Groundwater, flooding and hydrological functioning in the Findhorn floodplain, Scotland

A. M. MacDonald, D. J. Lapworth, A. G. Hughes, C. A. Auton, L. Maurice, A. Finlayson and D. C. Gooddy

ABSTRACT

A large floodplain of the River Findhorn, northeast Scotland, was investigated using hydrogeological and hydrochemical methods (including residence time indicators) to characterise groundwater/surface-water coupling and groundwater flooding. The study demonstrated widespread stratification within the floodplain: shallow (<8 mbgl) deposits are highly permeable (100 m/d); deeper deposits have low permeability (1 m/d) and limit interaction with the underlying sandstone aquifer. Hydrochemistry and groundwater-level variations show floodplain groundwater is recharged from the river, surrounding hillslopes and direct rainfall infiltration. The river loses water to groundwater as it enters the floodplain; further downstream, groundwater response follows closely river stage giving rise to complex exchanges; near the sea, groundwater continually discharges to rivers, tributaries and ditches. Groundwater flow is largely parallel to the river and mean groundwater residence times vary from 3 years to 20 years. Groundwater at the edge of the floodplain, close to the hillslopes, has distinctive chemistry and responds rapidly to local intense rainfall (daily total >30 mm). Persistent groundwater flooding occurs within topographical lows and also in the discharge zone where it is largely managed with a series of drains constructed in the 19th century. The significant and complex role of groundwater in floodplains, demonstrated by this study, highlights the importance of fully considering groundwater in flood management schemes.

Key words | aquifer, flooding, floodplain, groundwater, groundwater surface water interaction, superficial deposits

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INTRODUCTION

The role that groundwater plays in floodplain functioning is increasingly being recognised as an important area of hydrology. Groundwater within floodplains can: contribute to flooding (Vekerdy & Meijerink 1998; Macdonald *et al.* 2008); account for a major contribution of river flow within lower reaches of rivers (Capell *et al.* 2011; Tetzlaff *et al.* 2011); provide an important role in sustaining riparian wetlands and vegetation (Grieve *et al.* 1995; Grapes *et al.* 2005); regulate biogeochemical processes (Hill 1996; Lapworth *et al.* 2009) as well as provide an important resource for public and private water supply (Larkin & Sharp 1992; MacDonald *et al.* 2005). Research has shown that groundwater in floodplains can respond rapidly to river stage close to the river bank (Jung *et al.* 2004; Nowinski *et al.* 2012); however, it is less clear how connected floodplain groundwater is to other sources of recharge, such as hillslope runoff, deeper groundwater and direct rainfall infiltration. Understanding these different linkages is an important step in being able to forecast changes in groundwater levels and chemistry and help to mitigate the growing concern of groundwater flooding.

The recognition of groundwater flooding as a distinct flooding issue in Europe arose from severe flooding in the UK in 2000/01 as a consequence of exceptionally high groundwater levels in the Chalk aquifer, and the subsequent reactivation of many springs. A review estimated that

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380,000 properties in England and Wales could be at risk (Jacobs 2004) and provision was made for groundwater flooding in the 2007 EU Floods Directive (2007/60/EC). Four distinct mechanisms for groundwater flooding have been suggested (Macdonald *et al.* 2008; Hughes *et al.* 2011): (1) clearwater flooding, where groundwater in an unconfined aquifer rises and intersects the ground surface; (2) permeable superficial deposits flooding, where groundwater in floodplains connected to rivers rises to the ground surface; (3) groundwater rebound, where groundwater levels rise after pumping ceases; and (4) underground structures causing barriers to flow. Within Scotland, the second mechanism (permeable superficial deposits flooding) is the most significant source of groundwater flooding.

Permeable superficial deposits flooding occurs on floodplains in connection with rivers and can be difficult to distinguish from fluvial flooding. However, this distinction is important as it has a significant impact on the nature and design of mitigation schemes for the flooding (MacDonald *et al.* 2012a). For example, embankments will have little impact on groundwater flooding; and some interventions (such as installing impermeable barriers below ground) can even exacerbate groundwater flooding.

This study examines the hydrogeological functioning, including groundwater flooding, of a large floodplain of the River Findhorn as it passes near the town of Forres in northeast Scotland. Forres was subjected to one of the most catastrophic floods in UK history when the River Findhorn flooded in 1829 (McEwen & Werritty 2007). Since that time, the floodplain has been built on as the town of Forres has expanded, and Forres has been subject to several smaller floods (notably in 1997 and 2001). If a flood with a return period of 1 in 200 years was to occur in the River Findhorn there would be significant damage to the town (McEwen & Werritty 2007), therefore a flood alleviation scheme is being designed to protect the town. The site investigations for this scheme allowed the opportunity to examine groundwater within the floodplain.

The objective of this research is to use hydrochemistry, including groundwater residence time tracers, and groundwater-level variations, to examine groundwater within the superficial deposits of the lower Findhorn floodplain. In particular the study assesses the degree of connectivity between groundwater in the superficial deposits and the River Findhorn and identifies the presence of groundwater flooding.

Study area

The northeast coast of Scotland, between Inverness and Aberdeen, is an area of fertile soils and high value agriculture (Merritt *et al.* 2003). Previous glaciation of this area has resulted in the formation of a coastal strip of flat land approximately 10–20 km wide and underlain by 10s of metres of superficial deposits. The coastal strip receives relatively little rainfall compared to the rest of Scotland (<600 mm); large rivers originating in the higher rainfall area of the Grampian mountains to the south cross the coastal strip and discharge to the Moray Firth. The River Findhorn has a catchment area of 782 km^2 and mean flow from 1958 to 2005 is 19.4 m^3/s. The largest flood recorded in that period was 1,100 m^3/s (Marsh & Hannaford 2008).

Geology

A refined Quaternary (superficial) geological map (Figure 1) and interpreted cross-sections have been produced for the lower Findhorn floodplain. These are based on a rapid geological field survey, interpretation of geomorphology from aerial photographs and digital surface models and interpretation of engineer's logs from 30 piezometers and more than 50 trials pits (MacDonald *et al.* 2008, 2012a). The new map and cross-sections indicate that a complex sequence of Quaternary deposits exists in the lower Findhorn catchment and overly Devonian sandstone bedrock (British Geological Survey 2013). This complex sequence resulted from past glacier oscillations, relative sea-level fluctuations and river down-cutting (Merritt *et al.* 1995). The sequence is generally more than 10 m thick and more than 26 distinct units have been identified and mapped. These can be broadly grouped into: raised marine deposits; glacial till; peat; glaciofluvial sands and gravels; gravelly river deposits; sandy alluvium; and finer grained overbank deposits. The highly permeable sands and gravels occur widely throughout the floodplain whilst beds of less permeable material occur beneath, within and occasionally on top of these sands and gravels. The raised marine deposits are silty, more common at depth, and thick and extensive to the north of Forres towards the sea. A thin layer (<0.5 m) of loamy soil covers much of the floodplain, and glacial till commonly covers the underlying sandstone and conglomerate bedrock, which is Devonian in age.

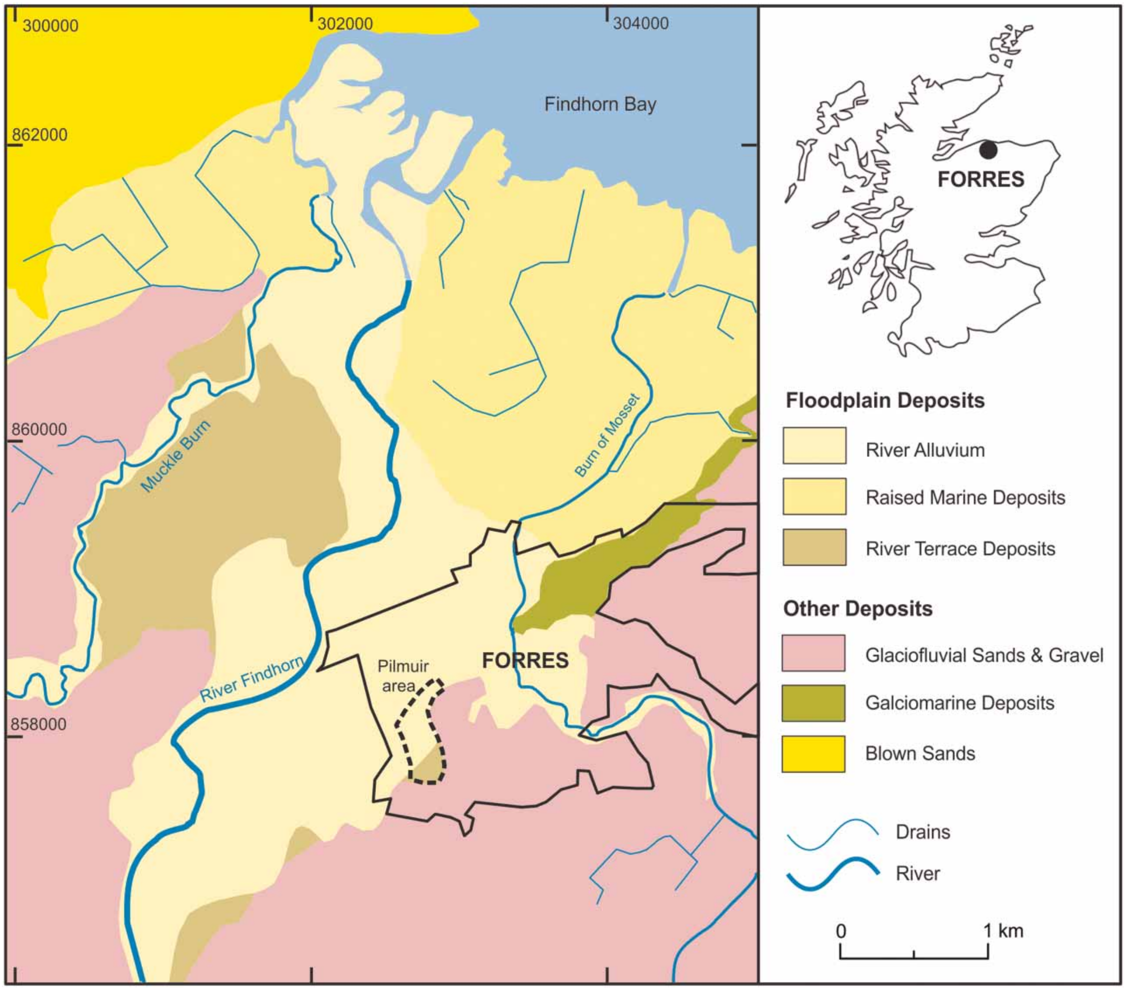

Figure 1 | A simplified geological map of the lower Findhorn Floodplain Topography © Crown Copyright. Licence No. 100021290.

Hydrogeology

The superficial deposits of the Findhorn floodplain and the underlying Devonian sandstone comprise a dual aquifer system. Within the bedrock aquifer, groundwater flow is primarily through fractures and transmissivity (permeability integrated over depth) is approximately 50 m^2/d (Graham *et al.* 2009; Ó Dochartaigh *et al.* 2010). The thickness and permeability of the superficial material which comprises the floodplain allows widespread movement of groundwater, although the complex multilayered nature of the deposits is also likely to affect groundwater flow and the connection with the underlying bedrock aquifer. There are several drains within the floodplain (see Figure 2) with more towards Findhorn Bay. As the floodplain of the River Findhorn approaches the sea it combines with the floodplains of the Burn of Mosset and the Muckle Burn. Small creeks form close to Findhorn Bay.

METHODS

Piezometers

Many of the piezometers drilled in the floodplain were equipped with pressure transducers to measure the change in groundwater levels. The location of the piezometers is shown in Figure 2. For piezometers drilled during the first phase of investigations, data were available for 13 months, March 2007 to April 2008. Data are available from

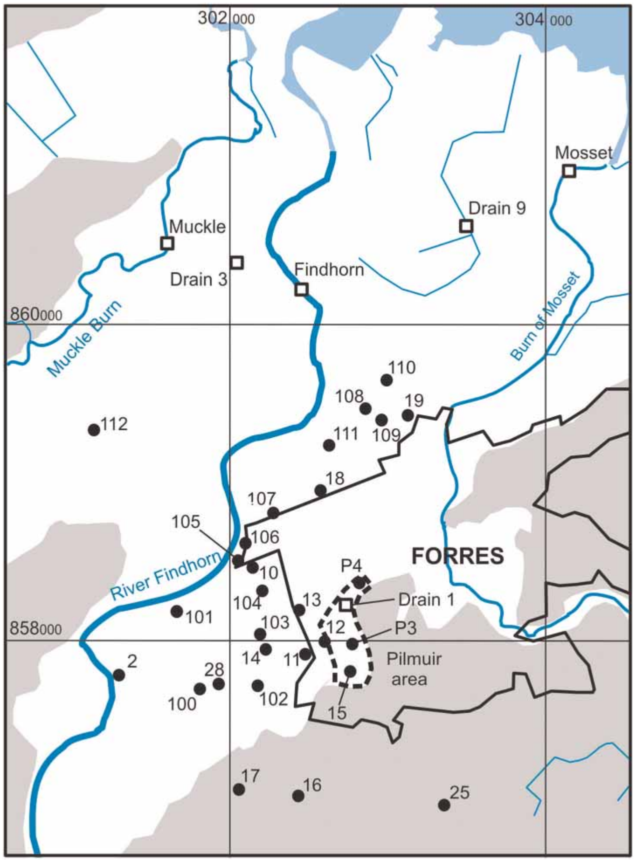

Figure 2 | Location of the piezometers drilled in the floodplain and surrounding deposits and samples taken for geochemical analysis. Topography © Crown Copyright. Licence No. 100021290.

December 2007 to April 2008 for the second phase of piezometers drilled. Each piezometer was levelled using a differential global positioning system (GPS) to an accuracy of better than 10 mm, and all pressures compensated for barometric pressure to give a measure of water-level relative to Ordnance Datum. River stage data are also available for the River Findhorn through the Scottish Environment Protection Agency river monitoring network, and daily rainfall data from the nearest Met Office raingauge at Wardend Bridge (NJ039558). A spot survey of river stage and groundwater levels was undertaken on 15th May 2007 to help identify relative groundwater levels and river levels. Lidar data were used to give an accurate representation of the floodplain elevation. There was less than 0.5 m difference between the measured river stage and the river level calculated from the Lidar data on the same day.

Pumping tests

To estimate the transmissivity of the superficial deposits, short pumping tests were carried out in all the piezometers. These were carried out while purging the borehole before taking groundwater samples for chemical analysis. Higher-yielding boreholes were tested using a centrifugal pump, which could pump up to 2 L/s. Lower-yielding boreholes were pumped using a narrow diameter 0.1 L/s Whale® pump. The tests fell into three categories: tests less than 1 hour; tests of 1–2 hours; and 4 hour tests; the data were analysed accordingly. The shorter tests were analysed using BGSPT (http://www.bgs.ac.uk/bgspt/home.html). BGSPT numerically solves the generalised well function developed by Barker (1985, 1988) for boreholes with finite borehole volumes in fractured aquifers and incorporates many other well functions as special cases. It evaluates the solution using numerical Laplace transform inversion and achieves a fit to data by least squares through a series of iterations. The longer tests were analysed using Jacob's approximation or the Theis Recovery Method (see Kruseman & de Ridder 1990) and most were checked using a radial flow model.

Residence time tracers

The use of chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6) as groundwater age tracers relies on the rise in their atmospheric concentrations over the last 70 and 40 years respectively together with certain assumptions about atmospheric mixing and recharge solubility (Plummer & Busenberg 2000). These gases are known to be well-mixed in the atmosphere so the curves are considered to be applicable to the study area. Groundwater studies undertaken by the British Geological Survey (BGS) in this study area have shown that CFCs are prone to degradation (MacDonald *et al.* 2008), however on this occasion there was little evidence for degradation in the majority of samples as there were mostly measurable concentrations of dissolved oxygen (DO) (Darling *et al.* 2012).

Sampling and chemical analysis

Piezometers were purged and sampled using a submersible pump. Stable readings were obtained for field parameters

(HCO_3, pH and specific electrical conductance (SEC), and DO) prior to sampling. Field parameters were measured using a sealed flow-through cell. Samples for cation and anion analysis were filtered (0.45 μm) in the field and stored in nalgene™ bottles at temperatures below 6 °C. Samples for cations were preserved with the addition of 1% v/v aristar grade nitric acid. Major cations and trace elements were analysed by inductively coupled plasma mass spectrometry (ICP-MS). Major anions were analysed by Dionex™ liquid chromatography. Dissolved organic carbon (DOC) was filtered using silver filters (0.45 μm) and stored in glass bottles prior to analysis by a Thermalox™ C analyser after acidification and sparging. Quality control standards from Aquacheck were used to validate the chemical analysis and ionic balances were within ±5% for all but one sample.

Samples for stable isotope analysis were collected unfiltered. Analysis was carried out using standard preparation techniques followed by isotope ratio measurement on a VG-Micromass Optima mass spectrometer. Data considered in this paper are expressed in ‰ with respect to Vienna Standard Mean Ocean Water. CFC and SF_6 samples, used in this study as a groundwater residence time tracer, were collected unfiltered and without atmospheric contact in sealed containers by the displacement method of Oster (1994). This method ensures that the sample is protected from possible atmospheric contamination by a protective jacket of the same water. CFCs and SF_6 were collected together in March 2007; for logistical reasons subsequent sampling in December 2007 was for SF_6 only. CFCs and SF_6 were measured by gas chromatography with an electron capture detector after pre-concentration by cryogenic methods, based on the methods of Busenberg & Plummer (2000). SF_6 measurements were corrected for excess air and a mean annual air temperature of 8 °C was assumed and used as the recharge temperature to calculate groundwater 'ages'. Measurement precision was within ±0.1‰ for $\delta^{18}O$ and ±1‰ for δ^2H with detection limits of 0.1 pmol/L and 0.1 fmol/L for CFC-12 and SF_6 respectively. Measurement of anions, stable isotopes, CFCs and SF_6 took place at BGS laboratories in the UK, cations were analysed by ACME, Canada.

Statistical analysis and geochemical plots were carried out using R (version 2.8). Cluster analysis was carried out to explore the geochemical characteristics of waters, using the 'Ward' hierarchical method, following scaling of major ion chemistry due to the effects of data closure. Mineral saturation indices were calculated using the PHREEQC computer programme (Parkhurst & Appelo 1999).

RESULTS

Transmissivity

The results of the pumping tests are shown in Table 1. The pumping tests indicate high variability of permeability in the superficial deposits across the floodplain: measured transmissivity varies by over three orders of magnitude, from less than 1 m^2/d to >3,000 m^2/d. This complements a wider study of the permeability of superficial deposits within the catchment which show similar results (MacDonald *et al.* 2012b).

A clear pattern emerges from the data in Figure 3. Transmissivity is generally high (often in excess of 1,000 m^2/d) at shallow depths (<8 m below ground level), where the deposits generally comprise glacial sands and gravels. The thickness of the gravel sequences suggest that their permeability is likely to be in the range of 100–1,000 m/d. Piezometers that penetrate a deeper sequence (>8 m) tend to have transmissivities of less than 10 m^2/d. These lower transmissivities can be attributed to a greater proportion of low permeability glacial tills and raised marine silts at these depths.

Groundwater levels

Figure 4 shows a map of river stage, ground elevation from Lidar and groundwater levels for 15th May 2007, (with some additional data for the north of the area from November 2007 when groundwater levels were at a similarly low level). The data highlight several significant issues:

- within the floodplain, groundwater flow is generally from south to north, running parallel to the river;
- the superficial deposits within the surrounding hillslope contain significant groundwater and contribute groundwater flow to the floodplain;

Table 1 | Location of piezometers and results of the pumping tests

BH	Easting	Northing	Ground level (mOD)	Top of screen (mbgl)	Base of screen (mbgl)	Transmissivity (m^2/d)	Comments
BH11	302486	857909	12.7	7	10	1.8	<1 hour test analysed using BGSPT
BH10A	302153	858464	12.6	2.5	5	2750	20 hour pumping test analysed using Theis recovery
BH10B	302153	858464	12.6	13.5	15	1	<1 hour test analysed using BGSPT
BH12	302603	857985	13.7	8	11	800	20 hour pumping test analysed using Theis recovery
BH13	302440	858180	10.9	4.5	7.5	1.4	<1 hour test analysed using BGSPT
BH15	302768	857798	13.1	2	4.5	210	20 hour pumping test analysed using Theis recovery. OBH gave $S = 0.11$
BH16	302445	857008	27.8	2	5	>1000	Estimate: pumped at 1.67 L/s for 20 min with no drawdown
BH17	302064	857049	23.4	5	7.5	230	20 hour pumping test analysed using Theis recovery
BH25	303363	856953	35.5	9	12	18	<1 hour test analysed using BGSPT
BH28	301943	857720	15.9	4	6	144	<1 hour test analysed using BGSPT
P3	302783	857969	12.3	Unknown	14	14	<1 hour test analysed using BGSPT
P4	302821	858361	10.2	Unknown	9	0.71	<1 hour test analysed using BGSPT
BH18	302631	858955	10.2	2.5	5	>500	Estimate: pumped at 0.1 L/s for 60 min with no drawdown
BH19	303056	859346	7.7	1.5	4	>500	Estimate: pumped at 0.1 L/s for 60 min with no drawdown
BH100	301822	857696	15.212	2	5	497	1 hour test analysed using Theis recovery
BH101	301681	858187	13.461	4	7	69	2 hour test analysed using Jacob's approximation
BH102	302183	857719	15.208	3	6	0.63	1 hour test analysed using Jacob's approximation
BH103	302203	858041	13.944	4.5	7.5	31.3	2 hour test analysed using Jacob's approximation
BH104	302216	858298	13.055	5	8	2839	5 hour test analysed using Theis recovery
BH105	302069	858501	12.4	2.7	5.7	1750	1 hour test analysed using Theis recovery
BH106	302101	858630	12.488	9	12	4.19	5 hour test analysed using Jacob's approximation
BH107	302285	858790	10.86	4	5	2035	1 hour test analysed using Theis recovery
BH108	302870	859455	7.511	3.85	6.85	62.8	1 hour test analysed using Jacob's approximation
BH109	302961	859390	7.744	3.6	6.6	1722	1 hour test analysed using Theis recovery
BH110	302996	859639	6.379	2.6	5.6	351	1 hour test analysed using Jacob's approximation
BH111	302635	859231	8.511	3.5	6.5	3099	1 hour test analysed using Theis recovery
BH112	301155	859330	9.875	5.1	8.1	760	1 hour test analysed using Theis recovery

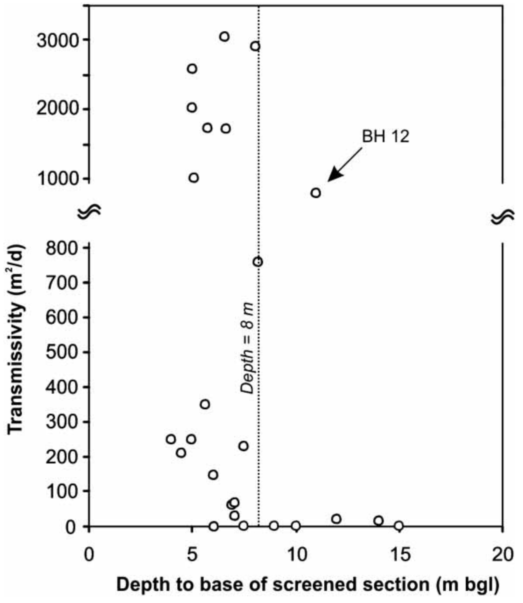

Figure 3 | Variation of transmissivity from pumping tests with depth of screened section.

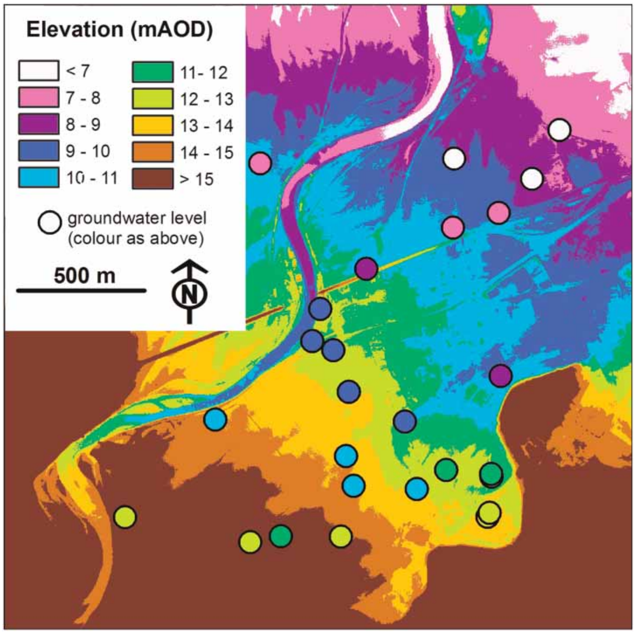

Figure 4 | Groundwater levels, river elevation and ground elevation for the Findhorn floodplain. This indicates: (1) general groundwater flow parallel to the river; (2) variations in groundwater level relative to river level along the river; and (3) areas where groundwater is close to the surface.

- groundwater levels are significantly lower (up to 2 m) than the river levels in the southern part of the floodplain as the River Findhorn emerges onto the floodplain (south of Northing 858000); this suggests that the river will lose water to the floodplain groundwater system;
- further downstream (north of Northing 858000), groundwater levels in the floodplain near to the river are similar to river stage implying more equilibrated interaction between river and groundwater.

By comparing the groundwater levels with the ground surface in Figure 4 it is possible to identify areas where groundwater is close to the surface and therefore at general risk of groundwater flooding. One particular part of the floodplain, the Pilmuir area (identified in Figure 2), has groundwater levels closest to the surface, and is most at risk of groundwater flooding. The area is largely undeveloped, has marshy channels within it, and local inhabitants say that for large parts of the year there is ponded water within it. Attempts have been made to drain the area and these drains tend to run full for much of the year, indicating significant groundwater discharge.

The piezometers

Groundwater level data from the piezometers within the study area follow a consistent response and fall into distinct groups: river bank piezometers, floodplain piezometers, and those in the groundwater flooding area. Figure 5 shows the response of piezometers within these different groups plotted against river stage and also rainfall.

All piezometers show little systematic annual variation. Groundwater levels are controlled by river stage, the response to individual rainfall events and the degree and nature of the response is dependent on the location of the piezometers within the floodplain.

Piezometers close to the river (generally within 250 m) show a marked connection to the river. Piezometers in this category include 101 and 106, 111, 110, and to a lesser extent 108 and 107. These piezometers respond closely to river stage. Piezometer 101 gives the greatest response, with the groundwater levels rising by more than 1 m in response to the high river levels in December 2007. Water levels took two weeks to recede and closely correspond to the recession of the river.

Piezometers in the middle of the flood plain (102, 103, 28, 14) do not respond to individual events, either rainfall, or river stage, but do respond to cumulative rainfall and relate to sustained increases in river stage. The amplitudes of water level rises are of the order of 0.5 m. It generally

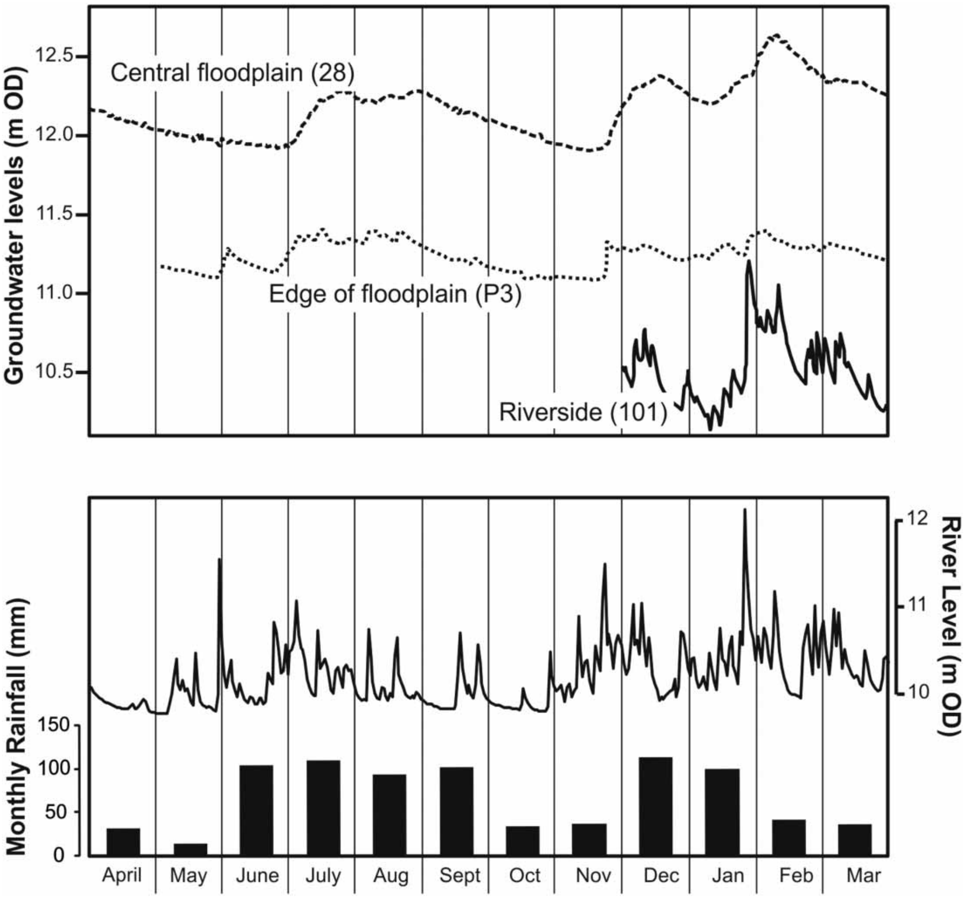

Figure 5 | Examples of groundwater level response and river levels for April 2007 to March 2008. The locations of the piezometers are shown in Figure 2.

takes 2 weeks to reach the maximum level, which often occurs after river levels have receded. Recession is much slower than in piezometers close to the river bank, following a linear, rather than logarithmic response.

Piezometers in the groundwater flooding area, Pilmuir, show muted responses, with total variations during 2007 of up to 0.5 m. Water levels can rise (up to 0.2 m) rapidly, generally in response to large rainfall events (daily totals >30 mm). Recession, however, is very slow and can take several months. Piezometers close to the existing drains show the most muted responses indicating that the water-levels are controlled by the elevation of the drains.

Hydrochemistry

Table 2 shows the chemistry results for field parameters (DO, pH, SEC, Eh), major elements, trace elements, DOC, stable isotopes and SF_6 from the survey of groundwaters, field drains and surface waters undertaken as part of this study.

Inorganic chemistry

The major inorganic chemistry of the different water types are summarised in a Piper plot in Figure 6. The groundwaters are predominantly Ca-HCO_3 type waters, however the shallow groundwaters from the surrounding superficial deposits have noticeably higher proportions of Na-Cl. Groundwaters sampled from the deeper sandstone aquifer and river bank deposits have low SEC (<400 μS/cm), samples from the floodplain have intermediate SEC (400–500 μS/cm), and samples from the surrounding superficial deposits have generally higher SEC (>600 μS/cm). The differences in water types and SEC reflect both water-rock

Table 2 | Chemistry results

FIELD ID	E	N	pH	T °C	SEC mS/cm	DO$_2$ mg/L	Eh mV	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	Si mg/L	Cl mg/L	HCO$_3$ mg/L	SO$_4$ mg/L	NO$_3$-N mg/L	DOC mg/L	Br mg/L	Fe mg/L	Mn mg/L	δ_{18}O %VSMOW	δ_2H %VSMOW	SF$_6$ fmol/L	SF$_6$ Modern fraction	CFC-11 pmol/L	CFC-12 pmol/L	Res time Years
Rivers																											
Findhorn	302556	860821	6.47	13.2	97	10.6	168	4.9	1.4	0.74	6.46	3.41	7.73	20	1.47	0.092	10.9	<0.02	0.323	0.004	– 7.75	– 55.3					
Mossett	304416	860957	7.23	13.4	288	12.4	58	28.1	3.58	2.92	20.5	6.08	34.3	74	14.7	2.09	6.42	0.054	0.337	0.023	– 8.03	– 55.8					
Muckle	301496	860381	7.45	13.1	315	11.8	135	34.4	3.38	2.61	16.3	5.28	28.8	87	12	3.84	7.24	0.057	0.282	0.025	– 8.17	– 56.4					
Field Drains																											
Drainl	302795	858185	6.67	10.7	585	5.48	334	59.7	5.39	3.66	38.1	5.93	65.7	118	24.1	8.66	3.97	0.136	0.007	0.006	– 8.41	– 55.9	1.68	0.58	24.28	3.02	12
Drain3	301925	860482	6.16	11.8	211	5.9	205	22.3	2.53	2.53	9.03	3.96	16.3	48	9.85	4.66	1.8	0.056	< 0.005	< 0.002	– 8.61	– 56.2					
Drain9	303454	860698	6.63	11.9	533	5.8	160	49.6	4.92	5.91	39	5.82	69.6	112	33.4	4.51	2.36	0.124	0.026	0.019	– 8.31	– 55.8					
River bank boreholes																											
BH 101	301682	858187	6.93	10.5	352	7.28	241	34.9	2.62	2.59	27.2	3.99	42.5	103	12.4	4.85	1.84	0.067	0.142	0.036	– 8.81	– 61.1	2.45	0.89			3
BH 107	302285	858791	6.83	11.3	341	4.45	213	17.7	1.6	1.98	12	3.61	22.4	38	6.14	2.21	3.96	0.026	0.047	0.009	– 8.9	– 61.5	1.69	0.58			12
BH 105	302069	858501	6.54	10.2	177	2.41	294	59.4	7.78	5.15	48.8	5.55	98.1	54	45.8	17	2.18	0.177	0.036	0.039	– 8.46	– 56.3	1.44	0.50			14
BH 100	301822	857696	6.92	10.5	287	10.8	133	49.2	4.18	3.74	43.3	6.04	65.9	116	22.1	8.31	1.96	0.122	0.009	0.021	– 8.78	– 59.9	1.06	0.37			18
Floodplain boreholes																											
BH12	302509	858439	7.19	11.9	548	3.63	240	51.8	4.41	3.42	30	5.13	60.4	119	20.5	4.92	3.37	0.105	0.03	0.139	– 8.34	– 56.4	2.23	0.77	5.89	3.10	7
BH10B	302141	858469	7.25	9.8	450	8.1	155	54.4	4.82	2.91	13.4	4.92	32.6	94	19.6	12.1	2.76	0.108	0.045	0.093	– 8.31	– 57.1	1.84	0.64	5.40	2.51	10
BH10A	302141	858469	6.67	9.8	456	8.8	148	51.7	4.52	2.97	13	4.97	36.1	62	18.7	17	2.91	0.132	0.05	0.016	– 8.1	– 53.6	1.63	0.56	6.96	3.68	12
BH 102	302183	857720	6.95	10.3	481	6.37	181	65.6	4.62	2.78	21.2	6.04	44.8	102	16.4	15	1.63	0.113	0.059	0.473	– 8.6	– 55.9	2.19	0.80			5
BH19	303058	859337	6.54	8.4	651	0.42	296	54.1	4.76	3.6	53.9	5.32	85	115	24.6	3.7		0.11	0.034	0.027							
BH28	301939	856944	6.91	11.9	414	8.45	336	51.4	4.01	2.69	14.2	5.21	30.4	87	16.7	10.4	3.69	0.101	0.01	0.043	– 8.15	– 55.5	1.62	0.56	7.74	2.72	12
BH13	302444	858159	7.47	10.6	459	0.63	346	60.1	2.41	2.59	18.7	6.12	35.5	170	16.3	2.42	1.28	0.072	0.177	0.313	– 8.37	– 56.3	1.59	0.55	0.67	1.19	13
BH 103	302204	858041	7.06	9.9	453	8.51	204	60	4.1	2.72	19.7	5.62	42.1	90	16.7	14.8	1.45	0.118	0.012	0.06	– 8.43	– 56.4	1.98	0.72			7
BH 104	302216	858298	6.74	10.4	413	8.2	199	52.9	4.01	2.67	17.2	5.58	38.1	82	16.9	16	1.34	0.114	0.057	0.015	– 8.51	– 56.3	1.85	0.67			9
BH 111	302636	859231	5.13	10.5	416	6.3	362	49.5	4.07	3.43	18.2	5.52	37.8	67	20	13.7	1.84	0.114	0.006	0.013	– 8.93	– 59.3	1.50	0.55			12
BH 110	302996	859639	6.76	10.1	500	7.14	149	39.1	3.19	2.48	13.5	5.74	17.6	94	17.9	6.34	2.06	0.087	0.085	0.035	– 8.91	– 60.1	1.03	0.36			18
BH11	302488	857900	7.56	11.1	450	0.78	120	62.2	3.93	4.98	20	10.3	35.5	169	19.6	1.68	2.65	0.07	1.29	0.863	– 8.29	– 55.8	4.00	1.38	0.46	0.60	
BH 108	302871	859456	6.8	10.7	446	6.51	165	44.4	3.82	3.71	49	5.87	71.2	118	20.3	6.04	1.84	0.114	0.023	0.016	– 8.89	– 62.8	1.44	0.50			14
BH 109	302962	859390	6.6	10.7	494	5.44	170	48.2	3.84	3.54	36.7	5.69	56.7	119	19.5	6.53	1.34	0.112	0.023	0.029	– 8.69	– 56.3	1.97	0.68			9
BH 112	301156	859330	6.42	10.7	658	4.04	220	35.8	3.15	3.29	21.7	4.77	35	68	15	8.25	1.66	0.065	0.023	0.004	– 8.7	– 56.8	0.82	0.28			21
BH18	302625	858936	6.51	10.8	518	7.66	300	56.1	4.82	3.44	22.9	5.63	46.3	72	20.8	16.7		0.122	0.037	0.085							
Surrounding Superficial boreholes																											
BH15	302768	857789	6.46	10.6	612	1.59	241	55.3	5.82	3.79	41.7	5.95	74.4	109	39.2	10.1	4.65	0.158	0.032	0.055	– 8.83	– 57.8	2.05	0.71	6.01	3.07	8
BH16	302432	858986	6.88	11	620	8.42	306	35.3	3.78	2.72	67.9	5.5	109	82	18.7	3.38	3.13	0.107	0.157	0.011	– 8.62	– 56.5	1.62	0.56	9.74	3.26	12
BH25	303362	856944	7.22	13.3	729	0.37	312	54.3	5.26	2.88	71.4	5.76	121	136	21.2	1.95	3.19	0.107	0.063	0.178	– 8.48	– 56.7	3.67	1.27	1.22	1.40	
BH17	302064	857042	6.19	8.9	578	8.05	303	57	5.81	3.2	23.6	4.85	57.9	34	15	25.9	3.99	0.133	0.046	0.011	– 8.04	– 53.2	1.44	0.50	7.69	3.76	14
Sandstone boreholes																											
P3	302787	857959	7.83	10.1	302	<0.1	144	44.5	1.65	2.07	11.8	5.23	16	140	5.84	– 0.05	1.54	0.054	0.021	0.033	– 7.43	– 49.9	0.92	0.32	0.10	0.11	20
BH 106	302101	858631	7.26	10.7	241	0.81	107	54.8	2.59	2.72	10.8	5.26	19.7	166	6.21	– 0.05	3.41	0.054	0.029	0.144	– 8.51	– 57.2	0.72	0.26			21
P4	302820	858345	7.91	11.1	316	N/A	N/A	49.8	1.93	2.15	12.5	5.25	21.8	158	10.7	0.114	1.93	0.065	0.033	0.248	– 8.79	– 59.2					

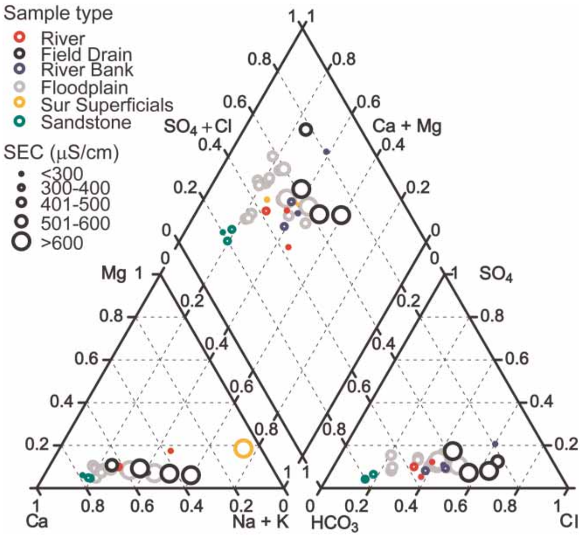

Figure 6 | Piper plot of major ion chemistry for groundwater and surface waters.

interactions during recharge and transport in the aquifer as well as local sources of contamination.

Table 3 shows the results of saturation indices for selected minerals. Only the sandstone piezometers and BH11 and 13 in the floodplain are in equilibrium with respect to calcite ($SI_{calcite} = 0 \pm 0.2$), see Table 3. Saturation indices are sometimes used as a measure of residence time due to the evolution of the groundwater as a result of water-rock interactions. The SF_6 data also suggest long residence times at these sites (Table 2). In contrast, groundwaters from superficial deposits and surface waters are undersaturated with respect to calcite, perhaps indicative of shorter residence times. Barium is readily available in the aquifers sampled with barite being well buffered ($SI_{Barite} = \pm 0.2$) in most groundwater samples and some drains (Table 3).

Figure 7 shows a cross-plot of Cl and Br; the rainwater/seawater line is shown for comparison. The deeper sandstone samples lie on the seawater line as do some of the field drains and groundwaters from the floodplain aquifer, indicating no or limited modification during recharge of maritime rainfall. There are a number of samples from most of the other types of waters that show deviation from the seawater line. For the surface waters, river bank and floodplain groundwaters the deviation is small, and could represent minor sources of contamination or incorporation of Br in organic material during recharge. Several sites from the surrounding superficial deposits indicate significant enrichment of Cl resulting in

Table 3 | Mineral saturation indices for waters. Those in bold are approaching saturation

Site ID	SI calcite	SI quartz	SI chalcedony	SI fluorite	SI barite
Rivers					
Findhorn	−3.30	***−0.10***	−0.55	−4.60	−1.60
Mosset	−1.07	***0.15***	−0.30	−3.42	−0.31
Muckle	−0.68	***0.09***	−0.36	−3.49	***−0.20***
Field drains					
Drain1	−1.32	***0.19***	−0.28	−2.94	***0.06***
Drain3	−2.81	***−0.01***	−0.47	−4.03	−0.35
Drain9	−1.45	***0.16***	−0.30	−3.02	0.28
River bank boreholes					
BH 101	−1.25	***0.02***	−0.45	−3.11	−0.36
BH 107	−2.04	***−0.04***	−0.50	−3.70	−0.70
BH 105	−1.87	***0.17***	−0.30	−3.30	0.59
BH100	−1.09	***0.20***	−0.27	−3.07	0.08
Floodplain boreholes					
BH12	−0.71	***0.10***	−0.36	−2.69	−0.31
BH10B	−0.75	***0.12***	−0.35	−2.90	***−0.07***
BH10A	−1.66	***0.12***	−0.34	−3.13	***−0.08***
BH 102	−0.99	***0.20***	−0.27	−2.77	−0.21
BH28	−1.16	***0.11***	−0.35	−3.02	−0.32
BH13	***−0.20***	***0.20***	−0.27	−2.70	−0.28
BH 103	−0.95	***0.18***	−0.29	−3.00	***−0.19***
BH17	−2.62	***0.13***	−0.34	−3.30	***−0.02***
BH108	−1.27	***0.18***	−0.28	−2.94	***0.06***
BH109	−1.49	***0.17***	−0.30	−2.91	***−0.01***
BH104	−1.43	***0.16***	−0.30	−3.14	***−0.19***
BH111	−4.29	***0.16***	−0.31	−3.18	***−0.06***
BH110	−1.46	***0.18***	−0.29	−2.76	***−0.19***
BH112	−2.10	***0.09***	−0.37	−3.00	***−0.12***
BH11	***−0.09***	***0.42***	−0.05	−2.52	***−0.03***
BH18	−1.77	***0.16***	−0.30	−2.96	***−0.06***
BH19	−1.60	***0.18***	−0.30	−2.67	***0.20***
Shallow superficial boreholes					
BH15	−1.69	***0.19***	−0.28	−2.98	0.26
BH16	−1.42	***0.15***	−0.32	−3.03	−0.25
BH25	−0.60	***0.13***	−0.33	−3.02	***−0.13***
Sandstone boreholes					
P3	***−0.02***	***0.14***	−0.33	−2.41	−1.01
BH106	−0.46	***0.13***	−0.33	−2.86	−0.32
P4	***0.17***	***0.12***	−0.34	−2.51	−0.60
Chapelton BH[a]	−0.56	0.21	−0.27	−2.62	−0.21

[a] Data from Edmunds *et al.* (1989).

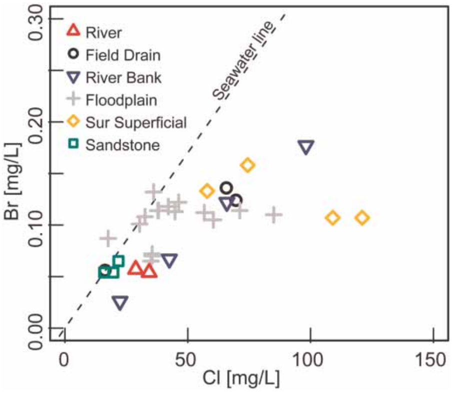

Figure 7 | Cross plot of Cl vs Br for all samples. The seawater line is shown for comparison.

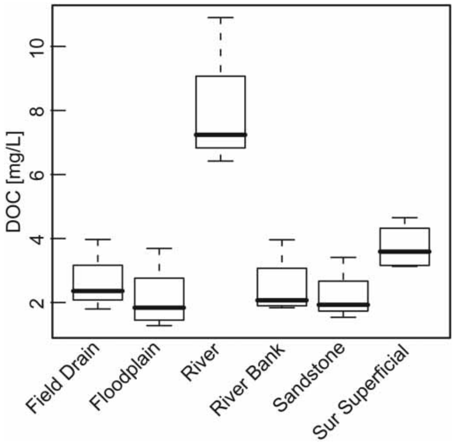

Figure 8 | Summary box plot of DOC results for the different water types in this study.

larger deviations from the seawater line. These sites are in well established Caledonian forest and the change in ratio may be due to high evapotranspiration associated with the edge of the forest coupled with significant incorporation of Br in the highly organic forest soils.

The groundwaters from the sandstone aquifer have the lowest NO_3 concentrations overall, indicating limited contamination from anthropogenic sources. These waters have low DO so denitrification processes cannot be ruled out as a reason for the low NO_3 concentrations. There is a large range in NO_3 concentrations found in samples from the floodplain, river bank and surrounding superficial deposits. The concentrations found in the surrounding superficial deposits are all below the drinking water limit of 11.3 mg/L, while several of the sites from the floodplain aquifer have concentrations in excess of 11.3 mg/L. Arsenic concentrations were found to be below 5 μg/L for all samples. Manganese concentrations were below the World Health Organization limit of 0.4 mg/L for all samples except two from the floodplain aquifer (0.47 and 0.86 mg/L) and are comparable to measurements of Mn in Scottish groundwater (Homoncik *et al.* 2010). The deeper sandstone aquifer had overall higher median concentrations (0.15 mg/L) compared to the shallow superficial, river bank and surface water samples (all <0.05 mg/L).

Dissolved organic carbon

The DOC results are summarised graphically as box plots for the different water types (Figure 8). Groundwaters all have similar median concentrations and ranges with median values around 2 mg/L and maximum concentrations below 5 mg/L. These concentrations are in keeping with other groundwaters in Europe where median concentrations of 2 mg/L are reported (Gooddy & Hinsby 2008). Groundwater in the surrounding superficial deposits, where Br concentrations were low has the highest DOC concentration. Field drain samples have comparable DOC concentrations to those found in groundwater. Surface water samples have much higher DOC concentrations overall, with median values of around 7 mg/L. These high concentrations are likely to reflect sources of organic matter from soil runoff, and the short residence time of these waters limiting the potential for microbial breakdown of DOC.

Figure 9 shows a cross plot of $\delta^{18}O$ vs $\delta^{2}H$ for the different types of water; the 'world meteoric line' (WML) defined as $\delta^{2}H = 8\delta^{18}O + 10$ (Craig 1961) is shown for comparison. None of the samples show evidence of evaporation prior to or during recharge and discharge. The samples fall either side of the WML, and there is no evidence of significant depletion due to altitude effects suggesting that recharge occurs locally, at or close to sea level. The values for this study are similar to published values ($\delta^{18}O$ values of between −8 and −8.5) for coastal aquifers in this area (Darling *et al.* 2003).

The CFC-12 and SF_6 data from March 2007 have been plotted against ideal lumped parameter mixing curves (Gooddy *et al.* 2006) in Figure 10. Most of the floodplain samples plot close to the binary mixing line as would be

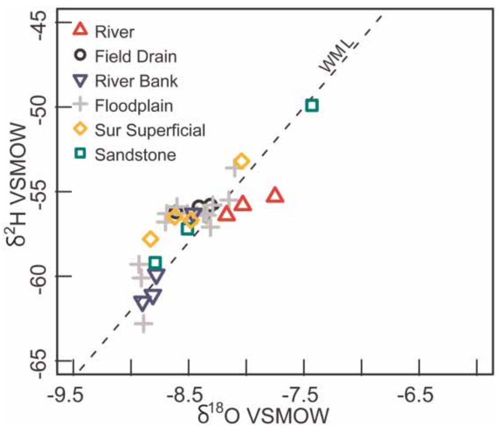

Figure 9 | Cross plot of $\delta^{18}O$ vs δ^2H for the different water types in this study. The world meteoric line of Craig (1961) is shown for reference.

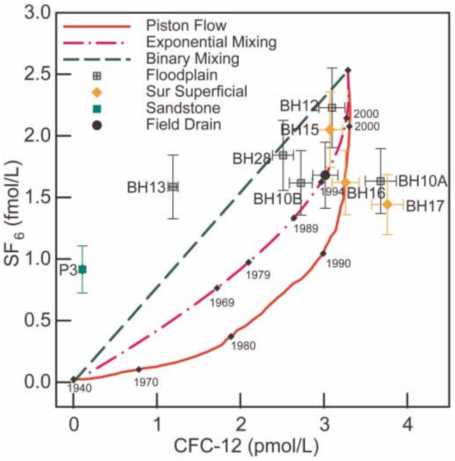

Figure 10 | CFC-12 and SF_6 groundwater data overlaid on ideal mixing model curves. An excess correction factor has been applied to all samples on an assumed 3cc/L excess air (see Gooddy *et al.* 2006). Recharge temperatures for calculation of groundwater age are based on 8 °C.

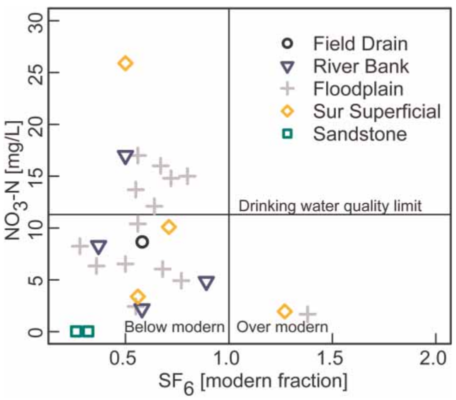

Figure 11 | Cross plot of SF_6 vs NO_3. The SF_6 data is shown as the fraction of modern water concentrations. For SF_6 fractions values of 0 are SF_6 'dead' water (pre 1960s water), values of 1 are equivalent to modern recharge (2007) and >1 show evidence for contamination. The European Commission drinking water quality limit of 11.3 mg/L NO_3-N is shown for reference.

expected in a floodplain environment. The shallow BH10A which is close to the river shows a slight excess of CFC-12 which may reflect a greater degree of interaction with colder surface water which would contain more dissolved gases. BH13 plots away from the binary mixing line but this could be explained by an insufficient excess air correction for this sample. The Devonian sandstone sample also deviates from the ideal curves, however this sample has no measureable DO and therefore it is likely that the CFC-12 is too low due to degradation under reducing conditions.

As the SF_6 dataset is more extensive than the CFC, a cross plot of the modern fraction of SF_6 and NO_3 is shown in Figure 11. The trend found elsewhere in Scotland of increasing NO_3 with a higher fraction of modern water (MacDonald *et al.* 2003), is not observed here. This is probably because the nitrate inputs across the study area are variable (from woodland, agriculture and urban). There are several samples that show SF_6 concentrations greater than would be expected from modern water (Figure 11), suggesting local contamination from mineral sources. These 'over modern' results were excluded from the groundwater age calculations.

Figure 12 summarises the groundwater residence times based on the SF_6. The deeper sandstone aquifer has median residence times of 20 years; these are significantly higher than other groundwaters sampled in the shallow

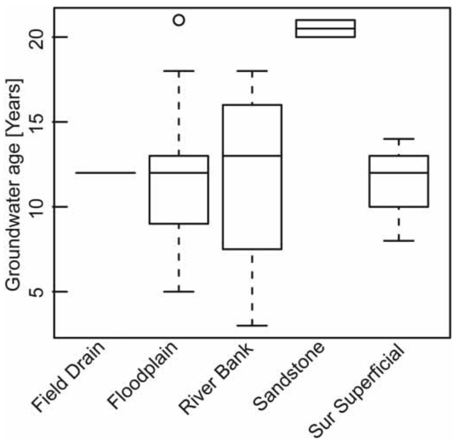

Figure 12 | Box plot of groundwater age for the different water types in this study based on SF_6 data.

aquifers. Samples from the surrounding superficial aquifers have similar median residence times of ca. 12 years, as does the single dated drain sample. The shallow floodplain and riverbank piezometers have a large inter-quartile range (see Figure 12) and some older groundwater (>15 years), which are mostly in the downstream parts of the floodplain.

Cluster analysis

After appropriate data standardisation, hierarchical cluster analysis was carried out to explore samples with similar chemical characteristics and divide the sites into groups. Four clusters are highlighted in Figure 13 which can be summarised as follows: cluster 1 was composed of sandstone groundwaters and one floodplain piezometer, cluster 2 was dominated by surface water sites and river bank piezometers as well as some floodplain piezometers and a drain, cluster 3 was composed almost exclusively of floodplain piezometers and cluster 4 was composed of groundwaters from the surrounding superficial sites, river bank, floodplain piezometers and some field drain sites. This provides further support to the chemical interpretation that the sandstone, floodplain and surrounding superficial groundwaters each have distinctive geochemical signatures, while groundwater within the field drains and close to the river bank is less distinctive and shows greater geochemical heterogeneity.

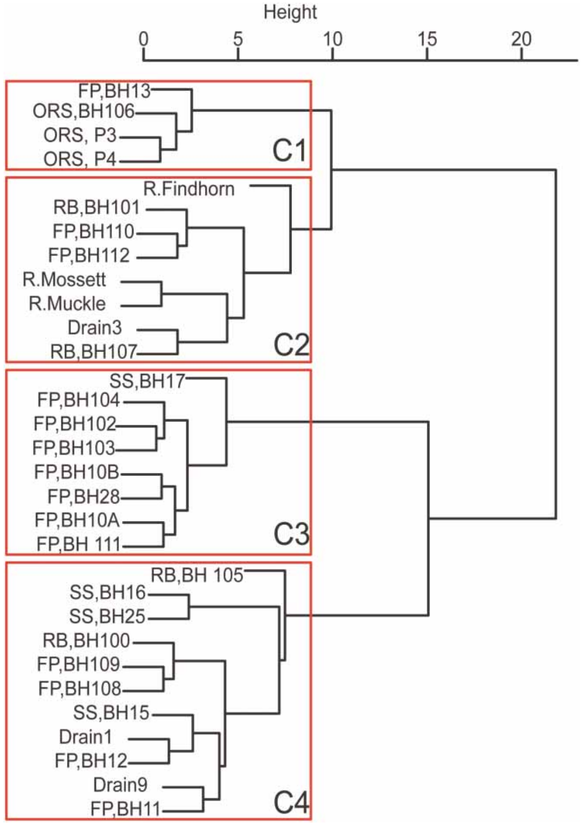

Figure 13 | Dendrogram obtained by hierarchical cluster analysis using standardised major ion chemistry. The sites are labelled according to water type and Field ID. FP = floodplain boreholes, SS = surrounding superficial boreholes, RB = river bank boreholes, ORS = Devonian Sandstone boreholes.

Cluster 1 sandstone groundwater

The distinct major ion chemistry in the sandstone aquifer shows that water-rock interactions with calcite, the primary accessory mineral and cement, is the dominant geochemical reaction taking place during groundwater transport. A floodplain piezometer, BH13, clusters with the sandstone groundwaters (Figure 13) reflecting the deeper completion of this piezometer. Results from a sandstone borehole (Chapelton BH) within this locality, reported in Edmunds *et al.* (1989), are shown in Table 2 for comparison. The groundwater chemistry and mineral saturation indices for this site are comparable with the results from this study, indicating that there has been no significant mixing of floodplain water with the deeper groundwater in the sandstone.

Cluster 2 surface water and riverbank groundwater

There is similarity between the surface waters in the main rivers, some of the drains, and some of the riverbank piezometers. Groundwater levels in piezometers close to the river respond rapidly to river levels demonstrating a high degree of connection. The cluster analysis indicates that this connection can lead to significant water transfer between river and the floodplain (e.g. similarity of water chemistry in RB 107, 101 to surface water). However, not all river bank piezometers are in this cluster indicating a complex system with varying degrees of interaction. One of the surface water sources (the Muckle Burn), although clustering with other surface waters, has calcite and barite saturation indices of −0.68 and −0.2 respectively (Table 3), closer to equilibrium than many shallow groundwaters. This could indicate a high degree of groundwater baseflow.

Cluster 3 floodplain groundwater

Many of the samples from piezometers within the central parts of the floodplain have similar chemistry. These groundwaters show evidence of being recharged locally, with elevated nitrate from agriculture on the floodplain, and young residence times. Groundwater level variations are also similar across this area and show a much lower degree of coupling with the river, with water levels rising slowly (a matter of weeks) in response to rainfall and high river stage. These locally recharged groundwaters flow northward to discharge to the rivers and surface drains.

Cluster 4 groundwater from superficial deposits surrounding the floodplain

Cluster 4 is largely made up of groundwater from the surrounding superficial deposits which have longer residence times. The SEC is higher, and the bromide/chloride ratio shows a relative enrichment of chloride, and the waters tend towards Na-Cl. Groundwater at the margins of the floodplain, furthest from the river, tend to also fall into this group indicating that flow from the superficial deposits surrounding the floodplain is a major source of groundwater in the floodplain.

DISCUSSION

Floodplain recharge, residence times and flow paths

The residence time data show evidence of the rapid recharge mechanisms in the floodplain: several piezometers in the floodplain have mean residence times of <10 years indicating a high component of rapid recharge. The relatively high DOC concentrations in many of the floodplain groundwaters and the surrounding superficial deposits also infer rapid recharge mechanisms. The rapid response of groundwater levels to rainfall or river stage in many of the piezometers also indicates rapid recharge mechanisms. Residence times in the underlying sandstone are longer than for much of the floodplain (ca. 20 years) and the low NO_3 concentrations and SEC suggest that there is limited downward leakage. Some sites within the floodplain (e.g. BH 104, 108, 110, 111 and 112) have mean residence times comparable with the sandstone (10–20 years) and tend to be located either downstream within the floodplain, away from the river or at greater depths in the floodplain. This most likely reflects the longer flowpaths of groundwater downstream in the floodplain: groundwater is mainly recharged in the southern parts of the floodplain and flows northward to discharge in drains, ditches and tributaries.

In addition to inflows from the River Findhorn, groundwater is recharged directly from rainfall onto the floodplain, as shown by the distinct geochemistry and elevated nitrate. Groundwater is also recharged from the surrounding hillslopes, which are underlain by highly permeable glacial deposits (MacDonald *et al.* 2012b) and have low Br/Cl ratios and elevated SEC. These three different sources of groundwater can be identified within the upstream and central parts of the floodplain; downstream, in the discharge area of the floodplain the groundwaters in piezometers, rivers and drains appear more mixed. There is no evidence of a significant contribution to the floodplain groundwater from the underlying sandstone aquifer.

Much of the groundwater movement within the floodplain is parallel to the river, to eventually discharge to drains, streams and the main rivers, close to the sea. This is in agreement with the findings of Larkin & Sharp (1992) who reviewed 24 alluvial systems in the USA and found that groundwater flow was more likely to be parallel to the river when the stream gradient was more than 0.001. The gradient of the Findhorn within the floodplain is approximately 0.002. It is likely that the presence of low permeability raised marine deposits close to the shore will reduce direct groundwater discharge to the sea. The mean residence time for groundwater increases downstream, from <10 years in the main recharge areas to approximately 20 years in the discharge areas.

Surface water/groundwater coupling

The piezometry and the hydrochemistry indicate complex interactions between groundwater and surface water on the floodplain. The floodplain is highly permeable in the top 8 m and there is no evidence of significant physical barriers to flow across the entire floodplain. Therefore coupling is controlled by the relative pressure changes across the floodplain, and between rivers, drains and groundwater. The presence of lower permeability material at depth within the floodplain (e.g. glacial till and raised marine deposits) limits the coupling between groundwater in the floodplain and the underlying sandstone aquifer. Figure 14 summarises the coupling between groundwater and surface water across the floodplain.

The piezometric and geochemical evidence of the direct influence of the River Findhorn on groundwater in the floodplain is greatest within approximately 250 m of the river. In the upstream section of the floodplain, as the river emerges from a deeply incised channel onto the floodplain, there is evidence that most of the water transfer is from river to floodplain. In the middle section of the floodplain, groundwater levels are similar to river levels and rise and fall with river stage with little or no lag time; groundwater has similar chemistry to the river water and short residence times. Therefore it is likely that water transfers between river and temporary storage in groundwater, driven by the heads and facilitated by the high permeability of the sediments. In the downstream section of the floodplain as the floodplain nears the sea, there is geochemical evidence that groundwater is constantly discharging to the rivers (e.g. the Muckle Burn) and large drains.

Groundwater flooding

Groundwater levels respond differently across the floodplain to river stage and rainfall. As discussed above, groundwater levels are closely coupled to the River Findhorn near to the river (up to 250 m). However, in the centre of the floodplain, groundwater levels are not observed to respond to individual rainfall events, but take several weeks to rise in response to rainfall or river stage, and take longer to fall.

Close to the edge of the floodplain, where much of the groundwater is sourced from the surrounding hillslope, groundwater levels are not linked to river stage, but respond to individual rainfall events. Daily rainfall of approximately >30 mm can elevate groundwater levels by 0.2 m; groundwater recession is slow, possibly due to the reduced discharge pathways. This has led to regular groundwater flooding at the edge of the floodplain in the Pilmuir area as evidenced by long-standing marshy and ponded areas described by local residents and data from the piezometers in the area (Figure 4). Ground levels are lower, probably due to the location of an old channel, groundwater levels are shallow (generally <1 m) and a drain in the area (Drain 1) constantly discharges groundwater, keeping much of the area dry under normal circumstance. A dated water sample taken from this drain had a residence time comparable with the shallow superficial groundwater in this area (ca. 12 years). Variations in groundwater level in the area are generally subdued, due to the effect of the drain and the ability for the groundwater to discharge to the surface. However, as discussed above, piezometers do respond to intense rainfall events resulting in a rapid increase in groundwater level which recedes slowly, over a matter of weeks. Therefore any additional water in this area, either due to increased surface runoff, or groundwater flow within the floodplain or from the surrounding superficial deposits, is likely to exacerbate groundwater flooding and lead to more persistent flooding.

The extensive drainage network developed largely during the 19th century is located in areas with shallow groundwater at risk of groundwater flooding. The cluster analysis (Figure 13) demonstrates that most drains reflect the groundwater chemistry monitored in nearby piezometers, indicating that the drain discharge comprises groundwater, rather than runoff. Therefore, this evidence suggests that groundwater flooding has been managed in this area since the 19th century.

Implications for flood management

Sustainable flood management is an increasing priority in the UK (Pitt 2008), and globally, as a consequence of recent floods and future forecasts of the impact of climate change (Min *et al.* 2011). Some of the more 'natural' approaches being considered include storing floodwaters on parts of floodplains to help reduce peak flows (McIntyre *et al.* 2014). Our current study offers some insight into how this may impact on groundwater, and also how the hydrogeological conditions may impact the effectiveness of the flood alleviation measures.

Elevated river stage leads to increases in groundwater levels close to the river and the infiltration of river water into the groundwater. Much of this infiltrated water will

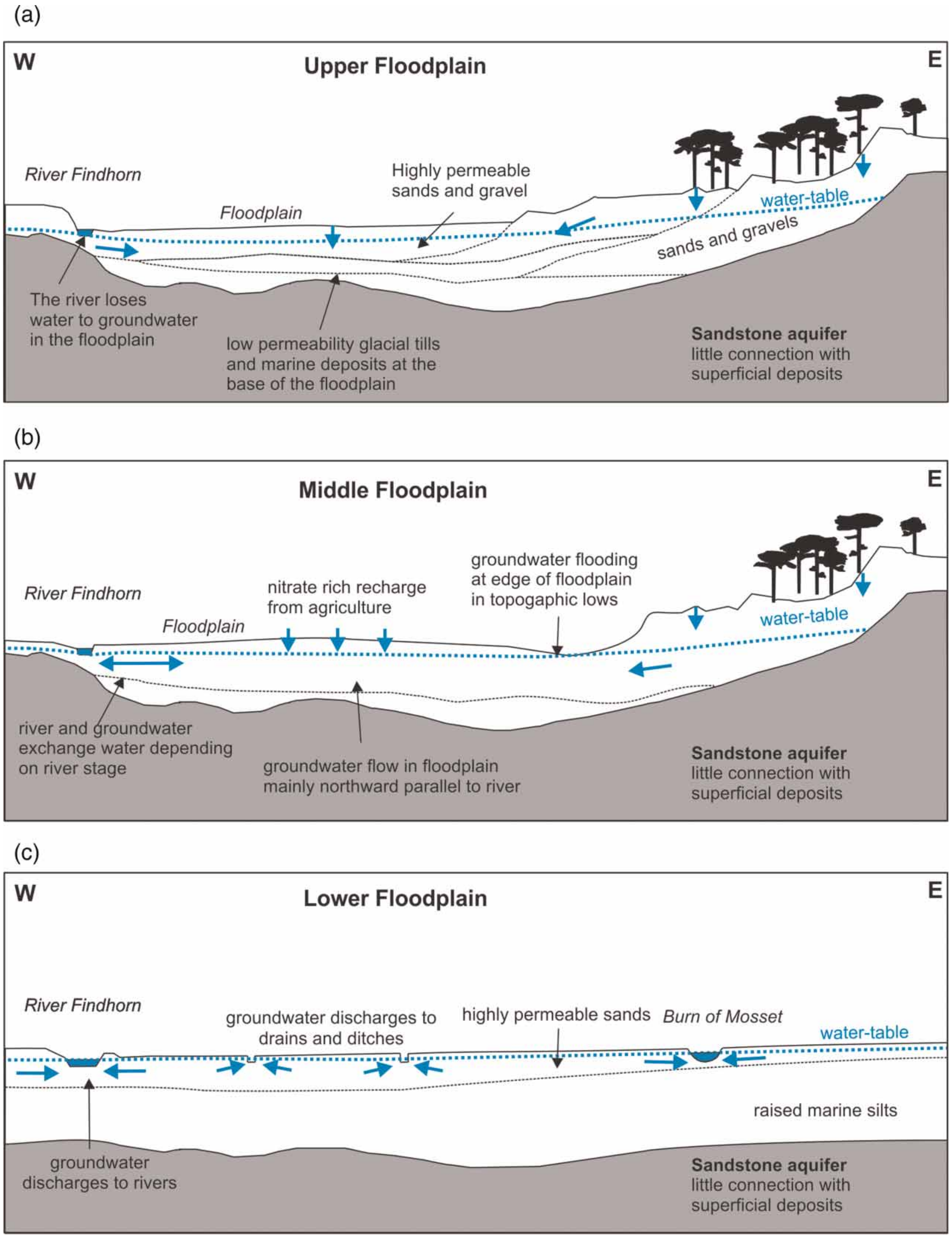

Figure 14 | Conceptual cross-sections of groundwater flow (a) upper floodplain, (b) middle floodplain and (c) discharge area. Note that much of the groundwater flow is northward, parallel to the River Findhorn.

return to the river once the river stage reduces and the groundwater gradient is reversed. However, some effects will be more widespread or longer lasting. In this study the increase in river stage rapidly and directly impacted piezometers within 250 m of the river, and a proportion of infiltrated river water remained in the groundwater and flowed with the general groundwater gradients. Beyond about 250 m, local rainfall infiltration or runoff from the surrounding hillslopes appeared a greater influence on the groundwater system. Therefore, schemes which store floodwater on floodplains can directly impact groundwater chemistry and volumes, with the largest and most immediate impact within several hundred metres of the inundated area. Not all groundwater responses during a flood event should be attributed to inundated river floodwater – rainfall infiltration, and runoff from the surrounding hillslope should also be considered.

One of the most significant impacts that groundwater has on the effectiveness of a flood alleviation scheme is to allow a route by which water can escape from a planned impoundment. Although this infiltrating water is unlikely to cause catastrophic damage it can raise groundwater levels and lead to more persistent groundwater flooding across the floodplain which could damage properties and influence ecology. Introducing sub-surface impermeable barriers will stop this occurring during a flood event but they are likely to exacerbate groundwater flooding under normal situations by acting as a barrier to groundwater discharge. A more effective solution is to install drains to capture the infiltration and facilitate the rapid discharge of this additional groundwater once river stage has returned to normal (MacDonald *et al*. 2012a)

The actual volumes of floodwaters that can be stored in the unsaturated aquifer are low compared with river flood volumes. For example it was estimated that a 1 in 50 year flood could lead to 100,000 m^3 of floodwaters infiltrating to groundwater for a particular scheme designed for the Findhorn (MacDonald *et al.* 2012a), which would only account for 100 s of the peak river flow recorded from 1958 to 2005 (probably a 1 in 100 year flood event) or 5 min of the median annual river flood (Marsh & Hannaford 2008). However, for much smaller events, or in smaller river channels the effect of groundwater storage is proportionally more significant; groundwater storage and then baseflow also performs important ecological and biogeochemical functions.

SUMMARY AND CONCLUSIONS

This study of the River Findhorn floodplain has provided insight into the role of groundwater in the functioning of floodplains. A series of piezometers were constructed, three-dimensional geological mapping undertaken and the pumping tests carried out to assess the permeability structure of the floodplain. This allowed the interpretation of 12 months of groundwater level monitoring and a campaign of sampling for hydrochemistry and residence time indicators. The following conclusions can be drawn from analysis of the different datasets:

1. Pumping tests from 27 piezometers demonstrate that the floodplain is highly permeable (100 m/d) in its shallowest 8 m where glacial sands and gravels are prevalent, but has much lower permeability at depth (1 m/d) where glacial till and raised marine sediments dominate. The glacial history of the area has been fundamental in the development of the permeability.
2. Hydrochemical sampling, and continuous water level monitoring in piezometers, indicate that groundwater coupling with the River Findhorn is most noticeable within 250 m of the river and the nature of the interaction changes across the length of the floodplain.
3. Analysis of the groundwater and river gradient across the floodplain, and hydrochemical interpretation of water samples from the river, drains and piezometers close to the river, show that the river loses water to groundwater as it enters the floodplain; in the lower section groundwater discharges to rivers, tributaries and drains; and in the middle section groundwater response follows closely river stage giving rise to complex interactions.
4. Chemical analysis indicates there are three major sources of groundwater recharge to the floodplain, the River Findhorn, the surrounding hillslopes, and rainfall recharge on the floodplain.
5. Groundwater flow in the floodplain is largely parallel to the River Findhorn and CFC and SF_6 analysis show

that the mean residence time of groundwater is <20 years, with the longest residence times generally in the discharge zone or at depth in the floodplain, and shorter residence times of 3 years sometimes observed in the recharge zones.

6. Interpreting groundwater level data with river level data and rainfall indicate that groundwater level response to rainfall and river stage varies across the floodplain: there is close coupling to river stage within 250 m of the river, a delayed integrated response to river and rainfall in the centre of the floodplain, and a rapid response to intense rainfall events (daily totals >30 mm) at the edge of the floodplain, close to the surrounding hillslopes.
7. Chemical analysis of waters and an interpretation of Lidar with piezometer groundwater level data show that groundwater flooding occurs within the floodplain in topographical lows, and also in the discharge zone close to the sea. It is largely managed with a series of drains constructed in the 19th century, which constantly discharge groundwater.

This study has demonstrated the significant and complex role that groundwater plays in the functioning of floodplains and highlights the importance of taking groundwater into consideration at an early stage when investigating flooding, or planning flood alleviation schemes.

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