{-1}$ ) groundwater inputs or surface water losses were observed, they coincided with specific geological formations and boundaries between two rock types. The Frome and Piddle catchments are normally considered to be representative of many lowland permeable Chalk catchments (Westlake & Ladle 1995; Sear *et al.* 1998; Howden *et al.* 2004). This is in agreement with Konrad (2006) who found that solid geological boundaries representing permeability contrasts appeared to be one of the key drivers of localized groundwater–surface water interactions in the Columbia River Basin, along with changes in the thickness of unconsolidated sedimentary deposits and the profile and plan form of river channels (considered to be less important).

Hence the coincidence of, in particular, geological boundaries with major occurrences of groundwater–surface water interaction is likely to occur in all such catchments. This suggests that it may be possible to predict the location of sites with strong groundwater–surface water interactions in lowland permeable catchments, by identifying geological boundaries from geological maps.

Further work is required but, should such predictions be reliable, it would be a major step in facilitating the implementation of the WFD and provide long-term protection to GWDTEs. The identification and assessment of GWDTEs, which are currently identified through the presence of ecological features that are wholly or partially dependent on groundwater supplies, would be more reliable if undertaken from both a hydrological/hydrogeological and ecological perspective.

## CONCLUSIONS

Previous studies (Price *et al.* 1993; Allen *et al.* 1997; Huggenberger *et al.* 1998; Grapes *et al.* 2005) have speculated on the control of solid geological structure over groundwater–surface water interactions. The high spatial resolution of measurements in our study has allowed groundwater–surface water interactions to be clearly and consistently identified above a number of solid geological boundaries (Greensand/Chalk and Chalk/Palaeogene) and formations (Oakdale Clay Member and Broadstone Sand Member).

The results of this investigation also highlight the large magnitude of interactions that can occur between hydrological and hydrogeological systems. However, the range of magnitude of the interactions suggests that other controls, in addition to solid geology, must contribute to the catchment-scale functioning of groundwater–surface water interactions. Further work will therefore be undertaken to assess the impact of additional controls on groundwater–surface water interactions and to determine if the location of groundwater–surface water interactions can be predicted from an understanding of catchment geology.

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