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CLIMAWAT:

Adapting to Climatic impacts on groundwater quality and quantity.

Final Report

March 2014.

Project Team

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Univeristé de Brest Occidental,
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CNRS

Industrial Support

1. INTRODUCTION.

It is generally accepted that we are experiencing a period of climatic change. In SE England and NW France, temperatures have increased over the last century by about 1ºC. Warmer and drier summers and milder and wetter winters are expected for the future in this area. Periods of infiltration entering groundwater systems (recharge) higher or lower than normal can affect groundwater quality either by changing contaminant transport pathways, changing groundwater chemistry, or both. The objectives of the CLIMAWAT project were to examine the effects of long-term climatic changes on water recharge to aquifers, and on the behaviour of both chemical and microbiological pollutants in groundwater catchment areas using techniques derived from the latest research. This information can then be used to inform adaptive responses in terms of land and water management strategies and to transfer this knowledge to relevant stakeholders. The project aimed to achieve this through a series of interlinked investigations including:

- Geological and geophysical investigations of transport pathways for groundwater recharge and contamination in fractured rock aquifers in SE England and NW France (Fig. 1);
- Simultaneous monitoring of rainfall, groundwater recharge and groundwater chemistry for potential contaminants and for specific chemical tracers;
- Computer and laboratory modelling of recharge and transport processes validated against monitoring and historical records;
- Ultimately, prediction of the impact of changing climate patterns on groundwater recharge and quality.

The outcomes of this project will be the enhanced management of drinking water supplies dependent on groundwater from fractured rock (chalk and granite) and a more general examination of risk management associated with the groundwater impacts of climate change and the viability of artificial recharge as a method for augmenting groundwater resources, principally in terms of the sustainable use of aquifers in Southern England and Northern France. The intended main outcomes of this project were:

(i) Prediction of the impact of climate change on recharge of groundwater resources and groundwater quantity and quality
(ii) Better understanding of flow, displacement, dispersion and adsorption of pollutants (for example nitrates and pesticides) in fractured porous aquifers.
(iii) Better understanding of the storage mechanism and impact of artificial recharge on water quality of the chalk aquifer in South East England and the weathered granite aquifer of NW France.

Figure 1: Satellite image showing the location of the studied catchments.

1.1 Project structure

The project ran from 1/4/2009, with the final actions (outside of reporting and financial closure) complete by 31/12/2013. During this period the project management group met every 6 months for a progress meeting. Wherever possible this meeting was also attended by members of the supporting bodies (UK Environment Agency, Southern Water, South East Water, Chalk Rock Ltd) and representatives of the INTERREG Channel and JTS. The main work of the project was organised into 4 work packages. These were:

WP1: Effect of Climate Change on Groundwater Resources

This work package aimed to quantify the amount of water entering the groundwater system, and the mechanism by which this occurred in the two study catchments. This was done in order to both assess the changes that may occur to available groundwater resources, and their influence on the distribution and impacts of contaminants. This was organised into 2 sub work packages (Fig. 2):

WP1.1: Quantification of Groundwater Fluxes

The study areas chosen already had well characterised catchments in the UK at Patcham (chalk), and in France at Ploemeur (granite). The project updated and modified existing models, particularly to include characterisation of the geology of the unsaturated zone. For both the studied catchments, maps were prepared in GIS format showing the physical and morphological parameters of the study watersheds. The study will also include characterisation of the surface drainage network. This section of the project included hydrodynamic parameters determination in chalk and granite aquifers by laboratory testing combined with data from previously conducted, or new pumping tests from boreholes in the study areas. The volume and rates of water flow were assessed using geochemical and geophysical techniques detailed in this report.

WP1.2: Local-Scale and Regional-Scale recharge mechanisms with climate change

Considerable uncertainties concerning the impact of future climate change on groundwater recharge remain. The main task of this Work Package was to integrate the estimation of recharge and evapotranspiration at different scales in order to provide estimates of large scale recharge, and also small scale variability. The work involved mainly a field monitoring approach, focussed on the hydraulic and transport response of the underground environment to intermittent rainfall and the possible changes in frequency and intensity of hydrological events resulting from climate change. The approach to this aspect of the investigation, again, involved both physical and chemical monitoring approaches. In particular the work package made use of instrumented sites in both catchments, alongside interpretation of novel chemical tracer techniques, most notably the use of CFC analyses of groundwater.

WP2: Groundwater Sustainability

Population growth in SE England and NW France and climate change pressures will cause the production of more sewage and reduce the quantity of available good quality water. One of the solutions in the management of available water resources in SE England is artificial groundwater recharge of the Chalk aquifer. However, there are issues related to this solution. A better understanding of the infiltration mechanisms of the chalk aquifer linked to WP1 and the long-term effect of artificial groundwater recharge using treated sewage waters on chalk water quality is needed.

WP2.1: Water Quality and long-term effect of artificial groundwater recharge using treated waters

In order to study the migration of potential contaminants to groundwater through the unsaturated zone, experimental sites in Brighton and Rennes were monitored on a monthly basis over the course of the project. Analyses included major water components, trace elements, nutrients and microbiological indicators. Correlation of changes in water chemistry with climatic conditions and flow processes in the aquifers was use to interpret the interaction of recharge with groundwater quality, and hence models of changing groundwater quality with changing climatic effects.

WP2.2: Mobility, distribution and retention of contaminants

The flow, dispersion, diffusion and adsorption of both chemical and microbiological pollutants in chalk and granite aquifers under the effect of climate change, was studied experimentally. Data from laboratory experiments was used in up scaling calculations designed to examine potential impacts and to inform the future design of effluent dispersal sites.

WP3: Risk Assessment and management of groundwater resources

The CLIMAWAT project aimed to use the concepts and models developed in other workpackages to propose methodologies for vulnerability assessment of fractured and karstic aquifers. Assessment of the geophysical model resolutions and solutions to properly convert geophysical properties (electrical parameters) was carried out. The ultimate goal is to find optimal mitigation strategies for the minimization of ground water vulnerability. The main objective of this work package was the development of a process-based geochemical flow and transport models, which will include detailed structural characterisation of the aquifer using geophysics and geology. These models aim to simulate the impact of climate change on groundwater recharge, quantity and quality and will be validated against physical and chemical data from the other work packages.

WP4: Dissemination and publicity

The results of the work undertaken have been disseminated to partners and other interested organisations by means of the six monthly project management meetings. The minutes of these meetings and any presentations given are available through a project website (http://www.climawat.info). This website is also the main means of dissemination to the general public. The site was mirrored in English and French in order to maximise accessibility. In addition, towards the end of the program, two end users dissemination events were organised and publicised both to the public, and to non-partner organisations with interests in the area of investigation, one in France and one in the UK. Dissemination to academic and industrial audiences will also be achieved by the means of conference presentations and publications in peer reviewed journals and professional trade publications.

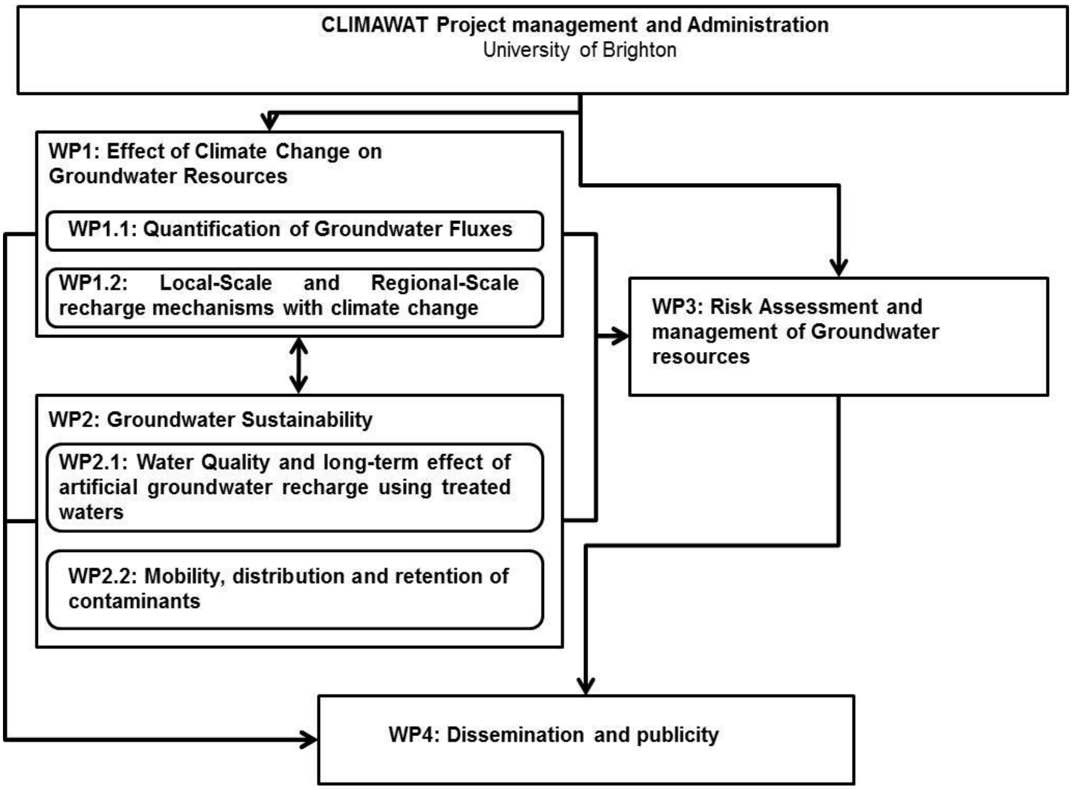


Figure 2: Summary of project structure and the relationship between work packages.

2. Physical execution of the project.

2.1 Work Package 1.1 Quantification of Groundwater Fluxes

Production of GIS data sets.

The University of Brighton team assembled a comprehensive GIS database (Fig. 3) for the study area. Data range in type and include both raster and vector format depending upon the nature of the data. The following base map layers have been collected for the CLIMAWAT project:

- Ordnance Survey (OS) Raster Maps at 1:10,000 and 1:50,000 scale
- OS Mastermap at 1:1250 scale
- OS Meridian 2 Mapping Data at 1:50,000 scale (infrastructure)
- OS Digital Terrain Model at 1:10,000 and 1:50,000 scale

Regional data showing main soil associations are available. The data are combined with base value data which provides quantitative data detailing drainage rates, permeability, pH, Organic Matter Content values etc. These data include maximum, minimum and weighted average values for soil associations.

A GSI3D Model was compiled by N Hadlow as work completed for the FLOOD1 project. The geological model and data have been made available to the CLIMAWAT team. The model gives a 3D representation of the Patcham catchment geology with the ability to create vertical (borehole) logs and cross sections at any location in the catchment. The geological model includes the BGS solid and superficial deposits and locations of solution features and springs. Local geological mapping work completed by N Hadlow in the Patcham catchment has also been fed into the GSI3D Model. Data from both the Standard GIS and the GSI3D model has been made available to all partners.

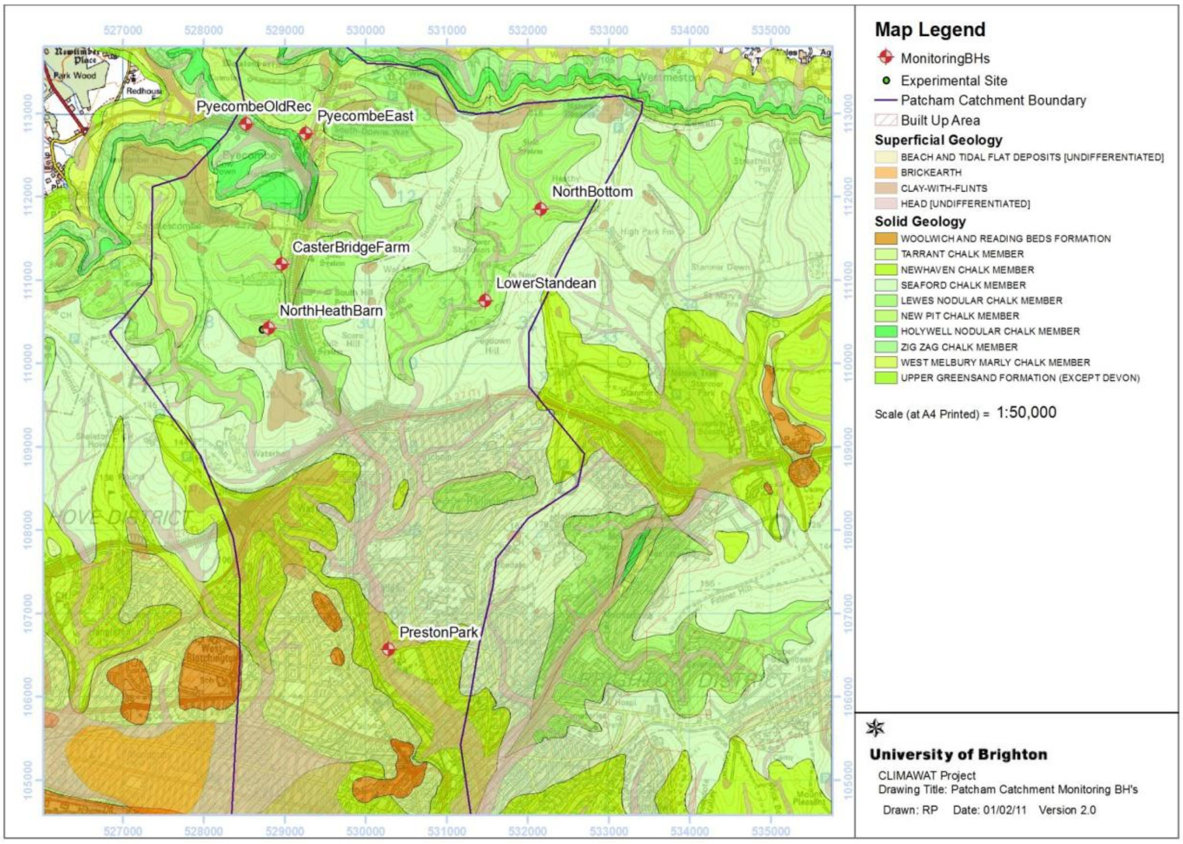


Figure 3: Example GIS output showing the geology of the Patcham catchment and the location of key monitoring boreholes.

In addition to the full GIS made available to project partners a simplified web enabled set of GIS information has been made available to the general public. This is visible at www.climawat.info and is linked to WP4.

In the Ploemur catchement this work package has led to the production of GIS maps and datasets presenting the main characteristics of the experimental site (Fig. 4), which have been disseminated through the national database H+. Data are available on line at hplus.ore.fr

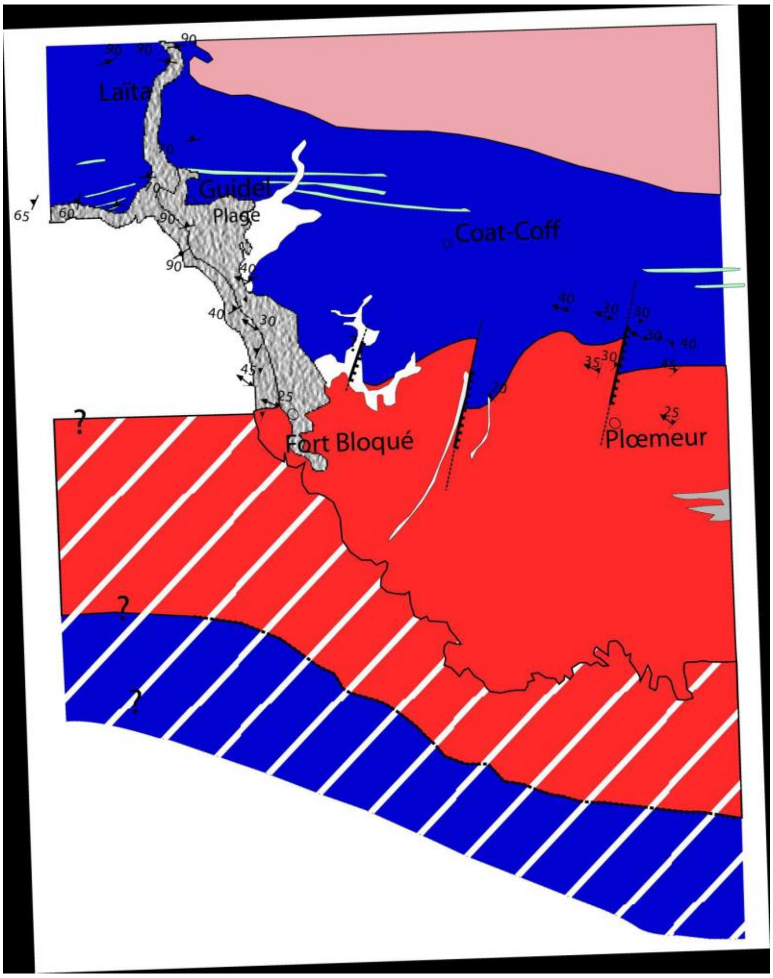


Figure 4 GIS of geological setting of the Ploemeur site..

Production of hydrodynamic parameters

Detailed characterisation of the hydraulic properties of both aquifers was a key underpinning of the work to be delivered under other work packages. This area of Work Package 1 has lead to the completion of 2 Master of Science dissertations (Agada, Boschero; See Appendix 1 and Evidence of Deliverables CD).

In the Patcham catchment a large body of data existed from the previous EU-RDF FLOOD1 project. This was tabulated into brief reports by the University of Brighton, which were then circulated to other partners to support the production of flow and reaction models (WP 3 at UEA) and models linking geophysical response to the hydrodynamic behaviour of the Chalk aquifer (WP 1.1 University of Brest Occidental). These reports are available as part of the Evidence of Deliverables CD. In order to support more detailed and rapid testing of the hydraulic properties of the rock matrices of the aquifers, the University of Brighton purchased a pychnometer for porosity determination and gas permeameter for permeability determination. These were used to cross reference data with previous determinations of permeability using triaxial cells, to test for correlations between porosity and permeability that could be used for permeability prediction, and to provide base line characterisation data for flow and reaction experiments (WP 2.2). The results from this study are in agreement with previous work that showed although there was some relationship between porosity and permeability, overall the limited correlation meant direct prediction of one variable from another would be difficult (Fig. 5), underlining the importance of detailed geological characterisation of aquifer heterogeneity, and the use of stratigraphic frameworks in preparing aquifer conceptual models to underpin computers models of all degrees of complexity to predict future aquifer behaviour.

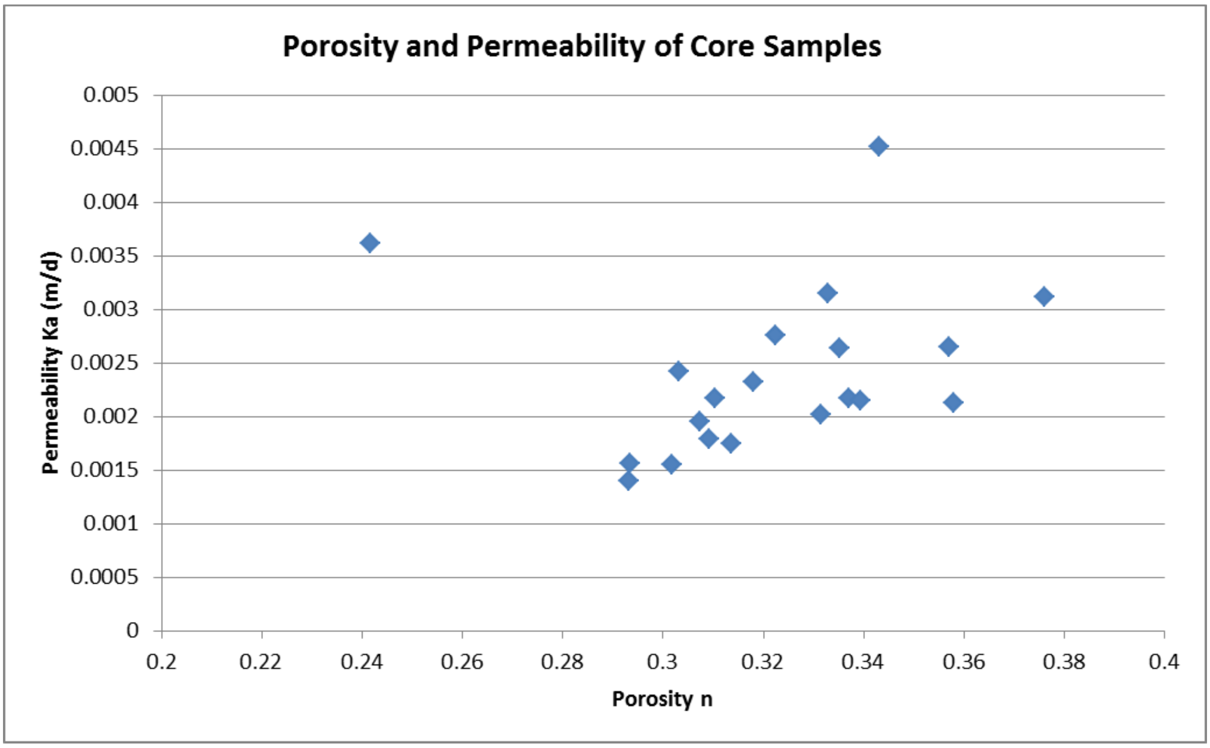


Figure 5 – Porosity-permeability relationships for Chalk samples tested using gas permeametry in this study.

A complete characterization of the unsaturated zone, including soil and weathered rock (granite), of a fractured crystalline-rock aquifer located in Ploemeur (S Brittany, France) took place in the framework of the unsaturated zone monitoring activity (WP 1.2). It includes, for the different soil horizons defined (Fig. 6), textural fractions (from sieve and laser method), bulk density (from undisturbed soil samples, steel rings), and infiltration test from Guelph and Double-ring permeameter to obtain hydraulic parameters (saturated hydraulic conductivity), in this last case only for the first horizon (A).

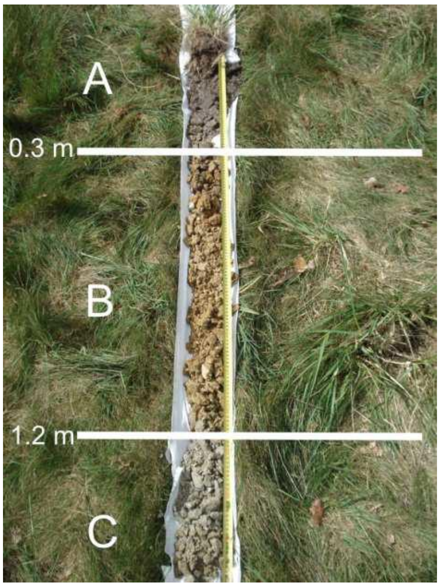


Figure 6 Soil column and different defined horizons

In situ hydrodynamic processes have been studied using a series of temperature and electrical conductivity profile measurements in boreholes under different hydraulic conditions: ambient and pumping. Some of them have been logged before which allowed comparison of results and estimates of the possible evolution of the flow system. Figure 7 below show the borehole logs realized during the last few years on the borehole F28 near to the pumping site. Results show that differences can be observed over the time.

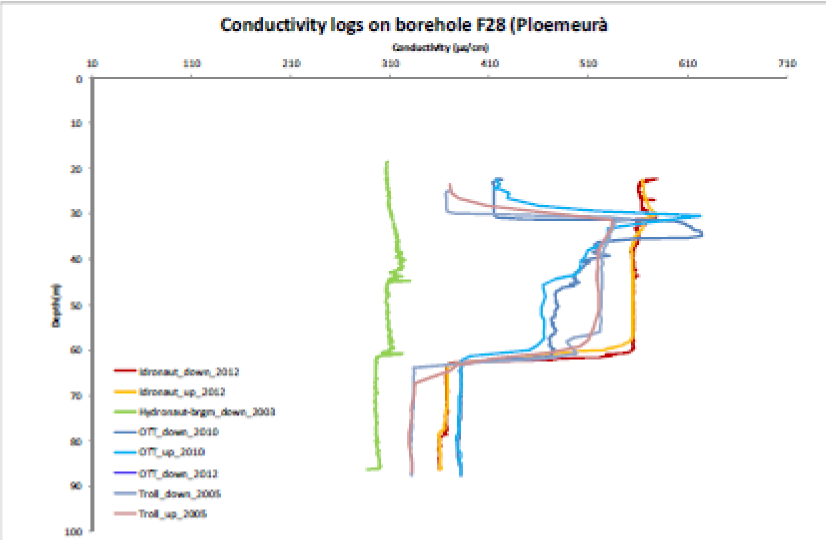


Figure 7 Examples of electrical conductivity profiles for different times at F28 observation well.

The Rennes team has also carried out borehole logging (pH, temperature, conductivity) in the Patcham area. This logging helped to identify and characterize water inflow in wells (Fig. 8). The results allow an optimized sampling depth.

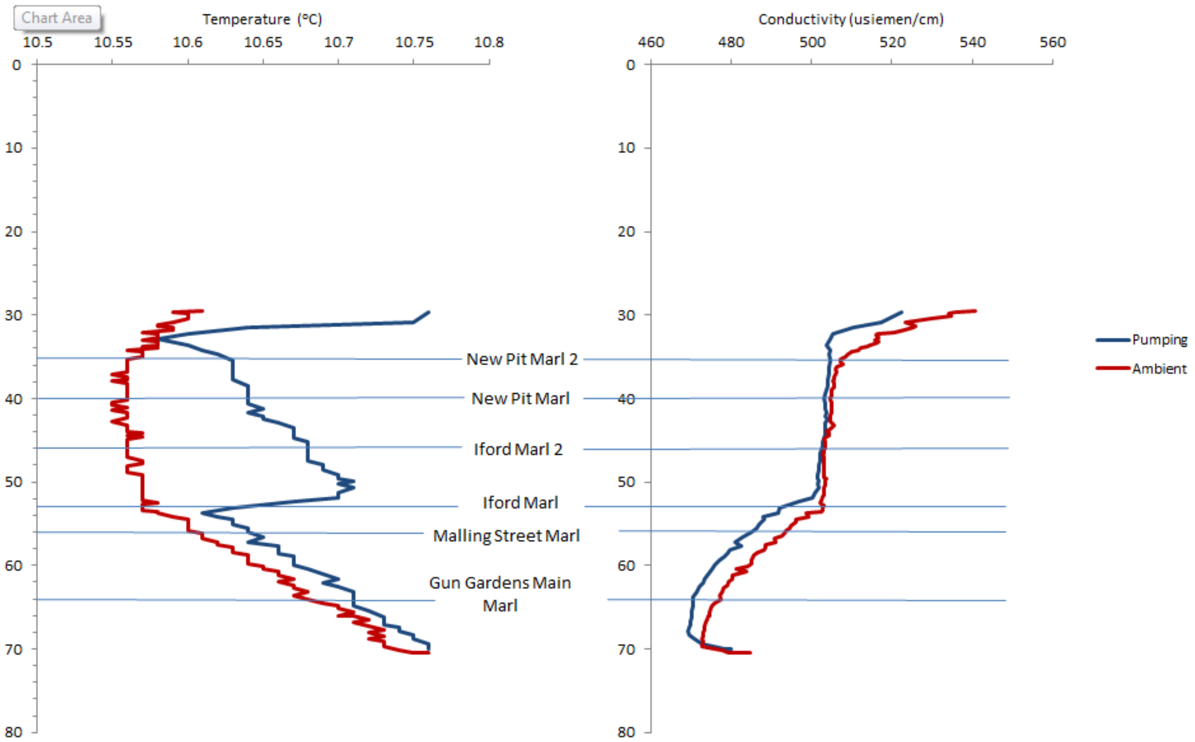


Figure 8 Example of a well fluid log from Lower Standean under ambient and pumped conditions.

To complement these data, flow measurement were carried out on some boreholes using the heat pulse technique. Especially, the boreholes on the Stang er Brune site, an experimental site which is located a few kilometres away from the pumping site, which has been a focus of a series of tracer tests experiments during the project. Figure 9 below shows flow velocities measured in borehole B2. The flow measurements are performed under ambient conditions but also with pumping either in the same borehole or in an adjacent well. Results show the depths where there is an important water inflow and provide estimates of the flow produced by these fractures. These data were important for the design of the tracer tests experiments (WP 2.2).

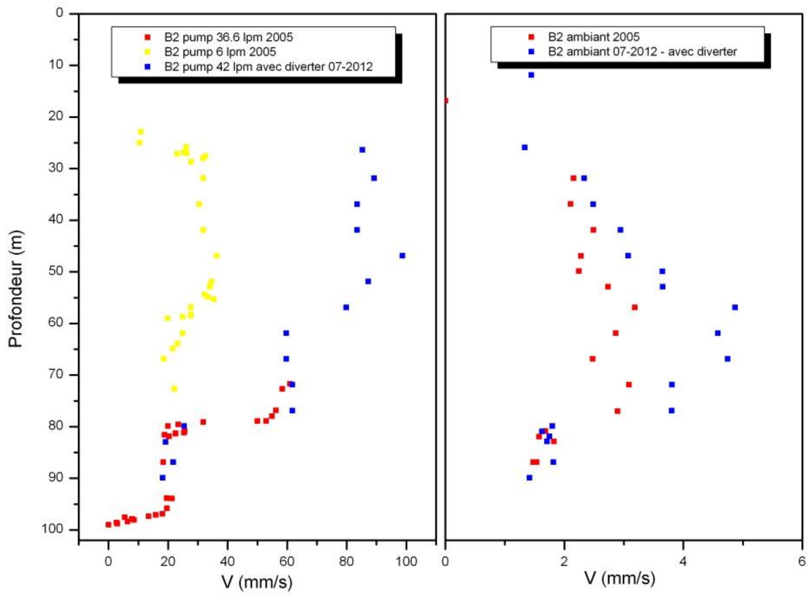


Figure 9 Flow (velocity, V) profiles, under ambient and pumping conditions, for different times at B2 observation well.

Measurement of distributed borehole flow with fiber optics

During the project, we have developed a new distributed borehole flowmeter from fiber optic cables with the Active-Distributed Temperature Sensing (A-DTS) method. The principle is that the temperature of an electrically heated cable, submerged in a flowing fluid, is a function of the fluid velocity (Fig. 10). We have demonstrated the deployment of the A-DTS flowmeter in a fractured rock aquifer. Over a velocity range of 300×10^{-3} m s^{-1}, a temperature range of 2.5^{o}C is observed (Fig. 11). The comparison with direct measurement of flow from a heat pulse flowmeter showed very good correlation. It is envisaged that this method will have applications where point measurements of flow are either excessively time consuming or fail to capture combined spatio-temporal dynamics.

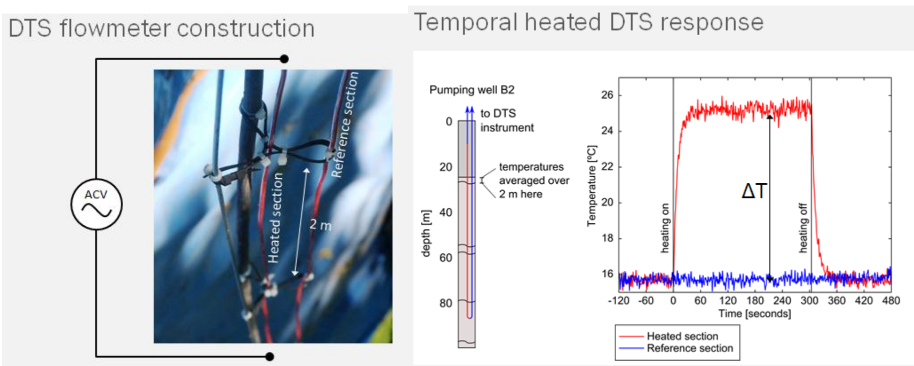


Figure 10 Photo of the cable setup, right : temperature response measured when heating the central cable.

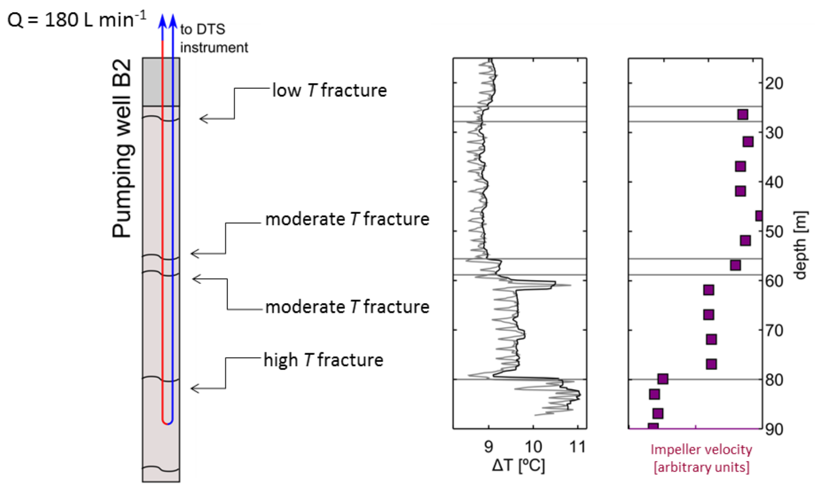


Figure 11 illustration of the fiber optic installation in the borehole, Right : comparison of the temperature response and the velocity profile.

Passive temperature tomography

The detection of preferential flow paths and the characterization of their hydraulic properties are major challenges in fractured rock hydrology. During the project, we have developed a new method based on the use temperature as a passive tracer to characterize fracture connectivity and hydraulic properties. In particular, we have proposed a new temperature tomography field method in which borehole temperature profiles are measured under different pumping conditions by changing successively the pumping and observation boreholes. To interpret these temperature-depth profiles, the method is based on a three step inversion-based framework. We consider first an inverse model that allows for automatic permeable fracture detection from borehole temperature profiles under pumping conditions. Then we apply a borehole-scale flow and temperature model to produce flowmeter profiles by inversion of temperature profiles. This second step uses inversion to characterize the relationship between temperature variations with depth and borehole flow velocities (Klepikova et al., 2011). The third inverse step, which exploits cross-borehole flowmeter tests, is aimed at inferring inter-borehole fracture connectivity and transmissivities. This multi-step inverse framework provides a means of including temperature profiles to image fracture hydraulic properties and connectivity. We tested the proposed approach with field data obtained from the Ploemeur fractured rock aquifer, where the full temperature tomography experiment was carried out between three 100 meter depth boreholes 10 meters apart. We identified several transmissive fractures and their connectivity which correspond to known fractures and corroborate well with independent information, including available borehole flowmeter tests and geophysical data (Fig. 12). Hence, although indirect, temperature tomography appears to be a promising approach for characterizing connectivity patterns and transmissivities of the main flow paths in fractured rock.

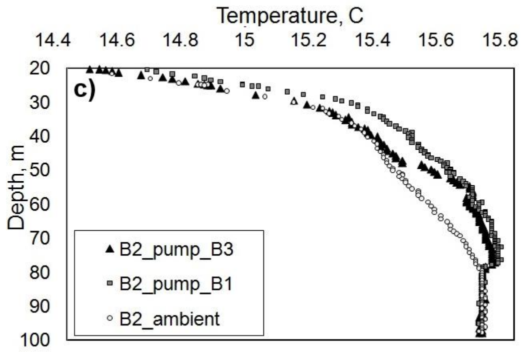


Figure 12a Measured temperature profiles in B2 borehole under different flow conditions

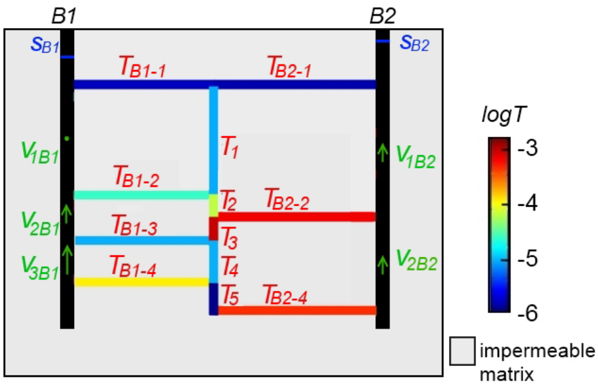


Figure 12b Inferred pattern of fracture hydraulic properties and connectivities between and around the B1-B2 borehole pair.

Geophysical monitoring and simulation

Synthetic models and field work preparation.

Initial work in this area by the Universite de Brest Occidental consisted of feasibility studies to estimate the best strategy for data acquisition to be optimized in terms of sampling and layout. Simple resistivity models representing the resistivity background of the field work sites were run for different configurations (Fig. 13). Meanwhile, equipment was upgraded (Terrameter 4000 at UBO loaned to IMAGIR, discussion to find the best solutions in term of EM equipment (frequency FEM or time domain TDEM system)).

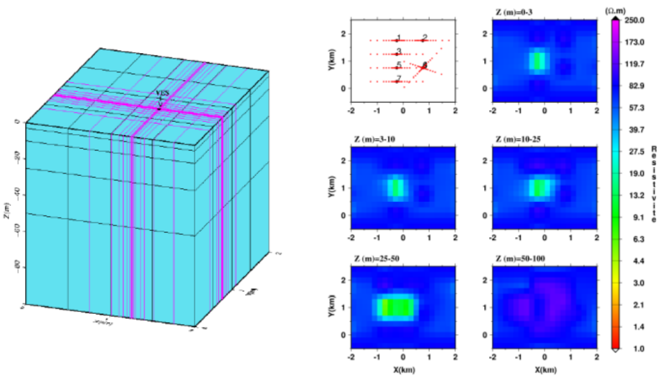


Figure 13 ***Left : 3-D resistivity model used to simulate underground structures. Right : an example of 3D inversion of synthetic data obtained along a series of heterogeneous profiles (top) simulating realistic data acquistion.***

A series of tests on 2-D and 3-D modeling of synthetic porous and fractured media using electric and electromagnetic techniques and taking into account the field characteristics (topography, presence of fences, maximum extension for the geophysical system) as well as the equipment existing on the market led us to conclude that only electrical resistivity tomography (ERT) could be used in the most efficient way. We nevertheless tried a time domain system during the first field work which confirmed that that technique could not provide the data needed in terms of lateral resolution.

Geophysical surveys were also carried out under this work package to better constrain the structure of Ploemeur and Saint Brice en Cogles sites. Several methods have been applied (seismic, electrical resistivity, electromagnetic mapping) to image hydrologically active structures. Both seismic and electrical resistivity methods have been applied. Figure 14 shows inverted resistivity for 2 different ERT arrays, Wenner – Schlumberger and Gradient. While the general structure is identical a few differences are interesting and lead to a different interpretation of the geological structure. The Granite – Micaschist contact zone (at ~250 m) shows stronger lateral gradients and deeper discontinuities. The Gradient array highlights a 50-m large conductive contact zone, instead of a horizontal resistive structure.

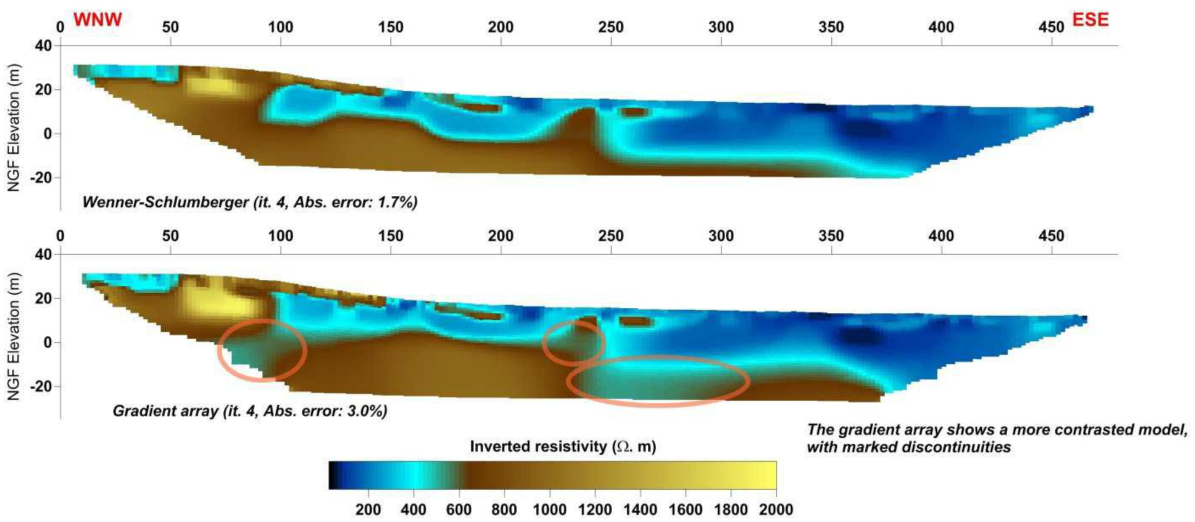


Figure 14 -Inverted resistivity for 2 different ERT arrays, Wenner – Schlumberger and Gradient at Ploemur.

Saint Brice en Cogles can be considered as equivalent of Ploemeur hydrogeological observatory but at a predevelopment stage. Geologically speaking, permeable structures are located at the contact zone between granite and mica-schist. Hydrogeologically speaking, the site is a natural discharge area for a deep fractured aquifer system. Applied geophysics surveys were carried out to better understand subsurface structures associated with the discharging deep fracture. EM34 mapping has been applied and highlighted the position and orientation of granitic intrusions. Consequently, these granitic intrusions were ruled out and have not created permeable fractures. They were created by younger tectonic events. Electrical profiles have also been repeated after the pumping experiment has been stopped to monitor the aquifer level rise. Figure 15 shows electrical resistivity measured on Dec.

12, 2011, just before the pumping was stopped and the second one 7 days later. Groundwater levels measured in the wells are also indicated. It is evident that resistivity has decreased in the central part of the profile, at the same time, water level has increased. Inversion of the resistivity profiles will provide estimation of soil storage.

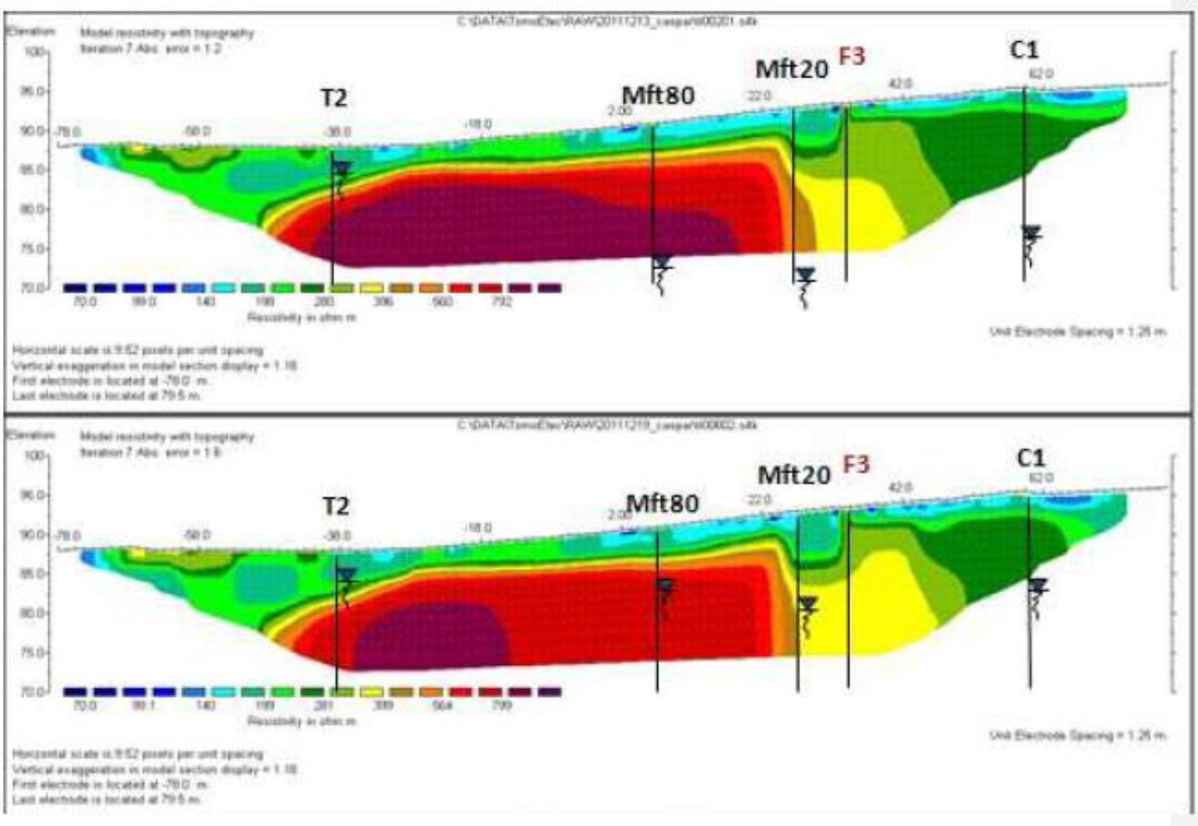


Figure 15 Electrical resistivity measured on Dec. 12, 2011, just before the pumped was stopped (top) and the second one 7 days later (bottom).

2.2 Work Package 1.2 Local-Scale and Regional-Scale recharge mechanisms with climate change

This work package aimed to integrate the long term monitoring of groundwater level with records of meteorological variables that could be linked to climate and detailed monitoring of the behaviour of the unsaturated zone of the aquifer. Alongside this a program of monitoring groundwater chemistry, directly linked to high resolution monitoring of water levels and unsaturated zone variables has been implemented in both catchments. Common analytical protocols were agreed, with variation in the method to optimise sampling and analysis for the particular geological settings and issues of each catchment.

Monitoring programs

At Patcham the integrated groundwater monitoring data acquired from the previous FLOOD1 project and CLIMAWAT now total eight years of data (Fig. 16). Under the FLOOD1 project the NHB1 borehole was instrumented with jacking tensiometers to 80m below the ground surface, and an adjacent site was equipped with equitensiometers to 5m below ground level. For CLIMAWAT existing monitoring of air temperature and rainfall (using storage and tipping bucket rain gauges) was enhanced by the installation of a new weather station capable of measuring air, temperature, relative humidity, solar radiation, wind speed, and wind direction. All of these were necessary to allow the accurate calculation of evapotranspiration of water from the soil layer and upper rock column.

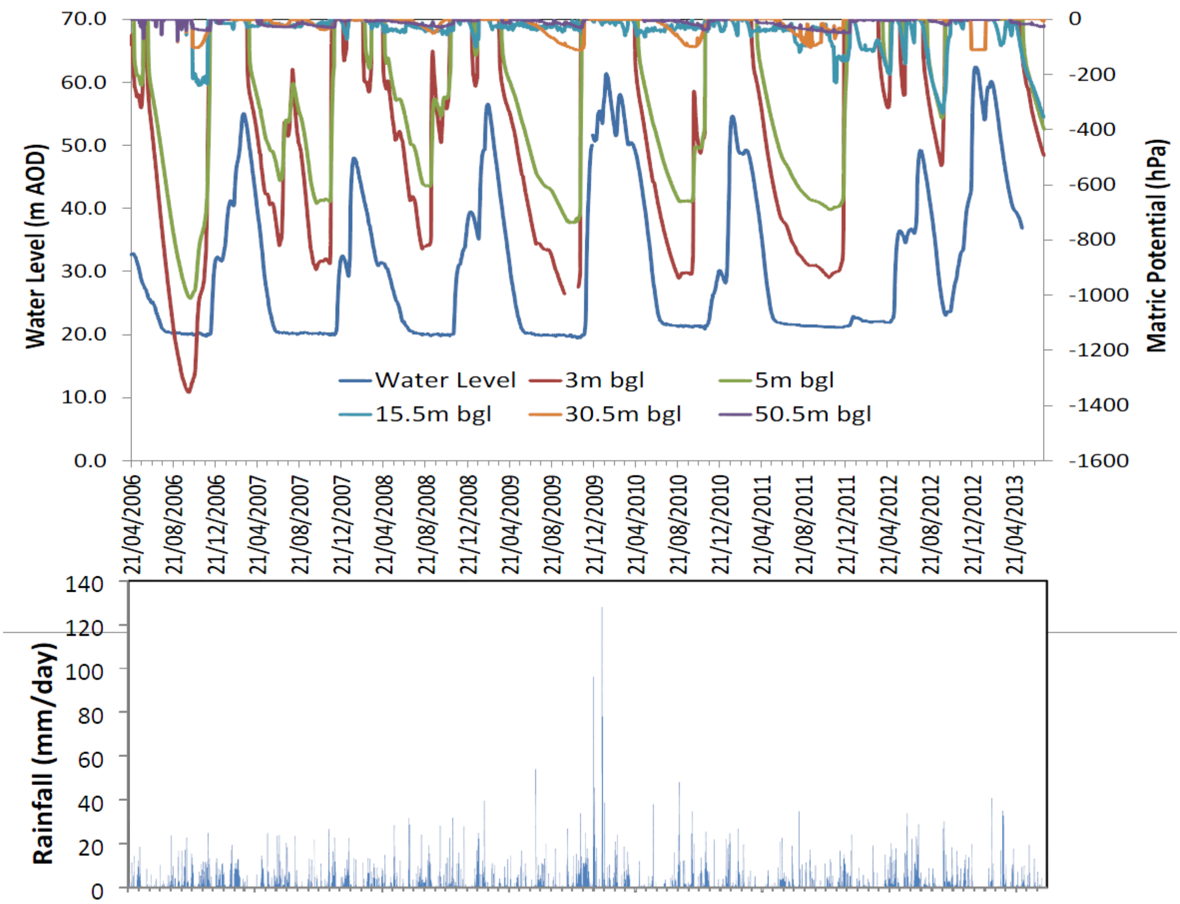


Figure 16 – Full unsaturated zone monitoring period for the Patcham catchment at North Heath Barn. Plots show the results of rainfall measurement, monitoring of pore fluid pressure (Matric potential) in the unsaturated zone using equitensiometers and the deep unsaturated zone using jacking tensiometers, alongside the water level record.

Interpretation of the data from the Patcham catchment was continuous throughout the project period, and supported one Master of Science dissertation project at the University of Brighton (Al Jaf; Evidence of deliverables CD). The data from the North Heath Barn monitoring site can now clearly be interpreted as indicating continuous unsaturated zone drainage through the Chalk matrix throughout the year, but that declining goundwater levels are a result of the balance between the amount of drainage and the amount of discharge during low rainfall periods. However, superimposed on this are effects whereby rapid fracture flow can be initiated whenever the time integrated rainfall raises matric potential above approximately -50hPa throughout the chalk matrix, or when the intensity of rainfall exceeds 10mm/day (Figs. 17, 18).

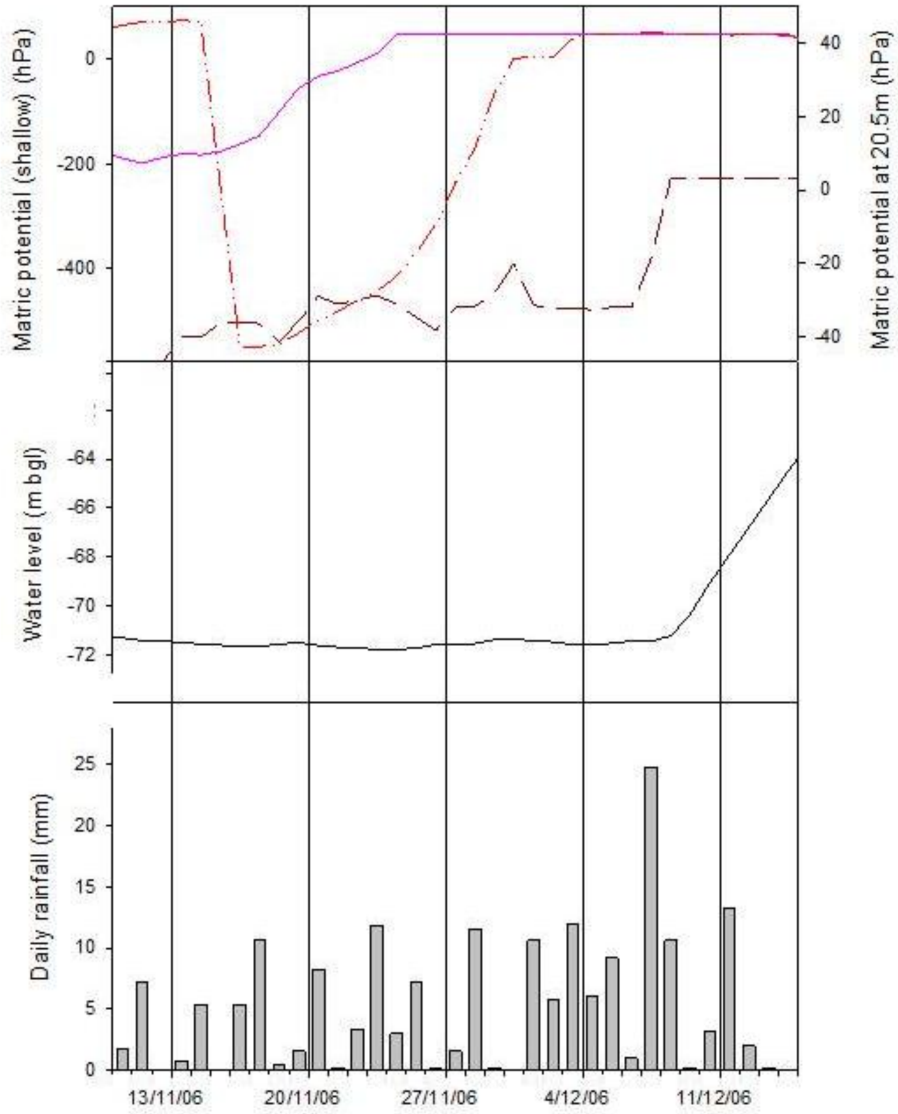


Figure 17 Behaviour of unsaturated zone at North Heath Barn in response to prolonged rainfall. Rainfall rapidly decreases deficit in shallow unsaturated zone. By end November all deep tensiometers at -50hPa or higher. From 30 November to 8 December, there was 82.8mm of rain, including 24.8 mm on 7 December. Sudden rapid rise in matric potential mirrored by rapid rise in water level. Preceding rainfall, followed by intense rainfall event leads to the initiation of fracture flow.

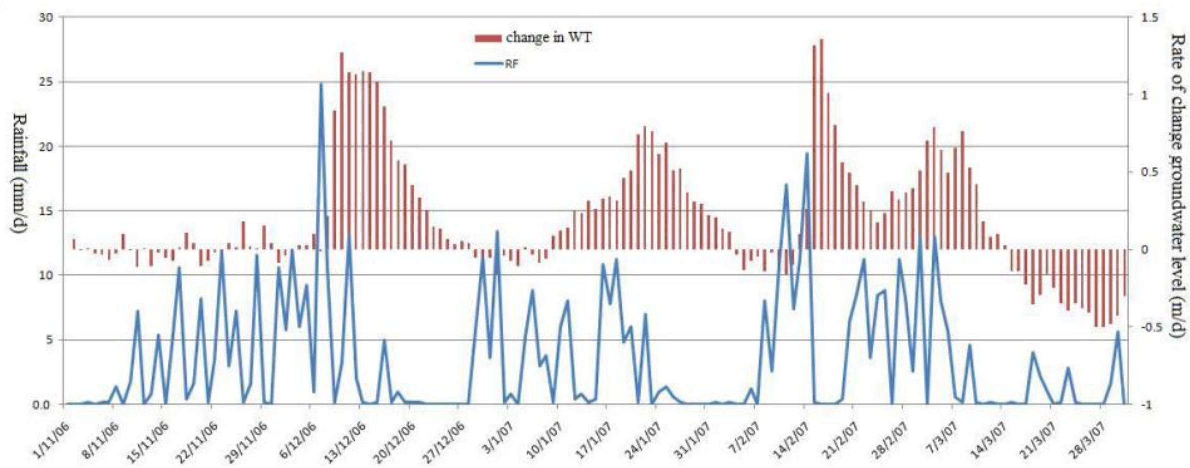


Figure 18 Behaviour of the unsaturated zone at North Heath Barn in response to high intensity rainfall events. The rate of change of groundwater level can be seen to increase rapidly immediately following rainfall exceeding 10mm/day.

The monitoring period now also includes a number of exceptional meteorological periods allowing closer examination of the impact of varying climatic conditions on aquifer behaviour. From November 2009 to August 2010 an extended period of intense winter rainfall occurred (Fig. 19).

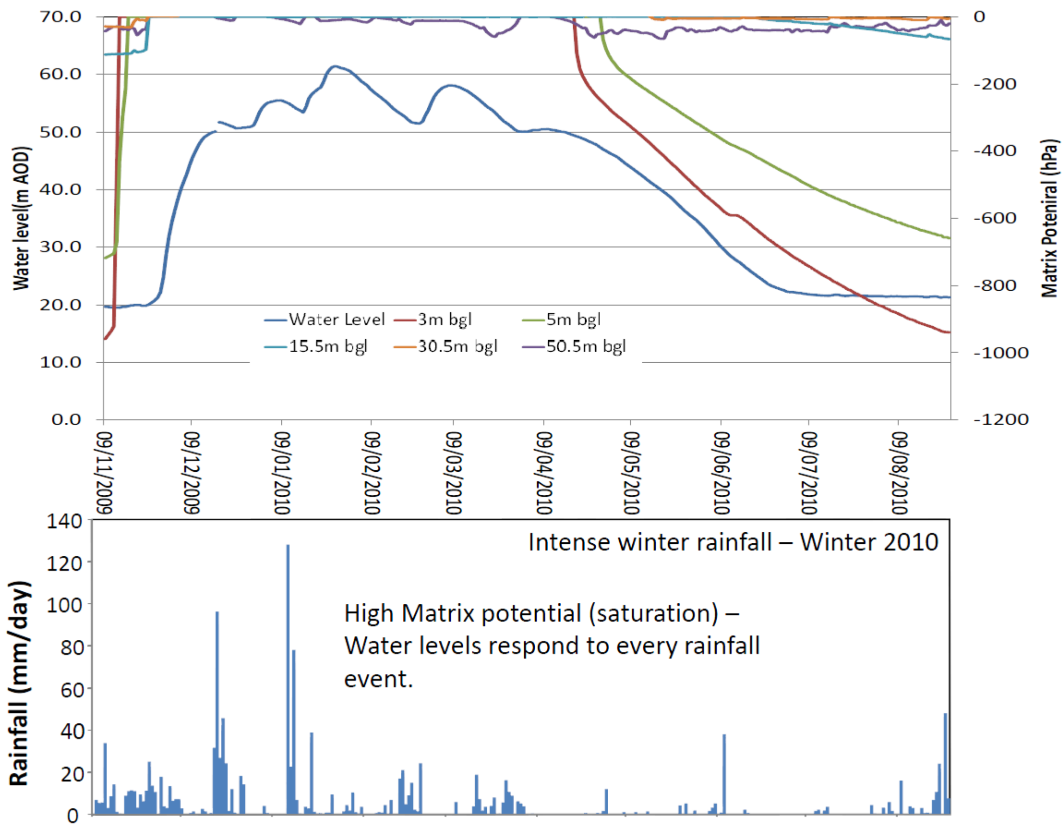


Figure 19 – Groundwater level and unsaturated zone matrix potential at North Heath Barn for the period November 2009 to August 2010. This was a period of high rainfall, and consistently high groundwater level. The data clearly show the tensions in the aquifer matrix remain close to saturation through this period, and the groundwater level responds to every rainfall event.

Examination of the monitoring data clearly indicates that the matrix potential in the unsaturated zone rarely dropped below -100hPa throughout this period, and the rapid response of groundwater levels to every rainfall event can be clearly observed, indicating the prevalence of fracture flow as a recharge mechanism. Conversely from May 2011 to December 2012 there was a drought period in south east England, extending through the winter season – normally thought of as the recharge period. Matric potential in the shallow unsaturated zone (<5m below ground level) became very low as the soil and rock system dried out. Very low matric potentials did not, however, extend into the deeper unsaturated zone (Fig. 20). This resulted in a period of virtually no winter rise in ground water levels. The drought period was ended by an exceptionally cool, wet summer, resulting in rising groundwater levels as early as May. These exceptional events allow interpretations to be made as to the impact of variable climatic patterns on groundwater quality (see below).

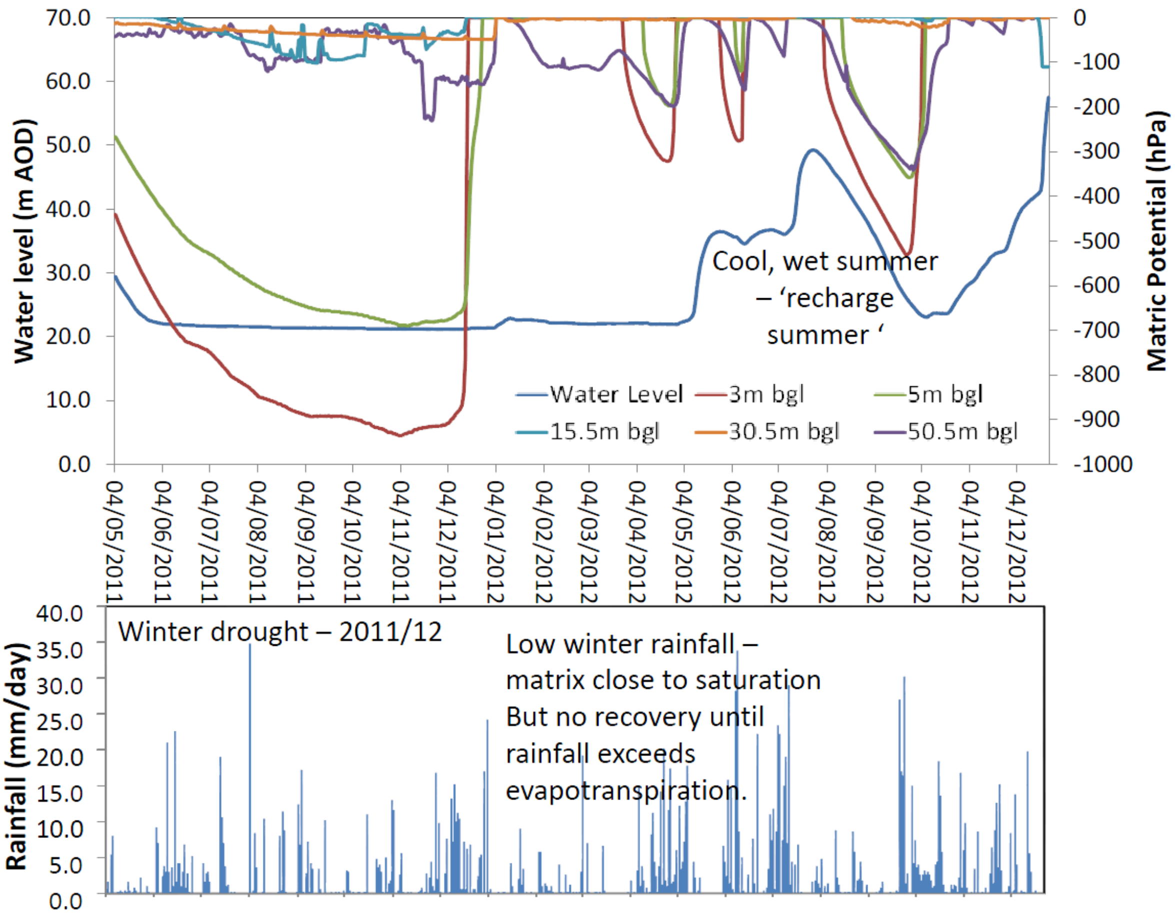


Figure 20 – Groundwater level and unsaturated zone matric potential at North Heath Barn for the period May 2011 to December 2012. This was a drought period, ad lead to the development of exceptional matric tensions in the shallow unsaturated zone. A low rainfall winter meant that although this water deficit was recovered, only very minro recharge to the water table occurred. An exceptionally wet summer, however, resulted in the only recorded instance for the aquifer of a 'recharge summer'.

Critically, throughout the drought periods now recorded by monitoring at North Heath Barn the development of very low matric potentials, indicating very high water deficits in the unsaturated zone, was limited to depths <10m below ground level. Although drying of the deeper unsaturated zone was observed it was relatively insignificant in comparison. This factor was critical in supporting conceptual models to support numerical modelling of aquifer behaviour as it allowed a depth to be defined below which the water deficit need not be taken into account. Importantly this indictates that the shallow unsaturated zone is critical in controlling aquifer behaviour (Fig. 21).

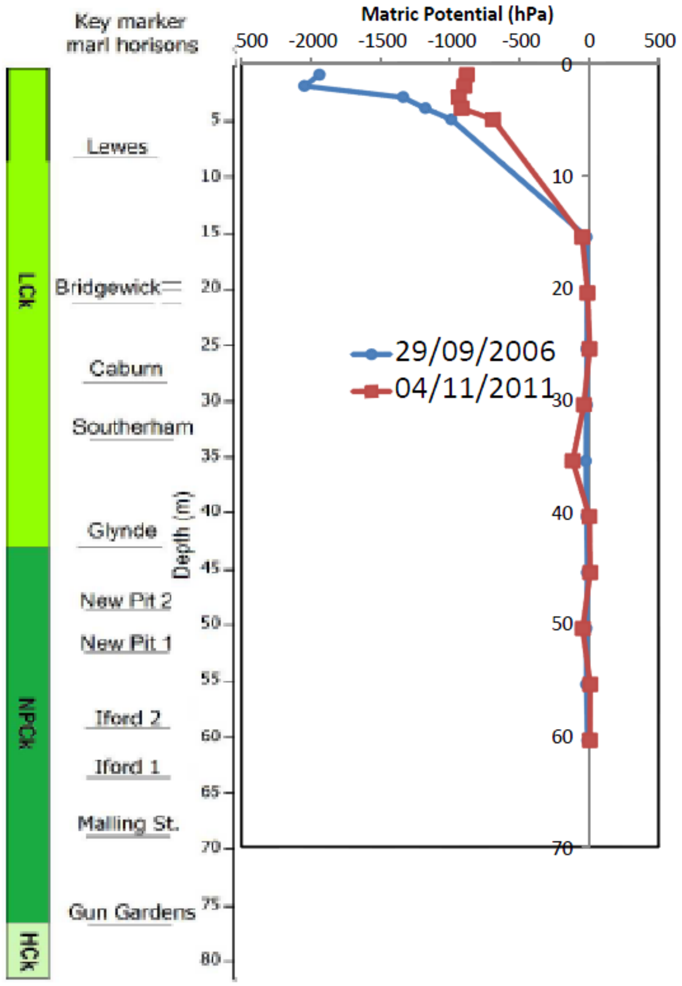


Figure 21 – Development of Chalk aquifer matric potential with depth during 2 drought periods. A significant water deficit (pore water content below saturation) is not developed below ~10m.

Determination of recharge mechanism in fractured granite

Quantification of the recharge in fractured aquifers is particularly challenging because of the multiscale heterogeneity and the range of temporal scales involved. The hydraulic response to recharge of a fractured aquifer, was investigated using a frequency domain approach. Transfer functions were calculated in a range of temporal scales from 1 day up to a few years, for the fractured crystalline-rock aquifer located in Ploemeur (S Brittany,France), using recharge and groundwater level fluctuations as input and output respectively (Fig. 22). The spatial variability of the response to recharge (characteristic response time, amplitude, temporal scaling) was analyzed for 10 wells sampling the different compartments of the aquifer. Some of the transfer functions follow the linear reservoir model behavior. On the contrary, others display a temporal scaling at high frequency that cannot be represented by classic models. Large-scale hydraulic parameters, estimated from the low-frequency response, were compared with those estimated from hydraulic tests at different scales. The variability of transmissivity and storage coefficient tends to decrease with scale, and the average estimates converge toward the highest values at large scale. The small-scale variability of diffusivities, which implies the existence of a range of characteristic temporal scales associated with different pathways, is suggested to be at the origin of the unconventional temporal scaling of the hydraulic response to recharge at high frequency.

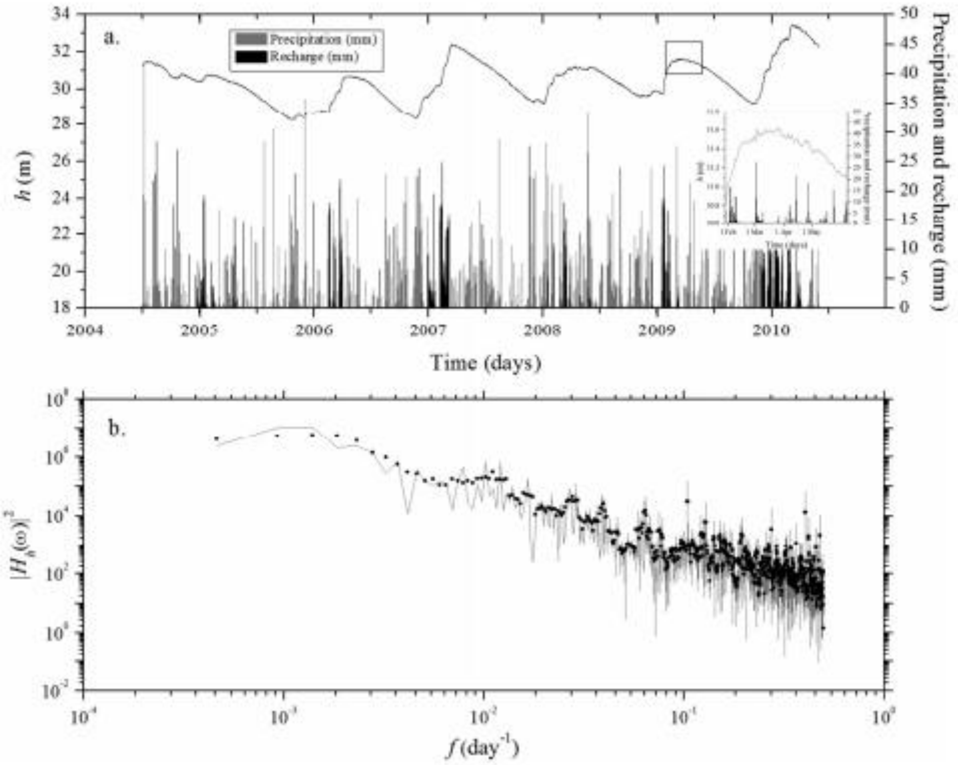


Figure 22 (a) Recharge and groundwater level fluctuations (*h*) at monitoring well F07 as input and output functions, respectively. (b) Empiric transfer function (gray line) and regularized transfer function (black dots) for monitoring well F07 as a function of frequency *f*.

Unsaturated zone monitoring at Ploemeur.

A complete monitoring of the unsaturated zone to identify correlation between recharge and flow, including soil and weathered rock (granite), was carried out at Ploemeur experimental site (Fig. 23). The monitoring includes the installation at different depths (0.15, 0.25, 0.5, 0.9, 1.4, 2 m depth) of different automatic devices: TDRs (time domain reflectrometry) to measure soil water content; tensiometers to measure pressure head; thermometers; and suction cups for water sampling. Commonly, for crystalline-rocks aquifers two recharge components are considered: regional recharge through a wide network of fractures and direct infiltration through the upper soil and weathered rock zone. The main objective of the current experiment is to quantify the second component, in order to reduce the uncertainty about aquifer recharge in this type of aquifer and a better understanding of the percolation mechanisms. The installation of thermometers will allow use of temperature as passive tracer, since the area is protected as a drinking water pumping site. The suction cups installed at different depth will allow study of the hydrogeochemical processes that take place in unsaturated conditions and for this kind of material as consequence of the water infiltration.

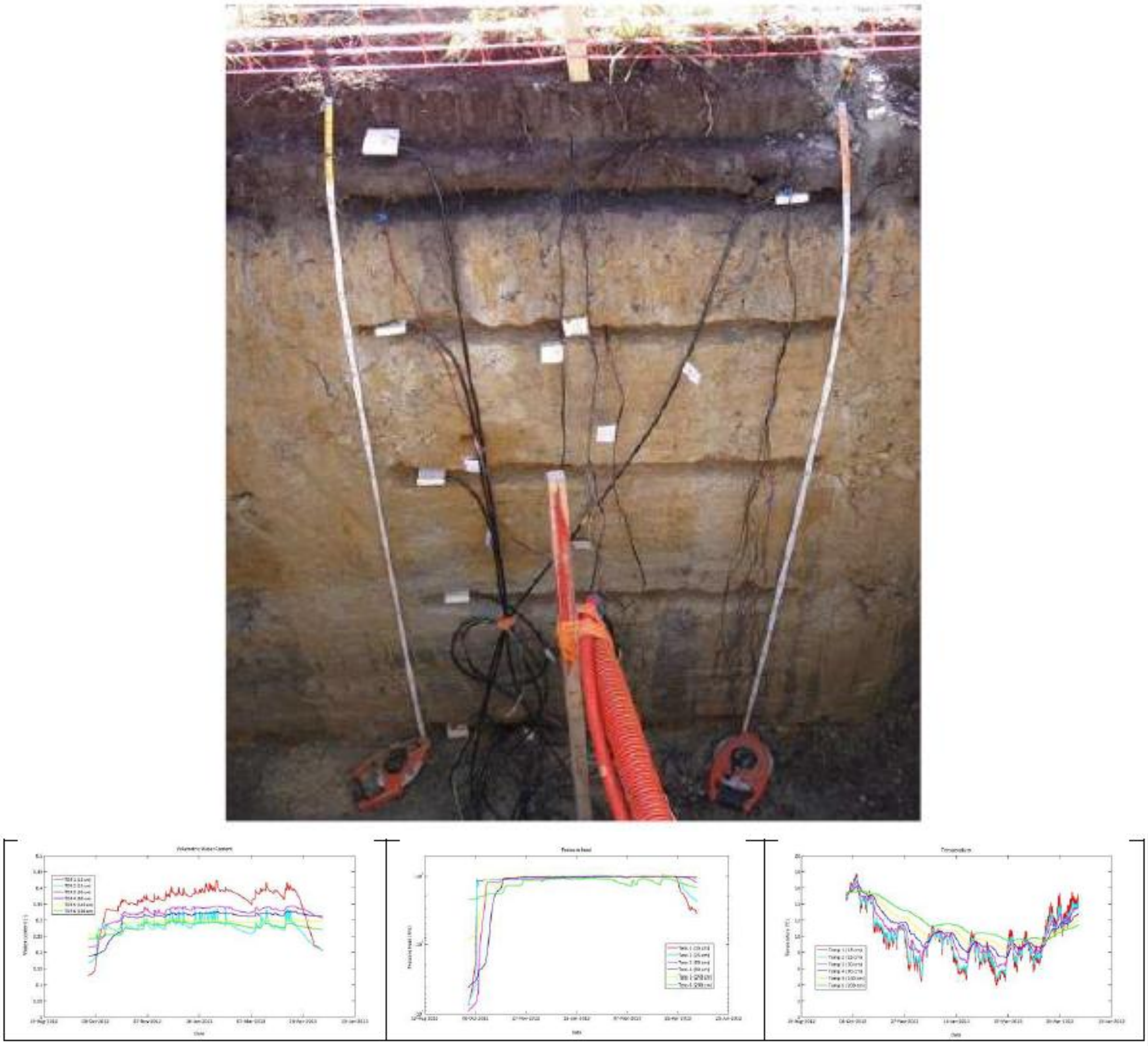


Figure 23 – Top – photograph of the unsaturated zone monitoring installation at Ploemeur. Base – results from the first season of monitoring.

Interaction of recharge with groundwater quality

In the Patcham catchment a monthly sampling program was used to monitor groundwater chemistry and microbiological organisms used to indicate microbial groundwater quality. After initial tests using a low-flow sampling pump approach it was elected to use hand bailers with 3 bailer volumes from a specified depth in a bore hole being disposed of prior to a sample being taken. This was because the rapid nature of water flow through karstic features in the Chalk meant that environmental parameters (pH, T, Eh, DO, Conductivity) monitored during continuous pumping reached constant levels within 5 minutes in all boreholes, corresponding to approximately 150ml of water pumped from the well. The results of groundwater chemical monitoring were then correlated in detail with the records of water level and aquifer matric potential. Analyses were carried out using field probes for pH, Eh, dissolved oxygen and conductivity, for cations using laboratory-based ICP-OES and initially spectrophotometry for anions (including nutrient compounds). It was noted early on that the later equipment was not giving sufficient accuracy and precision for the purposes of this project, including the experiments taking place under WP2.2, and so a budget change was made to allow the purchase of a Dionex Ion Chromatograph, which was subsequently used in analysis all groundwater samples and experimental solutions.

The results of correlations between groundwater chemistry, precipitation and groundwater level (and hence recharge mechanism) are shown in Figure 24. Contrasting behaviour was seen between sites in different geographic (minimal disturbance, effluent dispersal site, urban) and geological (thickness of unsaturated zone, aquifer stratigraphy) settings. At North Heath Barn and other relatively undisturbed rural sites (Fig. 24) both the total dissolved load (as indicated by water electrical conductivity) and specifically the concentration of nitrate (a key diffuse source, nutrient contaminant) varied directly with water level, with increases occurring during high water periods. At both Pyecoomb East (effluent discharge) and Preston Park (Urban), nitrate concentrations peaked out-of-phase with the water level.

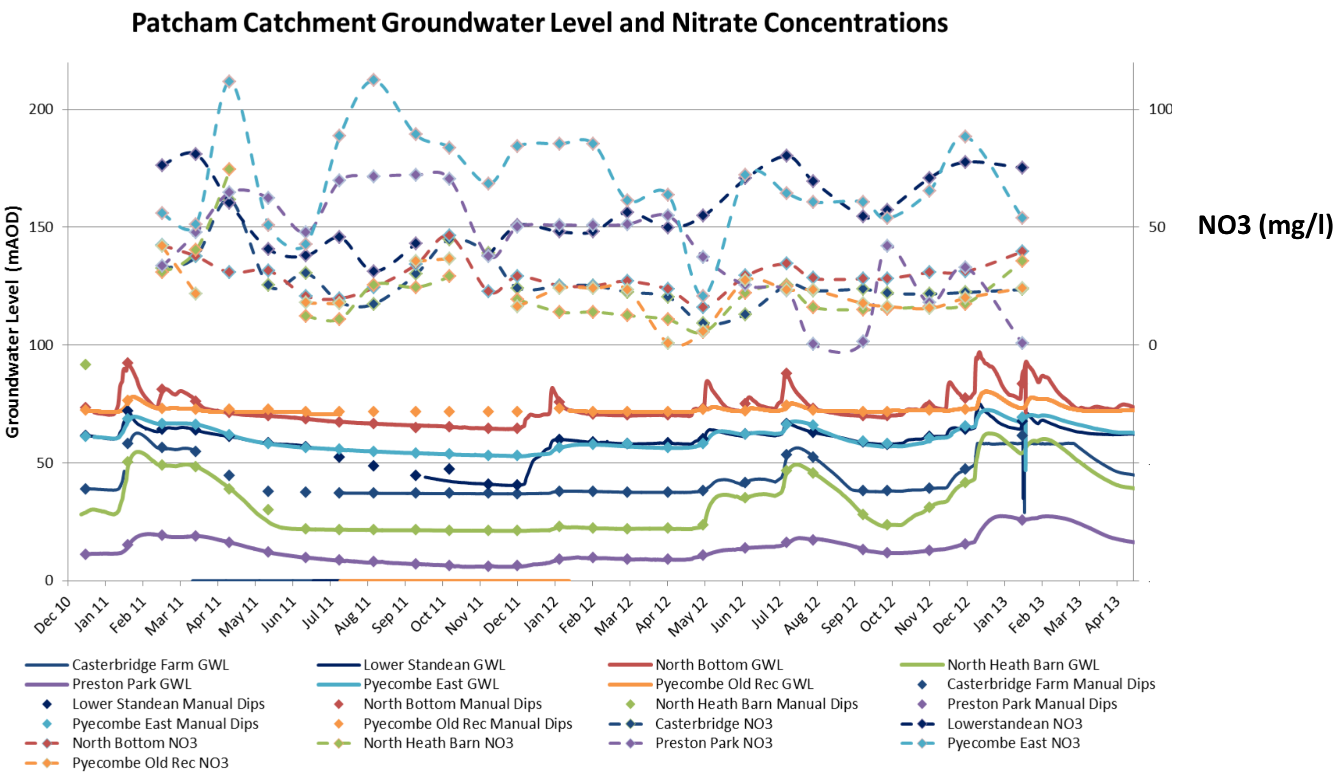


Figure 24 - Groundwater Levels and Nitrate Concentrations - Patcham Catchment

Nitrate is generally considered to be a non-sorbing solute and as such will migrate downwards through the unsaturated zone at the same speed as the infiltrating groundwater. More rapid fracture flow can occur when there is sufficient recharge for it to initiate. The mechanisms of nitrate movement, therefore, rely on the dual porosity aquifer model, that is in dry periods water moves slowly downwards through the Chalk matrix (normal piston flow) and during periods of heavy rainfall, fracture flow initiates and more rapid bypass flow occurs. The very small pore size of the Chalk matrix means that it is always close to saturation due to capillary tension and water held in the Chalk matrix is not very mobile due to these forces. The average downward migration rate for nitrate present in groundwater migrating through the Chalk matrix has been estimated as 0.5 to 1m/year (Stuart et al., 2009). This does not agree well with the observation of nitrate concentration increases during recharge periods. This observation has been recorded previously, and Stuart et al. (2009) identified a range of potential recharge mechanisms that may be responsible for nitrate transport:

A. Normal winter piston flow through unsaturated zone matrix;
B. Winter bypass (fracture) flow bringing nitrate directly from base of soil to saturated zone;
C. Water table rise due to water entering elsewhere in the aquifer system mixing with porewater containing nitrate;
D. Change in flow path giving access to a greater percentage of shallow high nitrate water (cutting off high transmissivity rapid flow paths).

The one month resolution of most chemical monitoring data is not truely high enough temporal resolution to allow detailed distinction between these mechanisms, and hence interpretations that will allow quantitative prediction of the impacts of changing climate on groundwater quality. For that reason the decision was made for the CLIMAWAT project to install a set of in situ logging devices that could monitor groundwater temperature, conductivity and water depth at 15 minute intervals. These loggers were installed a 3 key sites (North Heath Barn – relatively undisturbed, ~80m thick summer unsaturated zone, Upper Chalk; Pyecombe East – effluent dispersal site, ~50m thick summer unsaturated zone, Lower Chalk; Preston Park – urban site; ~20m thick summer unsaturated zone, Upper Chalk). The results of these loggers are shown in Figure 25. The behaviour of saturated zone groundwater conductivity is different in each case. At North Heath Barn conductivity is relatively constant throughout the low water period, but rises once groundwater levels start to rise in response to falls in evapotranspiration and the recovery of the water deficit in the unsaturated zone. After this point water conductivity varies a few days out of phase with the water level, suggesting that nitrate is being transported to the saturated zone both by slow piston flow in the chalk matrix, and rapidly during periods of fracture flow in response to rainfall. At Preston Park virtually no rapid response to recharge is observed, but conductivity is almost perfectly out of phase with the groundwater level.

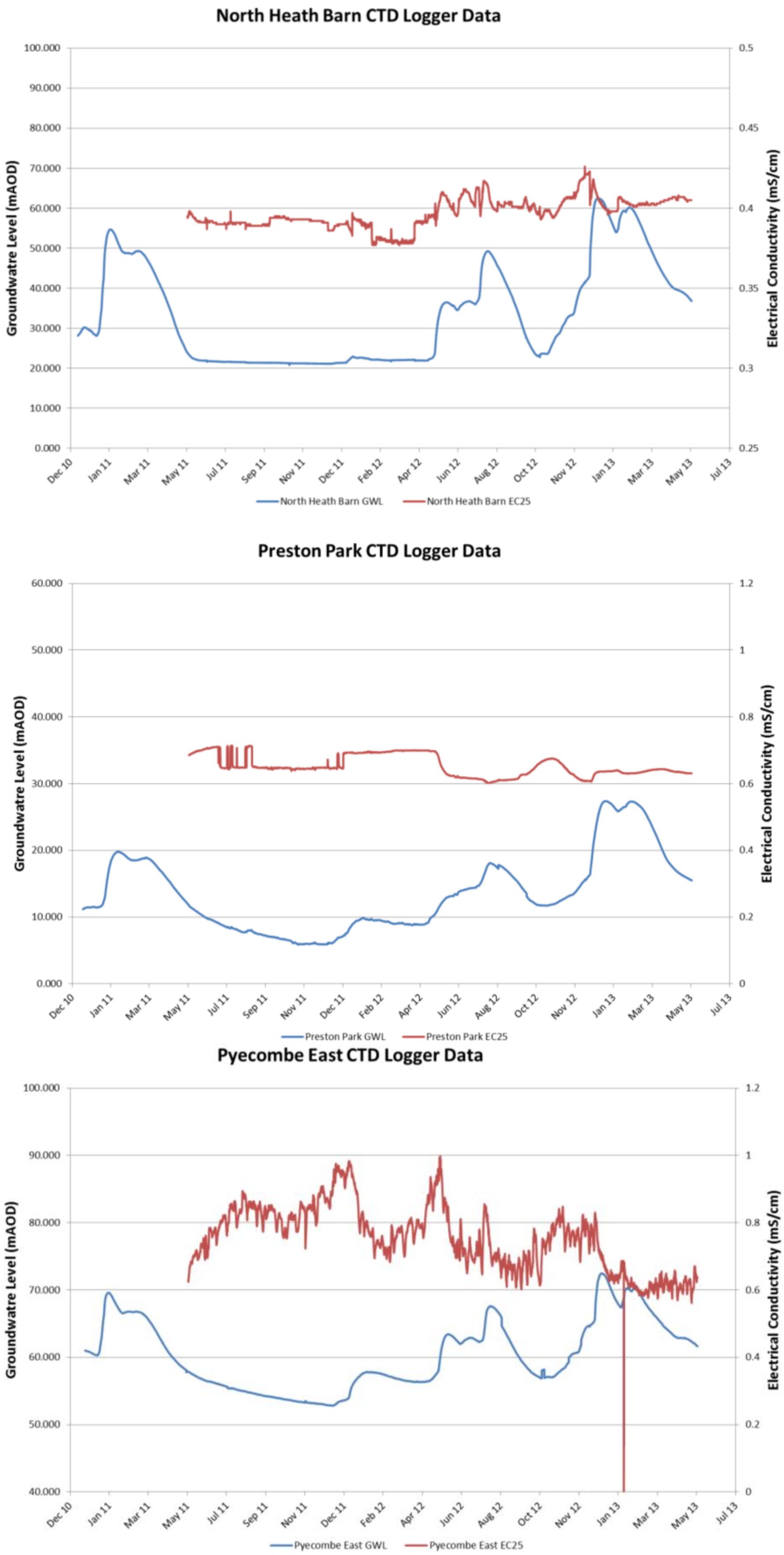


Figure 25 – Comparison of high resolution monitoring of groundwater conductivity with water level for three key sites in the Patcham catchment.

This is consistent with high nitrate input from urban sources year round, but dilution of this by accretion of flow from higher in the aquifer system in the lower reaches during winter high flow periods. At Pyecombe East conductivity at a low frequency is slightly out of phase with groundwater level. Conductivity increases at the beginning of the groundwater level recession period, consistent with a decreasing level of dilution of nitrate levels from effluent dispersal, but then decrease as the recession continues and slow piston flow begins to dominate the recharge mechanism. As evapotranspiration decreases and rainfall increases the nitrate levels begin to rise again as more rapid flow takes places, reaching a maximum during the period of the highest rate of groundwater level recovery. This suggests that nitrate transport is becoming enhanced by rapid fracture flow during the main recharge season. Super-imposed on this are high frequency cycles in conductivity whereby the conductivity rises approximately 24 hours after peak rainfall. Again this is consistent with rainfall initiating rapid fracture flow. The capacity for each rainfall event to do this occurs because the practice of effluent dispersal to the aquifer at this point maintains the whole aquifer column above the water table very close saturation so that fracture flow is much more easily initiated. Overall this suggests that slow piston flow will act as the dominant contaminant transport mechanism through much of the year, except for when high rainfall initiates fracture flow. However, in areas of artificial recharge the maintenance of high matric potential in the unsaturated zone leads to rapid bypass flow in response to every rainfall event. The impact of this will depend on the relative importance of the activation of rapid flow paths and the dilution effect of increased rainfall into contaminated environments.

Measurement of groundwater ages

The determination of the age of groundwater was important to this project in order to:

(a) Identify groundwater bodies which had received recharge from rainfall by different mechanisms, resulting in different flow periods.
(b) Identify the residence time of groundwater in the aquifer and hence the time available for natural remediation or attenuation of contaminant transport.

The CFC-SF6 dating technique is ideal for this purpose, where groundwater is being actively recharged and hence should be interacting with the aquifer on the scale of years to decades rather than longer time periods.

At Ploemeur the available database on the site allows to map mean residence time on the site (Fig. 26). Some old ages (more than 30 yr) are observed close to the main pumping well (PE, F38 and F11). These old ages are correlated with a special chemistry (WP2.1) and seem to indicate the contribution of an old, deep and saline compartment. A light difference is observed between the east and the west side: groundwater in the western part of the site seems a little bit younger than the eastern part. F35 is relatively young according to its depth. This could be explained by short circulation paths. This methodology was also applied at St Brice site during a 3-month pumping test. It was useful to identify several reservoirs which contribute to the pumped fluxes: old water observed in ambient condition, recent water coming from upper part of the aquifer and a SF6-rich reservoir. This demonstrates the influence of pumping on the dynamic of the aquifer and it's associated risks which could be completely disturbed by anthropogenic activities. CFC data have also been used in models to calibrate aquifer parameter and geometry by constraining porosity and dipping of the fault zone.

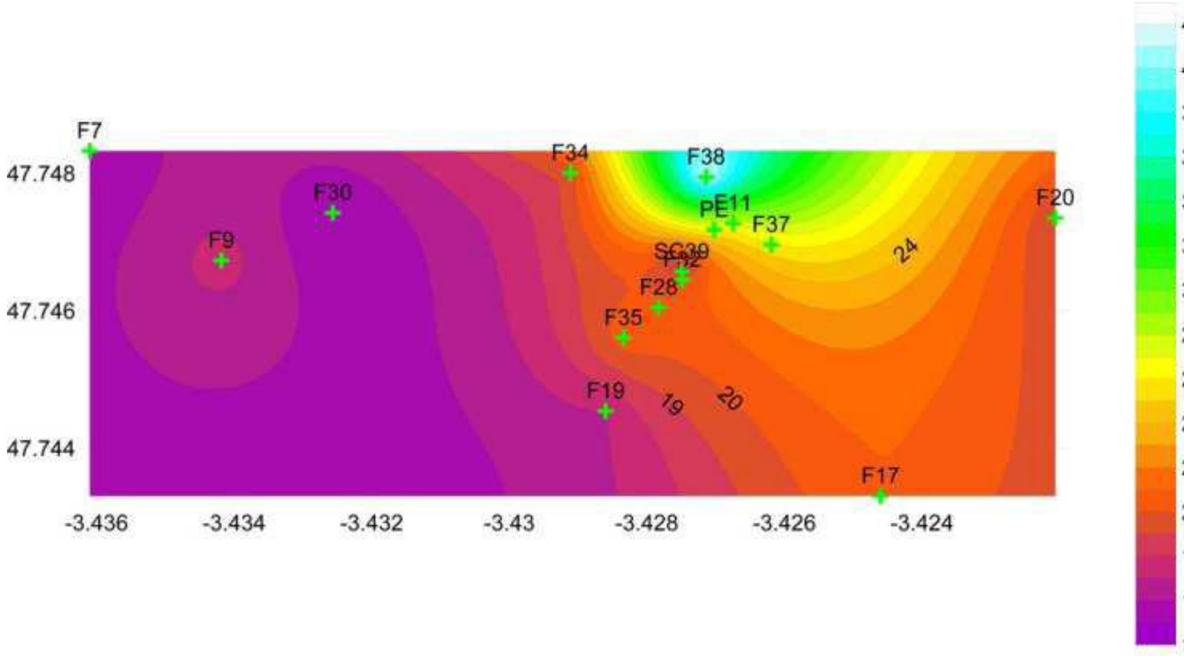


Figure 26 - Map of apparent groundwater ages at the Ploemeur site

The same technique was applied in the Patcham catchment. Three periods of sampling were carried out for groundwater dating studies. The first involved training of University of Brighton staff in sampling techniques by University of Rennes staff. Subsequently University of Brighton and UEA staff carried out the sampling using sample vessels supplied by the University of Rennes. All CFC and SF6 analyses were carried out by the University of Rennes. Samples were taken using a submersible Grundfos MP1 pump operating at high flow rates. The extracted water was continuously monitored for pH, Eh, dissolved oxygen, temperature and conductivity and a sample taken once these had reached constant values. This was taken as an indication that water had been purged from the bore hole and the samples were of fresh aquifer water that had not had time to interact with air. Samples were simultaneously taken for chemical, isotopic and noble gas analysis at the University of Brighton and UEA. The three sampling periods were chosen to target the groundwater recession, the low water period and peak water levels in order to identify changes in the dominant age component of the groundwater as the recharge mechanism to the aquifer changed (Fig. 27).

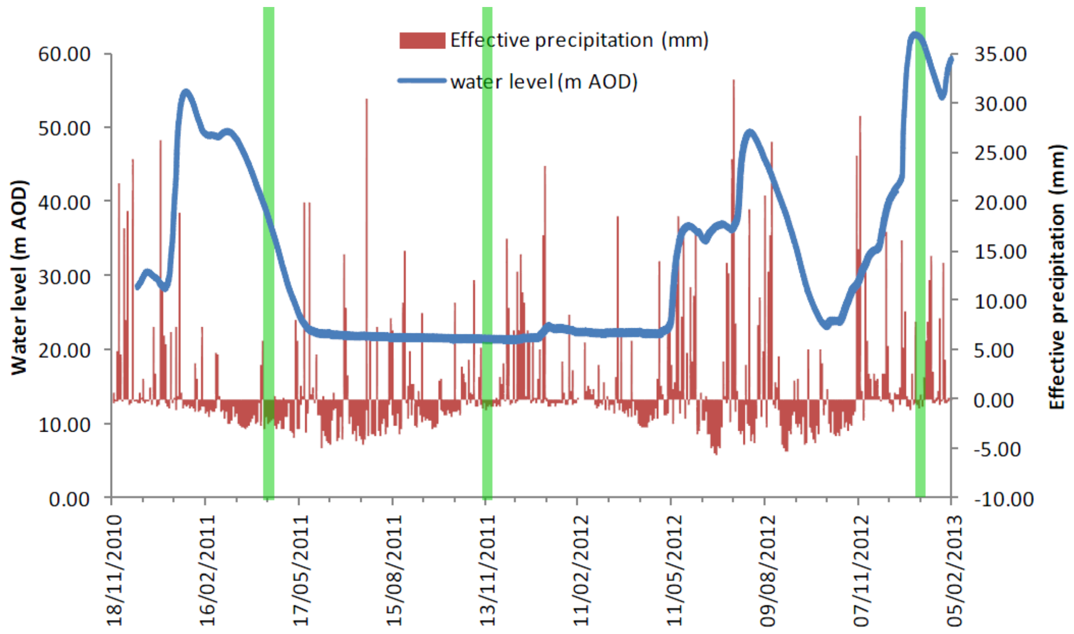


Figure 27 – Periods of groundwater sampling for CFC-SF6 analysis compared to the water level and effective precipitation (precipitation-evapotranspiration) at North Heath Barn.

The results of CFC-SF6 analyses are shown in Figure 28, where they are compared with mixing models for groundwaters of different ages. In a number of cases, notably from Pyecombe East and Preston Park, the concentrations of CFCs and SF6 exceed those predicted for modern groundwater that had acquired its dissolved load of trace gases purely by interaction with the atmosphere. This could be related to contamination from trace compounds in the dispersed effluent or urban drainage, or to mixing with additional gases within karstic flow paths or the thick chalk unsaturated zone. Other sites, however, showed consistent trends. Samples taken during the recession and low water period indicate mixing between ~30 year old waters with a small modern component. Those taken during the recovery/high water period show an increasing modern component, upto those that are dominated by modern waters. This consistent with water reaching the water table via slow piston flow during the recession period, but with an increasing component of rapid by pass flow as the recharge period continues.

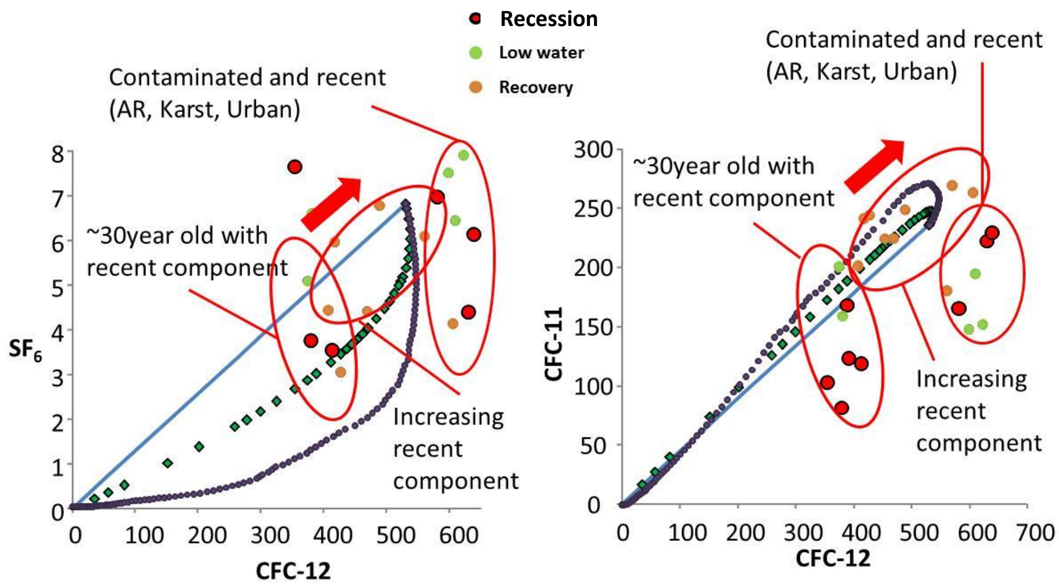


Figure 28 – Results of CFC-SF6 groundwater dating in the Parcham catchment.

Results of isotopic analyses.

Stable isotope and noble gas analyses were carried out at the Univeristy of East Anglia to develop a better understanding of recharge mechanisms in Patcham catchment Chalk using stable isotope (δ^2H and δ^{18}O) and dissolved noble gas (He, Ne, Ar, Kr and Xe) tracer techniques. These tracers were used to quantify groundwater fluxes in response to short- and long-term climatic events, to assess changes in groundwater recharge mechanisms, and to estimate groundwater residence times in the saturated and unsaturated zones. Groundwater sampling for δ^{18}O and δ^2H was undertaken on a monthly basis within the Patcham catchment for the period April 2011 to October 2012. The results shown in Figure 29 show that the isotopic composition of groundwater throughout the sampling period was very constant and in agreement with typical groundwater compositions for South East England as reported by Darling *et al*. (2003). The five data points that plot to the right of the main cluster are primarily from the Pyecombe Old Rec site which is the only open well that was used for sampling. The stable isotope data suggest that detecting rapid recharge via the fracture network using isotope tracers is not a trivial task. There are a number of explanations that could explain why bypass flow and rapid recharge were not evident in the stable isotope data. The most likely reason is that the seasonal isotopic signature of precipitation is lost very quickly in the unsaturated zone and also due to mixing with existing groundwater below the water table. The spatial and temporal resolution of the sampling campaign might have also been insufficient to capture pulse-like recharge events that are characteristic of bypass flow and rapid recharge to the Chalk. Hence in this study stable isotope tracers proved to be of limited use in understanding recharge mechanisms to the Chalk.

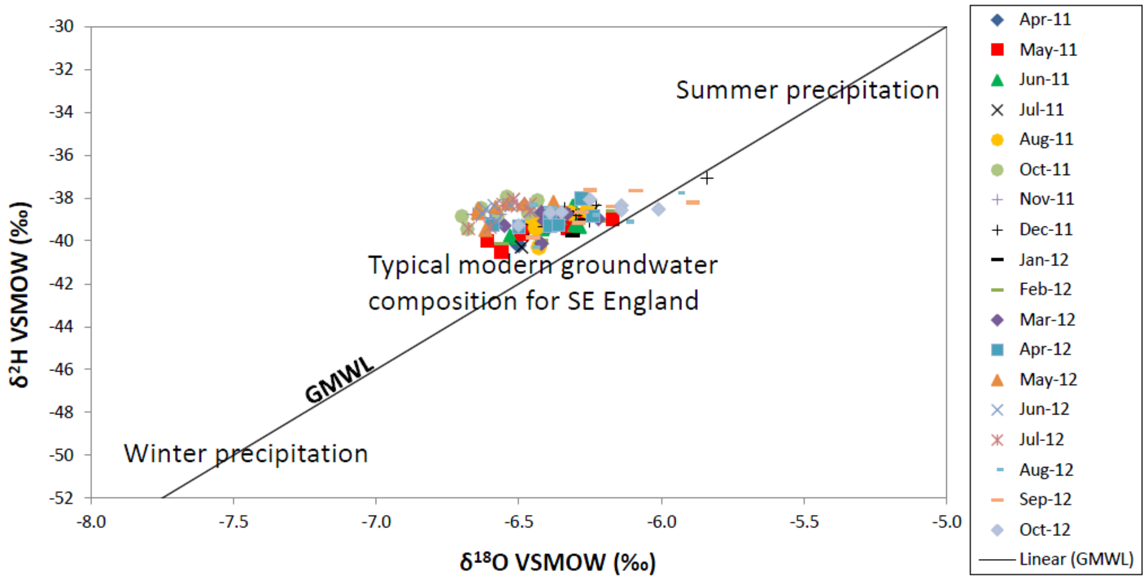


Figure 2 Isotopic composition of Patcham catchment groundwater (April 2011 – October 2012).

Two Patcham catchment field sampling campaigns (May and November 2011) were undertaken to collect groundwater samples for noble gas analysis. Groundwater was collected from observation boreholes using a Grundfos MP1 submersible pump and 'pinched-off' copper tubes following the standard sampling protocol for noble gases as described by the USGS. Groundwater samples were analysed at the British Geological Survey (BGS) noble gas laboratory in Wallingford, UK. The noble gas data are presented graphically (e.g. Fig. 30) as well as modelled using NOBLE90 (Fig. 31).

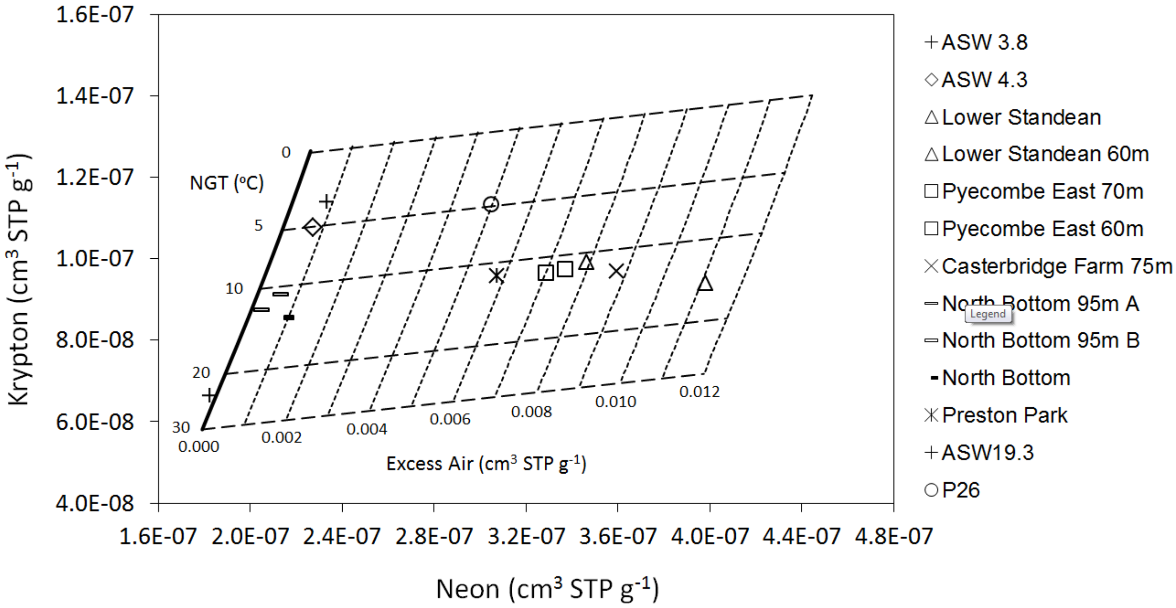


Figure 30 Cross plot of krypton against neon to determine noble gas recharge temperatures and excess air concentrations for Patcham Catchment groundwater.

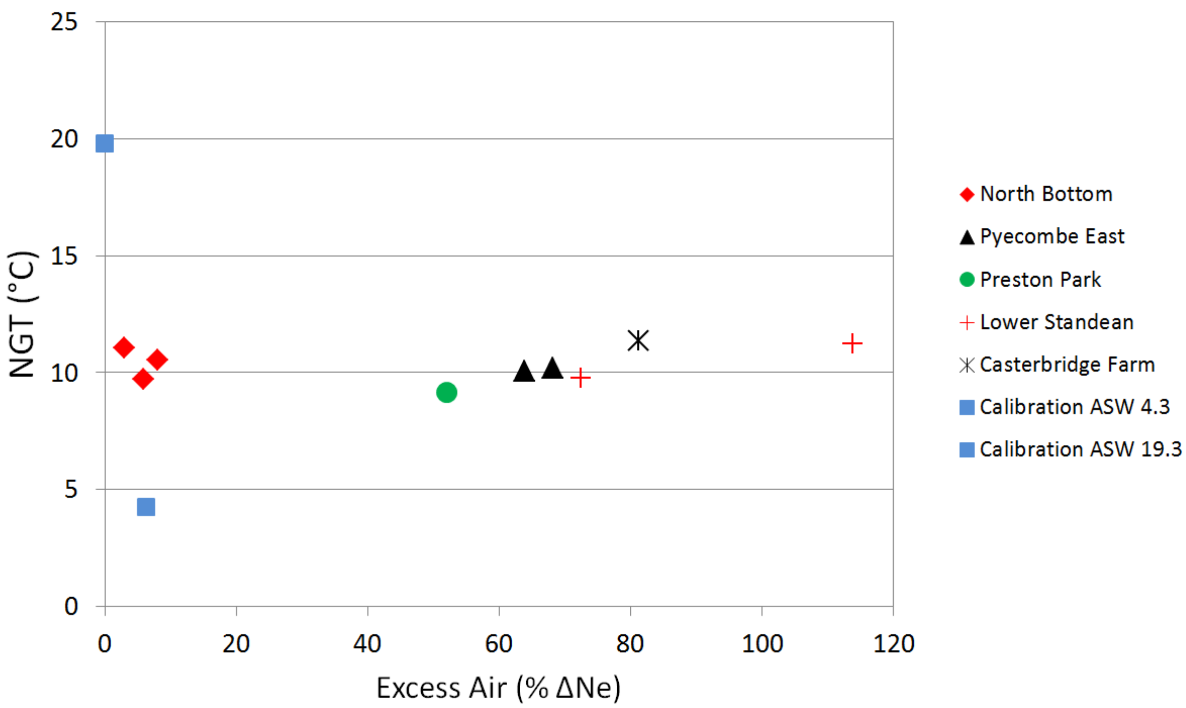


Figure 31 Modelled noble gas recharge temperatures and excess air concentrations for Patcham Catchment groundwater.

The data confirm the presence of modern groundwater with a recharge temperature in the range of 9.2 – 11.2°C which is in good agreement with the mean average annual surface temperature for the region. Pleistocene recharge which typically displays a recharge temperature several degrees C lower than that of Holocene recharge was not identified. It was hypothesised that excess air could be a valuable tracer for groundwater flow in the proximity of Pyecombe East where treated effluent is used as artificial recharge. Studies have shown that artificial recharge is typically characterised by very high excess air concentrations caused by increased air entrainment and large fluctuations of the water table (Cey *et al*., 2008). However, groundwater samples analysed from the Pyecombe East borehole showed lower than expected excess air concentrations. The reasons for low excess air concentrations at this site are uncertain but it is possible that large natural fluctuations of the water table are subdued by the artificial recharge which might help maintain a more constant potentiometric surface throughout the year in this part of the Chalk, and thus leading to lower than expected excess air concentrations. Excess air concentrations are also surprisingly low at the North Bottom site. This is a rather unexpected result as the North Bottom borehole is the deepest of all the sampled boreholes and typically groundwater samples at greater depth (and hydrostatic pressure) have higher excess air concentrations. Excess air concentrations close to solubility equilibrium with the atmosphere (as observed at North Bottom) would generally only be expected in close proximity to the water table. Low excess air concentrations at North Bottom could also be explained by atypical recharge conditions or an influence of natural de-gassing mechanisms in the subsurface, although the exact cause is unknown and require further investigation. In general the application of both stable isotopes and noble gas tracers have proved to be of only limited use in understanding recharge mechanisms to the Chalk.

Geophysical monitoring of Unsaturated zone flow.

Following the feasibility study to establish the best strategy for data acquisition in terms of sampling and layout, we prepared and carried out three geophysical field work experiments on some of Brighton sites (Fig. 32) in July 2011, March and November 2012. We studied 3 sites, Pyecombe, North Bottom and North Heath Barn, 3 sites with drill hole and water pumping at each. We carried out electrical resistivity tomography (ERT) at different scales with a maximum penetration depth of about 50 m. The 2011 ERT data showed a strong degree of heterogeneity in the undersaturated zone with areas of dissolution of large size (Fig. 32). The following experiments shed light on the evolution of the water flow in the vadose area.

The limited size of the fields we worked in prevented measuring ERT profiles of large size everywhere, which is necessary to reach the greatest depths. Hence, we measured ERT profiles with different sizes for the acquisition system.

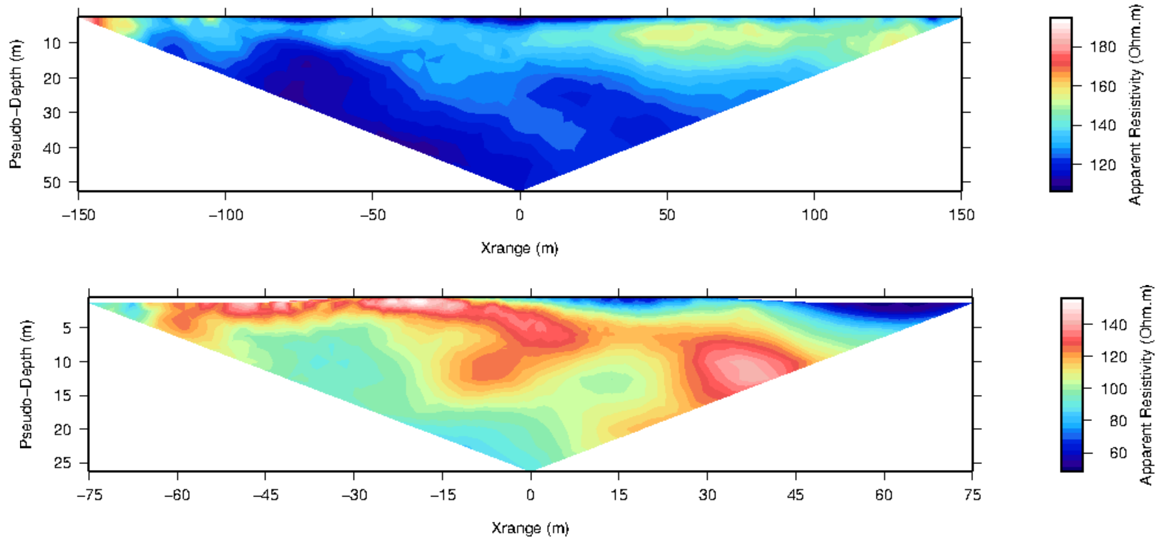


Figure 32 ***Examples of ERT data. Apparent resistivity as a function of injection distance (pseudo-depth). Top North Bottom, below, Pyecombe.***

The sections presented in Figure 32 are the raw data. The variations in color depict the variations of electrical properties of the ground. To obtain a geological section, that is a section showing vertically the true depth and the distribution of the physical properties, namely the true electrical resistivity, we have to carry out an inversion analysis. We developed techniques to improve the resolution of the models. Some results of inversion are shown in Figure 33. In a fairly homogeneous (in terms of composition) geological medium such as chalk, the variations of electrical resistivity are due to water content in the porous medium as well as clays in the dissolution areas.

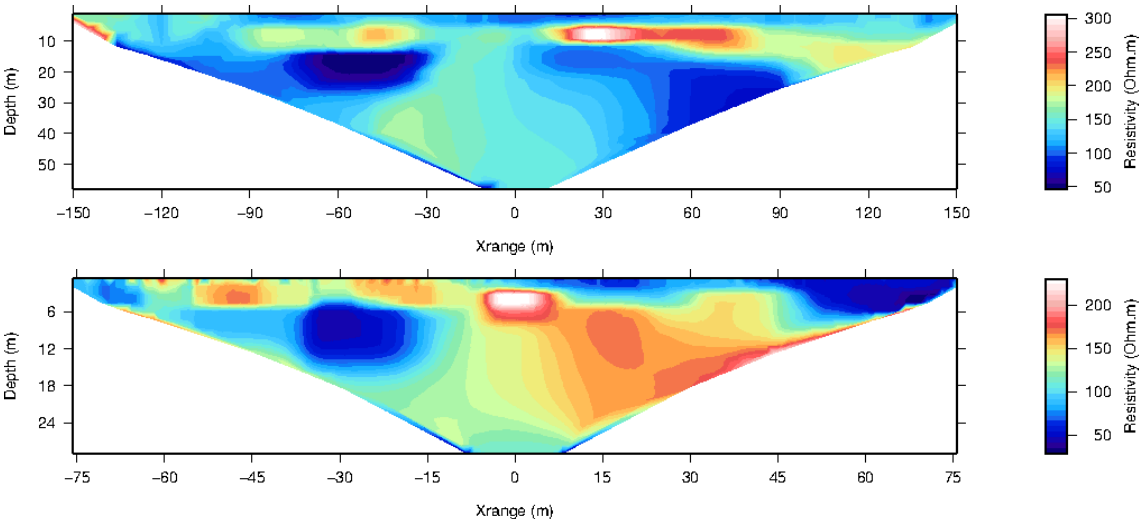


Figure 33 : True electrical resistivity as a function of depth resulting from the numerical inversion of ERT data for both sections shown in Figure 3a. Top North bottom, below Pyecombe.

In Figure 34, we present the comparison between 2011 and 2012. Small but significant changes are observed in both sites studied in 2011.

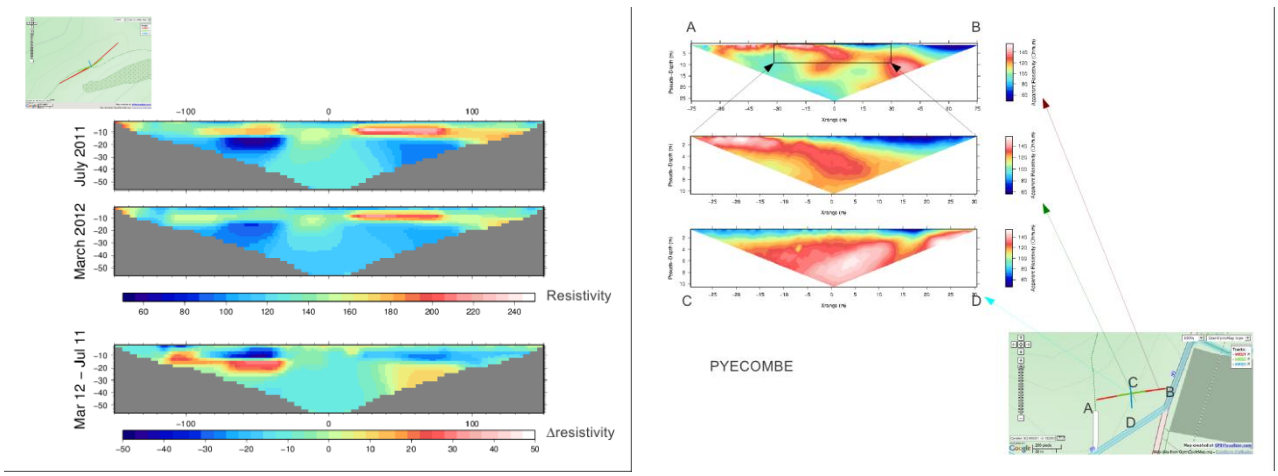


Figure 34 : Pyecombe *North Bottom*

2.2 Work Package 2.1: Water quality and long-term effects of artificial groundwater recharge using treated waters

Water quality, climate and flow process

The development of groundwater sampling and analytical protocols is described above, as is the initial interpretation of the correlation of groundwater chemistry with climatic variables. The monitoring data from the Patcham catchment also allow detailed assessment of the groundwater chemistry and its evolution as a result of changing recharge mechanism and water-rock interaction. The results of analyses of major anions and cations are summarised in Figure 35 using a standard Piper major ion plot. In all cases the majority of boreholes show relative major ion chemistry typical for unconfined chalk aquifers where the major ions are dominated by the formation of carbonic acid by dissolution of atmospheric CO2 and subsequent dissolution of carbonate minerals. The exceptions to this are 2 boreholes from the Pyecoomb area which show relatively elevated concentrations of NaCl. This can be attributed to a significant component of discharged effluent at Pyecombe East, and a minor component of this effluent present in some Pyecombe Old Rec analyses.

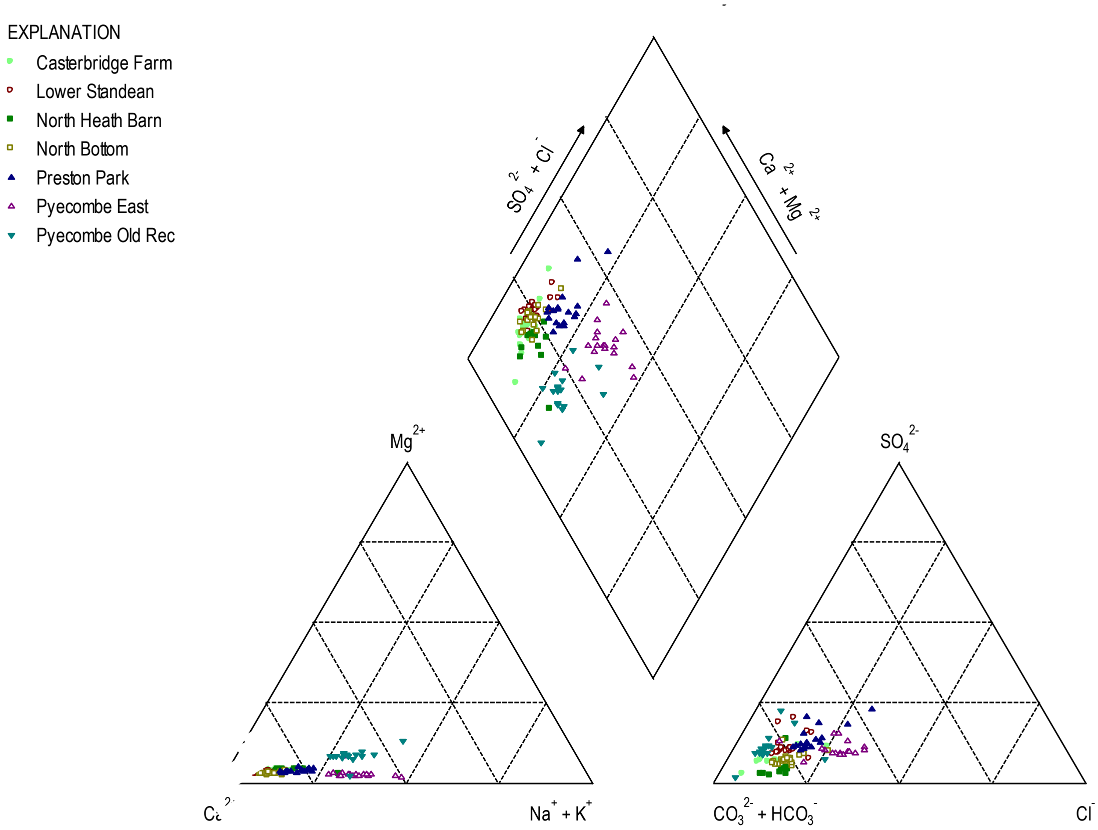


Figure 35 – Relative major ion composition of groundwaters in the Patcham catchment shown as percentage of cations and anions in meq/l.

The distinction in groundwater chemistry between Pyecombe East and the rest of the catchment is also clearly visible using plots which consider the total concentration in solution. For anion components these can also give clear guides to aquifer processes. Chlorine forms a major anionic component in groundwaters, and at high levels can significantly impact water quality. Bromine is a much more minor component, but both usually remain in solution and do not strongly interact with the rock matrix of the aquifer they can used as tracers of anion source and fluid flow pathways. For the majority of the aquifer these two elements occur in ratios comparable to seawater, albeit at much lower concentrations, suggesting the prime input to the chloride content of the waters in this case is either sea spary in precipitation (as the aquifer is coastal), or a minor component of saline intrusion. This is possible at Preston Park as this is the most southerly of the boreholes sampled. The only major departure from seawater ratios comes at Pyecombe East, where the Br/Cl ratio is lowered (Cl enriched) relative to seawater. This is likely a result of salts present in the treated waste water, and provides an indication that the artificial recharge at this point has only relatively minor mixing with the remainder of the aquifer. There is potentially some mixing of this water with aquifer water observable at Pyecombe Old Rec, but this is only discernible in one analysis. Otherwise it appears the effluent signature is removed by dilution (halogens will not be mineralised out of solution, or removed by microbial activity) during the normal groundwater flow regime (Fig. 36).

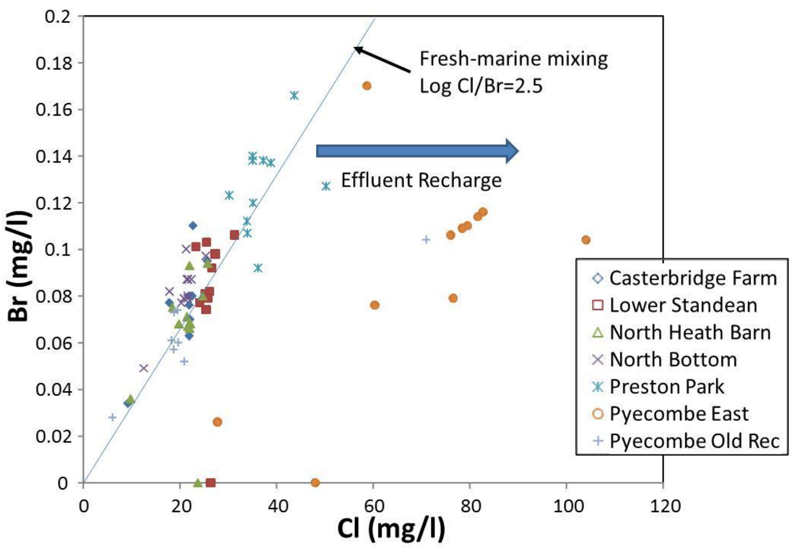


Figure 36 – Relationship between Chloride and Bromide in the groundwaters from the Patcham Catchment.

The behaviour of other anionic components of the groundwater can be assessed by comparison with chloride. Sulphate shows a positive correlation with chloride in most sampled boreholes, consistent with a marine component in the aquifer. There is a trend for increasing sulphate with constant chloride at Pyecombe Old Rec,

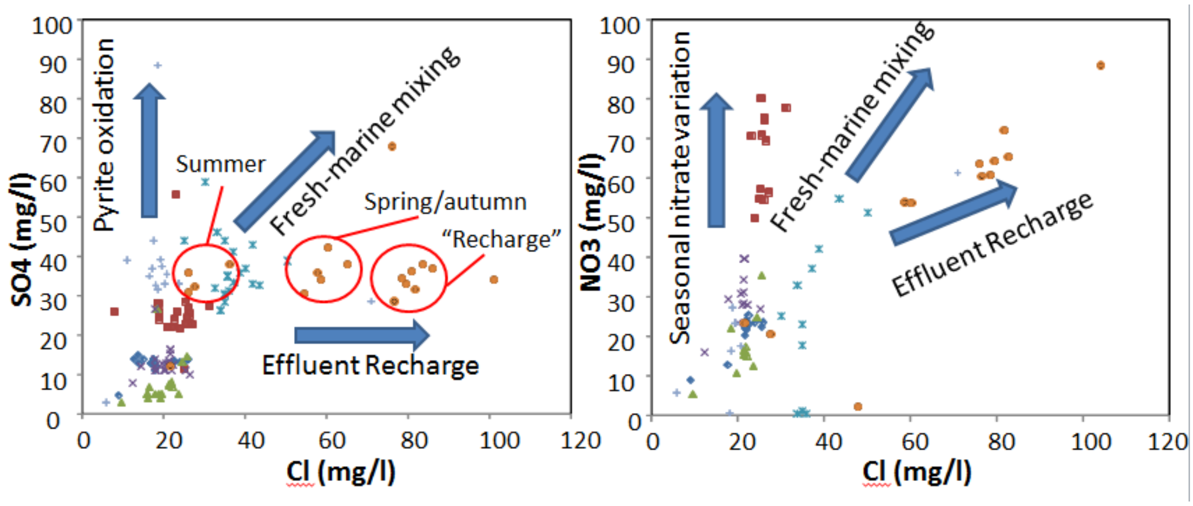


Figure 37 – Variation of common anion concentrations

which can be attributed to the dissolution of sulphates during winter high water levels, following oxidation of pyrite in the lower Chalk during summer low water levels (Fig. 37). Nitrate also follows a linear trend in some boreholes, suggesting a possible marine input. However, there is a trend to high nitrate at constant chloride in the Lower Standean borehole, reflecting marked seasonal variation in nitrate concentration. This may reflect the release of nitratre from soil during ploughing as this is an arable farmed site. In addition the analyses of water from Pyecombe East show higher nitrate levels, with a distinctly different slope in the trend between nitrate and chloride. This indicates again, the presence of a distinct water composition spatially associated with the effluent dispersal site. None of these water quality variables exceed maximum levels of components from drinking water guidelines so there is no current issue observable with artificial recharge using treated waste water effluent. Changes in recharge pathways with more intense rainfall are unlikely to impact this, as they will also be accompanied by increased dilution of the effluent component.

In addition to monitoring chemical indicators of groundwater quality in the Patcham catchment, monthly assays of the abundance microbial faecal indicator organisms (Escherichia coli; Enterococci) were carried out to assess the microbial flux to groundwater, both from normal groundwater recharge mechanisms, and from artificial recharge with treated waste water using simple, standard methods to estimate bacterial numbers within 48h. This process involved serial dilution of samples followed by filtration through 0.45mm nitrocellulose membranes, bacteria trapped on membranes grown on appropriate agar media for quantification & identification. Additionally, total viable counts (TVC) of all aerobic heterotrophic bacteria were carried out, to ascertain bacterial loadings. Pilot water sampling methods were performed as follows: the TVC of planktonic cells was enumerated by filtration of 40 ml of water under vacuum using cellulose acetate membrane filters (1.2 mm pore size, Millipore). The number of Colony Forming Units (CFU) was determined by plating 0.1 ml of suitable decimal dilutions of the filtrate onto Plate Count Agar (PCA, Difco) and incubating plates for 48h at 25ºC.

The results of microbial monitoring are shown in Figure 38. For both E. Coli and Enterococci there is both a geographical and temporal variation in the abundance of colony forming units. The highest values occur at Pyecombe Old Rec, where the site was accessible to domestic animals so there may be some risk of contamination, and at Pyecombe East, where remnant organisms in treated waste waters may be present. In all cases there are periods of the year where microbial abundance is very low, in many cases below the detection limit of the techniques used. Notable highs occur for a number of boreholes during periods of high rainfall and high groundwater level. These are periods when the unsaturated zone is thinner, and hence transport distances are less, and when matric potential is high allowing the activation of flow through fractures and karstic zones through which micro-organisms may be more effectively transported. Thicker unsaturated zones, with non-saturated fracture and karstic pore space, will result in more effective filtering. The exception to this is at Pyecombe east, where high E. Coli counts occur during periods of low recharge This may reflect lower dilution of remnant organisms in treated effluent by rain water during these periods.

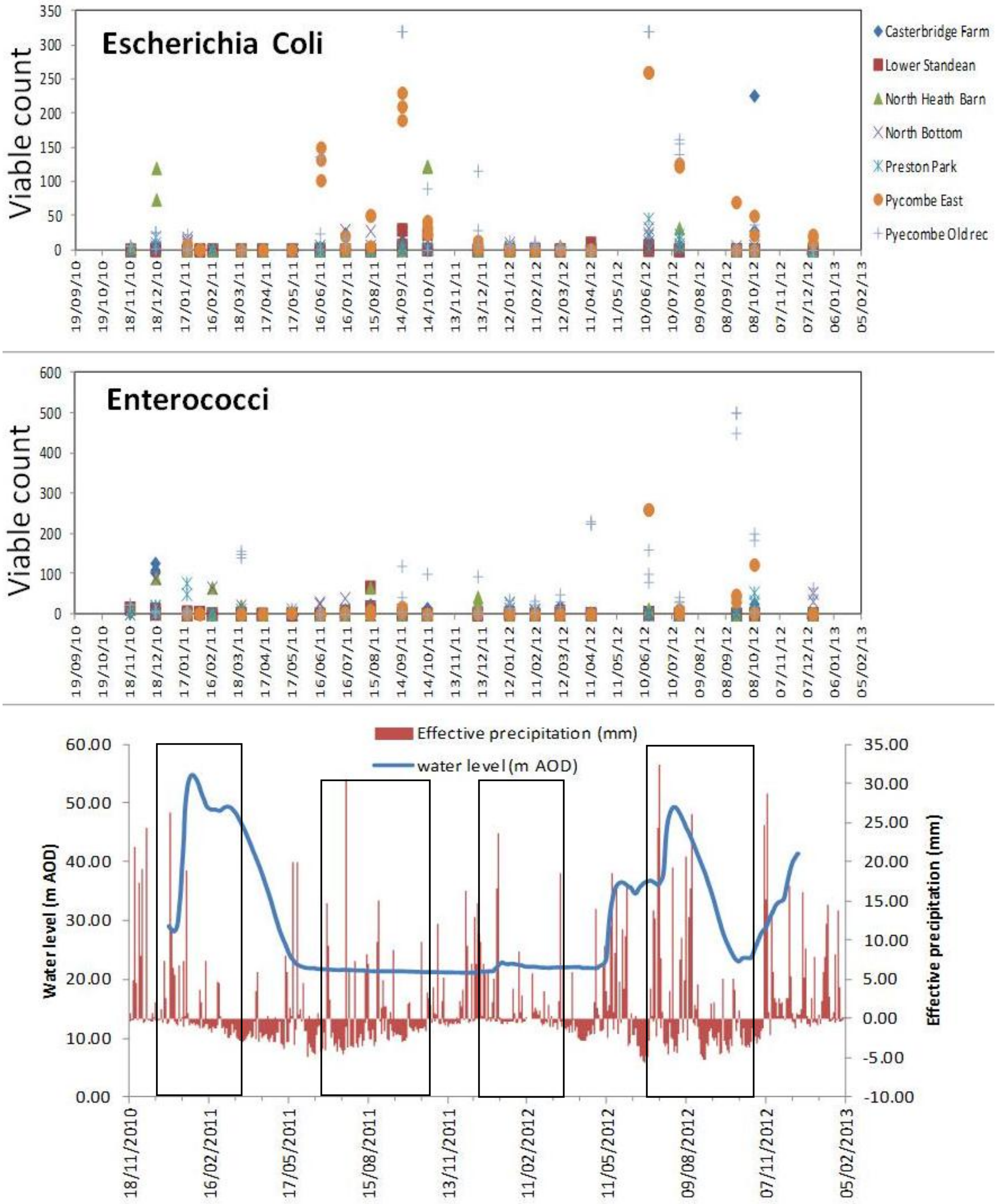


Figure 3 – Viable count of colony forming units for faecal indicator organisms in the Patcham catchment for each borehole compared with rainfall and water level at North Heath Barn for the monitoring period. Boxes indicate periods of high colony forming unit viable count.

At Ploemur statistical analysis has been done on the chemical data acquired since 1991 and stored in the chemical database. The results show that 4 components could be distinguished: (1) “natural” groundwaters like F9, (2) groundwater with short circulation path, (3) water from the weathered zone like MF1 and (4) old, deep groundwater like F38 (Fig. 39). The relative contribution of each component in each borehole has been computed. The map obtained is close to the mean residence time map (WP 1.1) with a greater influence of F38-like component near the main pumping zone (PE). Moreover the slight difference observed between east and west part of the site in dating is confirmed by chemistry: the weathered compartment has a bigger contribution in the eastern zone (F17, F20).

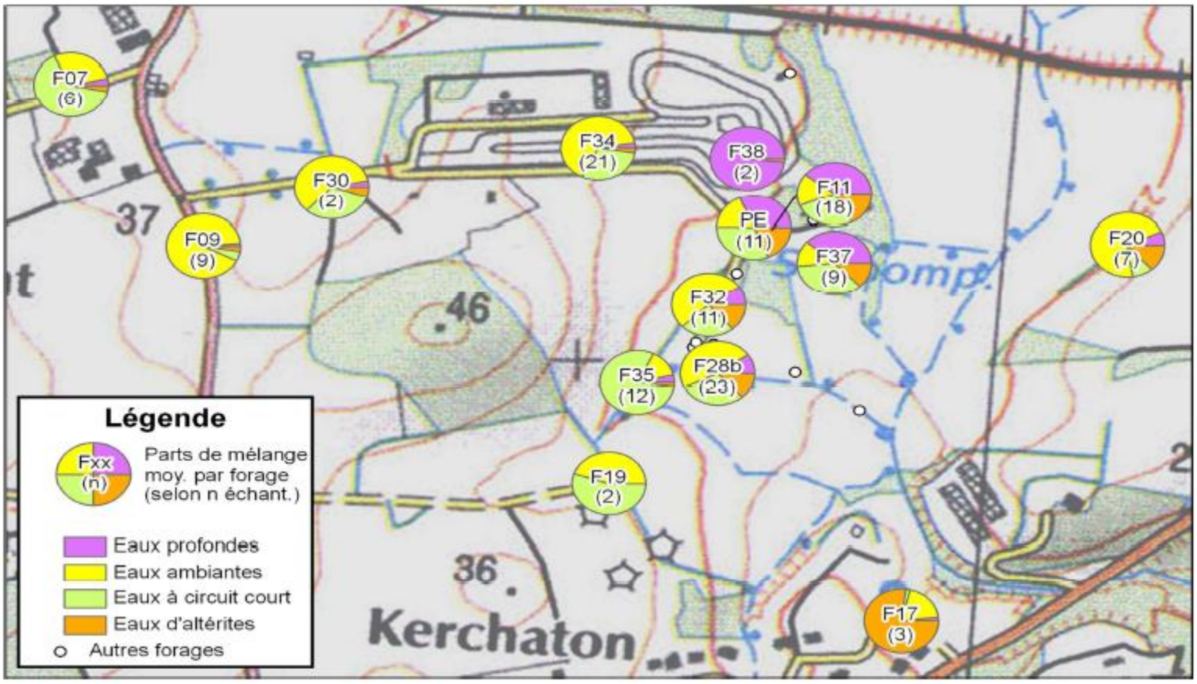


Figure 39 - Proportion of each "end-member" in the boreholes from Ploemeur site according to statistical calculation.

Radon analyses have been carried out in order to improve the understanding exchanges between surface and groundwater, as well as the spatial and temporal variability. The 222Rn concentrations have been measured at Ploemeur experimental site (lake, rivers and piezometers) to monitoring the groundwater flux. To quantify the groundwater discharge to the surface water bodies a black box model has been used. The study shows that the groundwater contribution to the surface drainage of Ploemeur is low in contrast with the East tributary. Downstream of the convergence between the East and West tributaries (out of the pumping site influence area) the groundwater contribution increases strongly.

Prediction of the long term evolution of groundwater quality

At Patcham both frequency and time domain transfer function approaches to the prediction of ground water levels predict significantly more frequent incidents of ground water induced flooding which will impact upon the quality of surface water in the short term due to the effect of high ground water levels on the surface and foul water drainage systems (see WP3 below). However what may be of greater long term significance to the quality of water supplies is the quality of the water held within the aquifer itself. Assuming this contamination originates from surface deposits (fertiliser, crop spraying, animal waste etc), the concentration of any one soluble contaminant will be affected by the amount of effective recharge.

An analysis was carried out on the basis that :-

- The sources of contaminants remained constant over the relevant periods
- Contaminants build up in the soil and upper levels of the unsaturated zone during recession periods
- Soluble contaminants would mainly reach the aquifer during recharge events

The annual effective rainfall for the control period was calculated to be about 400mm and this was shown not to increase significantly by the period 2050-2080 and only by about 2% by 2080-2110. From Figures 40 and 41 it is clear that, on average, there is predicted to be progressively greater effective rainfall in the winter months and less in the autumn relative to the control period.

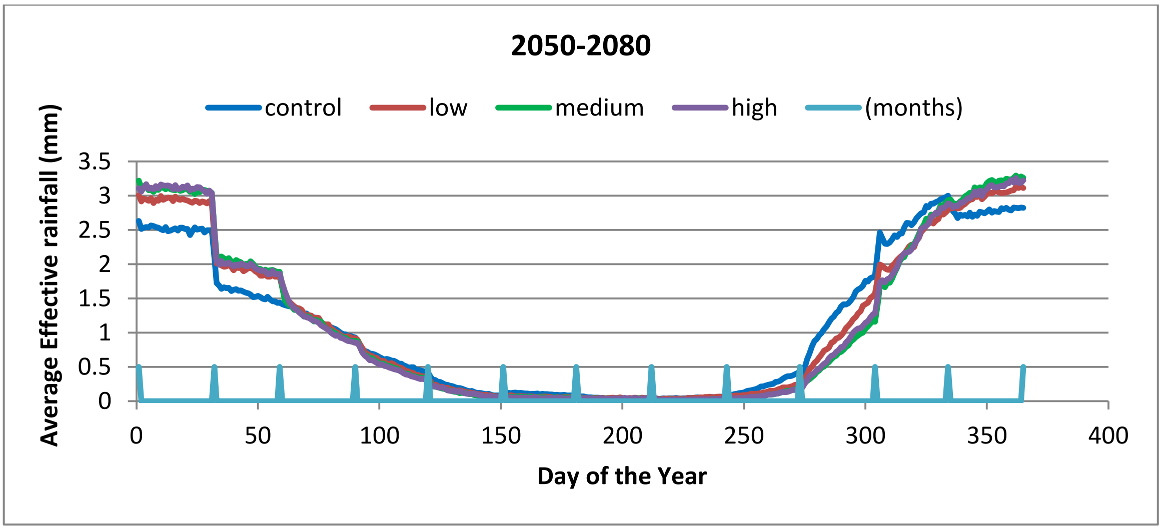


Figure 40- Predicted average distribution of effective rainfall 2050-2080

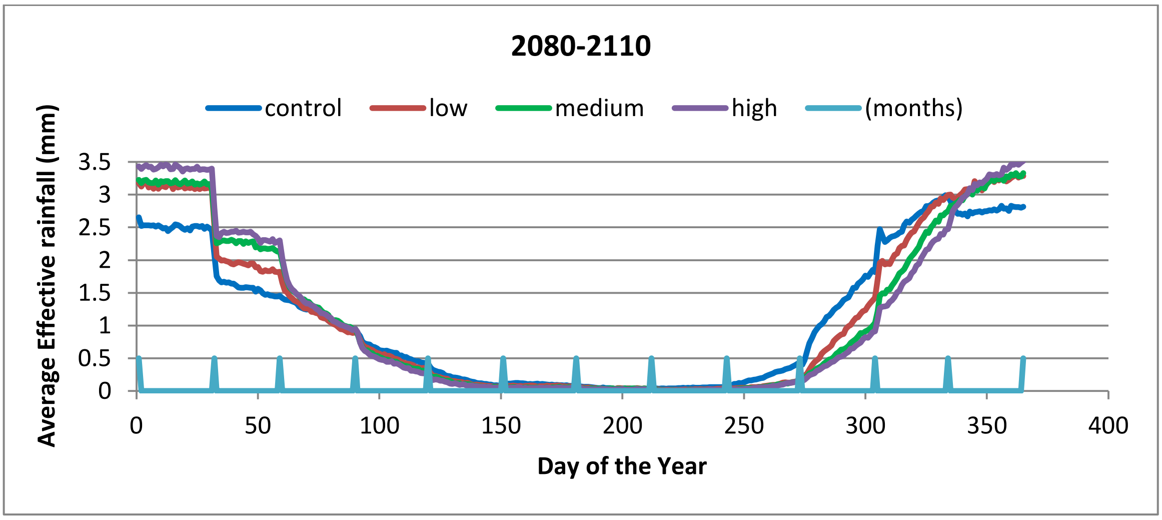


Figure 41 - Predicted average distribution of effective rainfall 2080-2110

An examination of the average annual effective rainfall distribution indicates that a more significant proportion of that effective rainfall fell during the months of November, December, January and February (~17% for 2050-2080 and ~25% for 2080-2110) when the aquifer is most likely to be saturated and susceptible to ground water induced flooding.

The obvious conclusion, in the absence of any other routes of contamination loss, is that the average concentration of contaminants is likely to reduce very slightly due to increased effective rainfall and hence recharge. However, due to the gradual change in distribution of this recharge throughout the year, with longer recession periods and higher winter recharge, the movement of contaminants into the ground water may peak more significantly at the onset of recharge. Some of this will be absorbed within the chalk matrix until it becomes saturated at which point rapid bypass recharge through fractures will then take contaminants directly through to the ground water. Any contamination held within the chalk matrix will still reach the water table eventually, over several years in some cases, but at less variable concentrations.

Impacts for effluent dispersal

The data presented here indicate that treated effluent dispersed to the Chalk aquifer forms a chemically distinct water body. However, even within that body drinking water guideline values for key compounds and microbial indicators are not exceeded. Aquifer flow dilutes the effluent component to the point at which it is undetectable except for under exceptional circumstances proximal to the discharge site. This seems to apply even at much large sites than that studied here (Munn, 2009). Current standards for waste water treatment prior to dispersal are adequate, as are guidelines for the siting of dispersal works. Geological characterisation of sites if the practice is to expand, however, would seem to be critical as the evidence presented here shows the artificial recharge maintains the unsaturated zone at high matric protential throughout the year, leading to the potential for rapid bypass flow in fractures and karst. Effluent dispersal sites should aim to avoid heavily fractured and karstified regions and maximise the depth to the water table. The practice should be sustainable for the future as the prevalence of high intensity rainfall events is predicted to rise, leading to greater dilution effects despite the more frequent activation of rapid flow paths. Greater monitoring may be necessary in low rainfall periods however, to ensure that contaminant levels reaching the water table remain low through periods of low dilution of dispersed effluent.

2.3 Work Package 2.2 Mobility, distribution and retention of contaminants

Contaminant mobility in Chalk

In order to provide quantitative constraints on contaminant transport in the Chalk aquifer matrix a core-flood experimental rig was constructed, and used for a series of experiments. Core experiments were conducted to simulate the flow of contaminants present in treated wastewater through the Chalk matrix. The experimental system consisted of a stainless steel Hassler core holder, connected to an automatic pressure controller, which provided a confining pressure on the core to be tested. The test solution was driven through the core using a Jasco 980U HPLC pump, and samples were collected using a GE Healthcare fraction collector (Fig. 42).

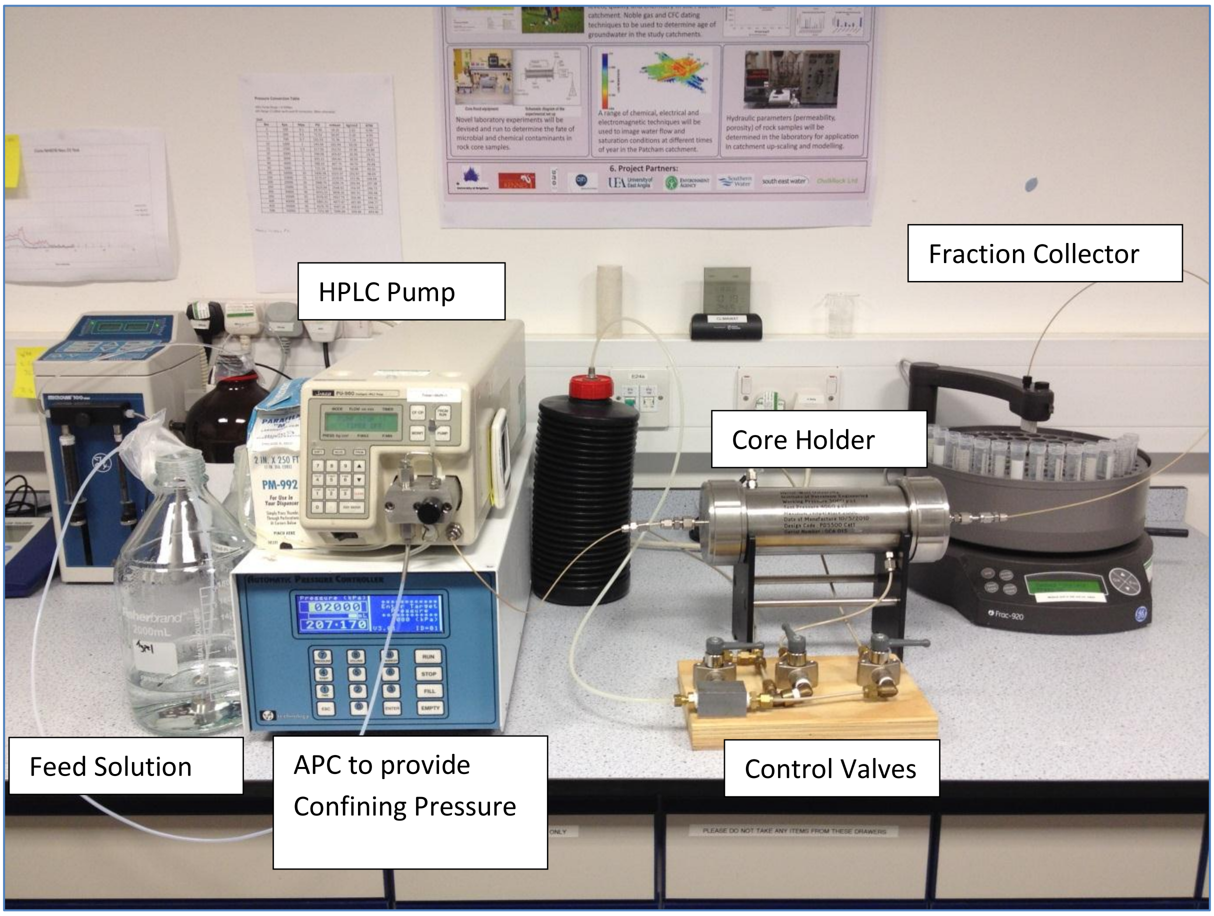


Figure 42 – Photograph of the CLIMAWAT flow and reaction experimental system at the University of Brighton.

The Chalk samples used in the core experiments were selected from the University of Brighton core collection, and were representative of the producing levels of the Chalk aquifer in the Brighton area. The hydraulic properties (porosity and permeability) of the core samples were measured before and after core experiments to determine if there has been any reduction (clogging) or increase (dissolution) of the Chalk matrix during the experiments. In addition to the flow and reaction experiments, batch experiments involving the reaction of a known amount of crushed chalk with a test solution for a fixed period of time were carried out to determine the maximum removal capacity of chalk for phosphate. Anion concentrations were analysed after the experiment using ion chromatography (NO_3^-; PO_4^{3-}), and gas chromatography (atrazine).

In total 6 experiments were conducted on nitrate transport in the chalk, and an example of the results are shown in Fig. 43. Experiments were conducted under conditions of a continuous feed of nitrate solution into core previously saturated with distilled water, under conditions of a single pore volume of nitrate solution injected, and then displaced by distilled water, with a single pore volume injected and then shut in for 6 days, and with nitrate solution injected into complete dry core (to simulate entry into unsaturated chalk). Experiments were also carried out with continuous monitoring of pH and using calcium saturated nitrate feed solution in order to study the effects of carbonate dissolution on nitrate behaviour. The nitrate core experiments have allowed for the identification of breakthrough curves as it migrates through the chalk matrix. The nitrate breakthrough curve is seen to have a very distinct, abrupt shape and is seen to be similar under either saturated or unsaturated conditions. The data have been used to derive the co-efficient of hydrodynamic dispersion for nitrate in the chalk matrix, which can be used in subsequent numerical modelling studies of nitrate transport. Overall the core experiments completed as part of the laboratory programme have shown that nitrate behaves as a non-sorbing solute when it migrates through the chalk matrix, with the mass balances showing that all of the injected nitrate is fully eluted from the core during the duration of the test. This is shown to be the case in both the unsaturated and saturated cores and when the nitrate solution was 'locked-in' for an extended period of time.

These results show that, under the conditions tested, that there is no potential for nitrate to be removed by the chalk matrix by either sorption or biological processes, and that when nitrate enters the chalk matrix is will be seen to behave conservatively, with advection the main contributor to the transport of the contaminant with a small amount of hydrodynamic dispersion occurring at the front of the plume. As this study focussed on the movement of nitrate through the chalk matrix only no degradation of nitrate due to biological activity was expected due to the pore sizes being smaller than that of the microbes that facilitate this process, the microbiological communities are precluded from entering the matrix. This supports the current scientific consensus that nitrate generally behaves conservatively in both the deep chalk unsaturated zone and saturated zones (Brouyere, 2004; Jackson et al., 2008; and Price et al., 1993).

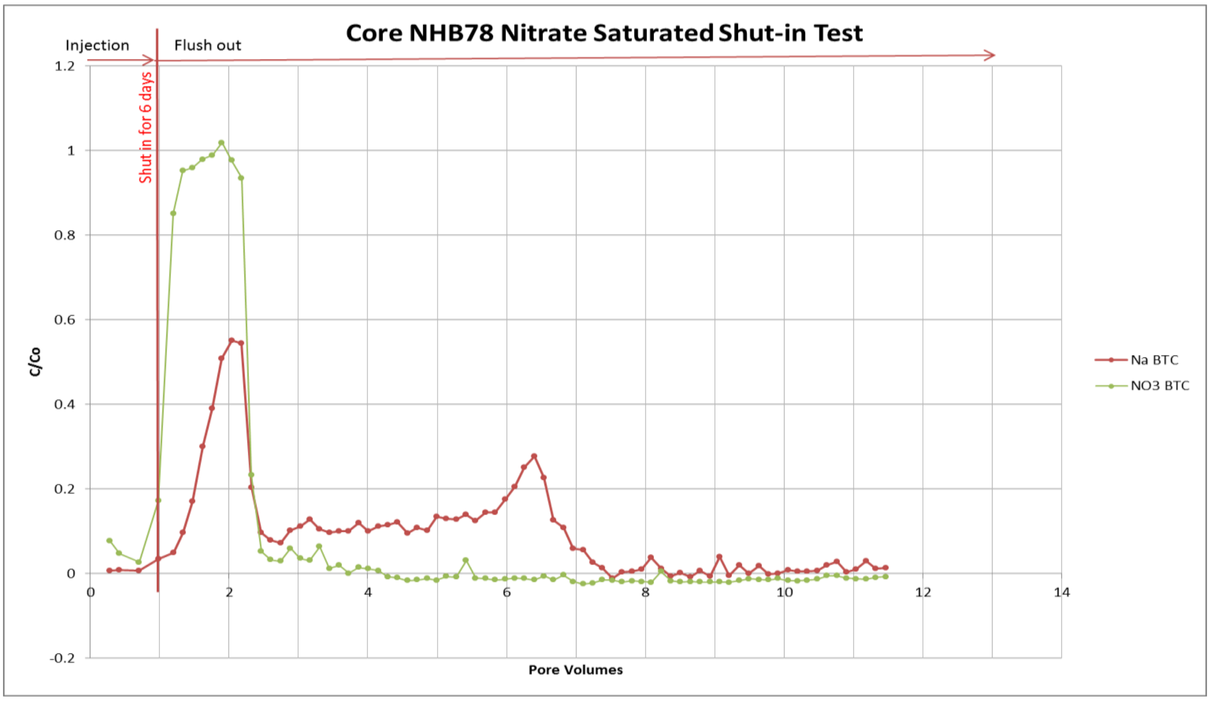


Figure 43 – Example of a nitrate flow and injection test. In this case 46.5mg/l KNO3 solution was injected into the core at a flow rate of 0.5ml/min. The core was then left with no pumping for 6 days, followed by a resumption of pumping using a distilled water feed solution.

In total 25 experiments were conducted involving phosphate transport in the Chalk matrix. These covered the same range of conditions as the nitrate tests, but included initial experiments to determine optimum run conditions (initial tests allowed no phosphate at all to move through the core), and tests at a range of pH and phosphate concentration. These were necessary as it was found that phosphate is effectively removed from pore water by flow through chalk. This necessitated post-experiment analyses of the solid core materials as well as the extracted pore waters using X-ray diffraction (XRD) to determine phosphate mineralogy, and Scanning Electron Microscopy (SEM) to characterise the distribution of reaction products. An example of test results is given in Figure 44. In contrast to nitrate the results of the core experiments show that the chalk has the potential to remove phosphate when it is pumped through the chalk matrix. The breakthrough curves show a dual phase profile, with an initial period of total removal occurring before a partial breakthrough which then plateau's at an intermediate C/C_0 ratio. The core experiment results and subsequent analysis have shown that there a relationship exists between the feed concentration of the phosphate solution and the number of pore volumes of total removal before the breakthrough commences, with higher feed concentrations breaking through before lower concentrations.

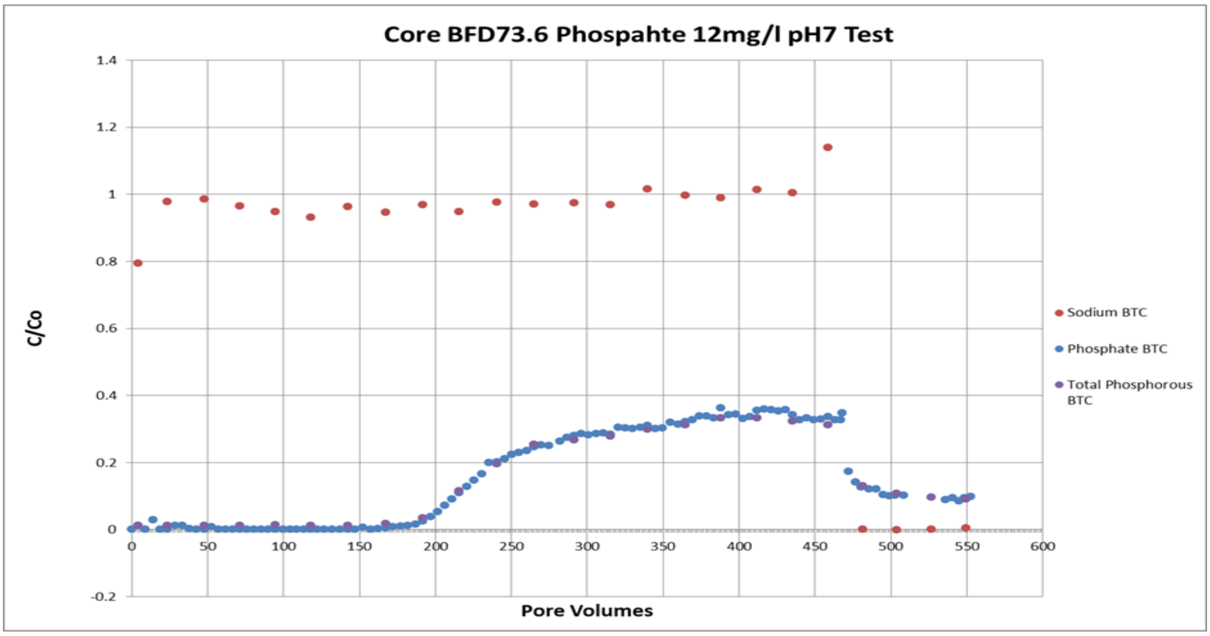


Figure 44 – Example of a phosphate flow and injection test. In this case a solution containing 12.24mg/l PO4 with a pH buffered at 7.5 was injected in drill core pre-saturated with distilled water at a flow rate of 0.5ml/min, and then subsequently flushed out again using distilled water.

A relationship also exists between the flow rate and the number of pore volumes before the breakthrough commences, with slower flow rates seeing a longer period of total phosphate removal. X-ray diffraction and SEM examination of tested cores shows that phosphate is being removed during aquifer flow as the the phosphate minerals brushite at low pH (4.5) and hydroxyapatite at high pH (9.5). The SEM imagery shows the typical coccosphere, coccoliths and laths for the clean chalk sample and when this is compared to the post-phosphate core experiment sample a new mineral deposit is seen on the surface of the chalk matrix. The mineral precipitate is seen to commence growth on the surface of the calcium carbonate matrix and then increase in growth into a web-like deposit that increases in size and coverage over the matrix surface (Fig. 45).

In order to quantify the capacity of the chalk to removed phosphate batch experiments were carried out, reacting 0.05g of crushed chalk with increasingly high concentrations of phosphate. Experiments were carried out at pH 4.5 and 9.5. Analysis of isotherm curves (expressing the initial concentration against the amount removed from solution; Fig. 46) shows that curves flatten between 800-900mg/g for the low pH solution, indicating that maximum amount of phosphate than can be removed is ~850mg per gram of chalk. From the high pH isotherm, it is seen to flatten at around 400mg of phosphate removed per gram of chalk.

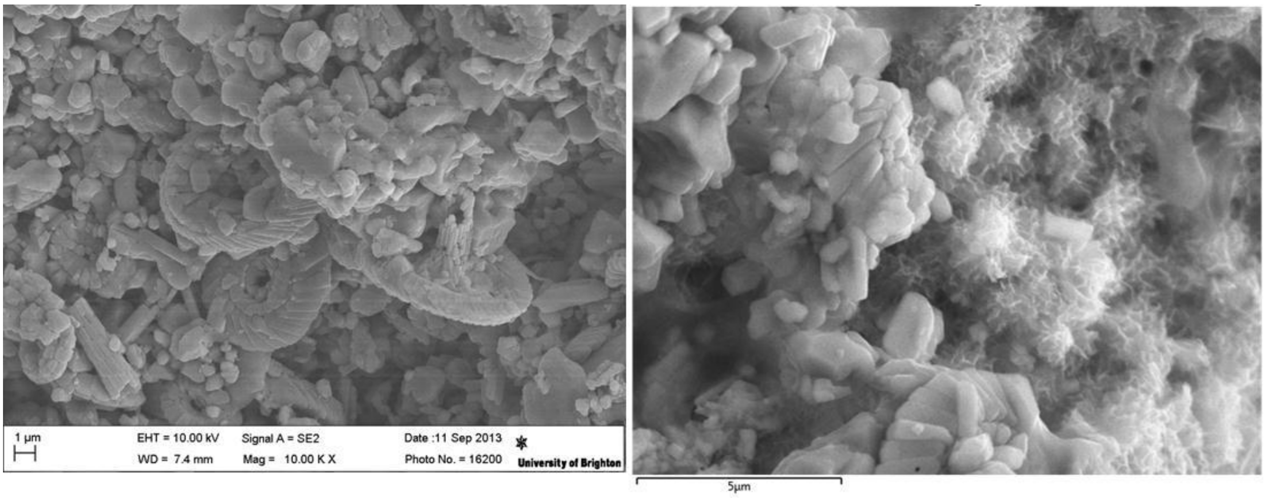


Figure 4 – SEM images showing the chalk structure in drill core prior to phosphate injection, and after a phosphate injection experiment. The web of needle-like minerals in the image to the right is hydroxyapatite ($Ca_5(PO_4)_3OH$).

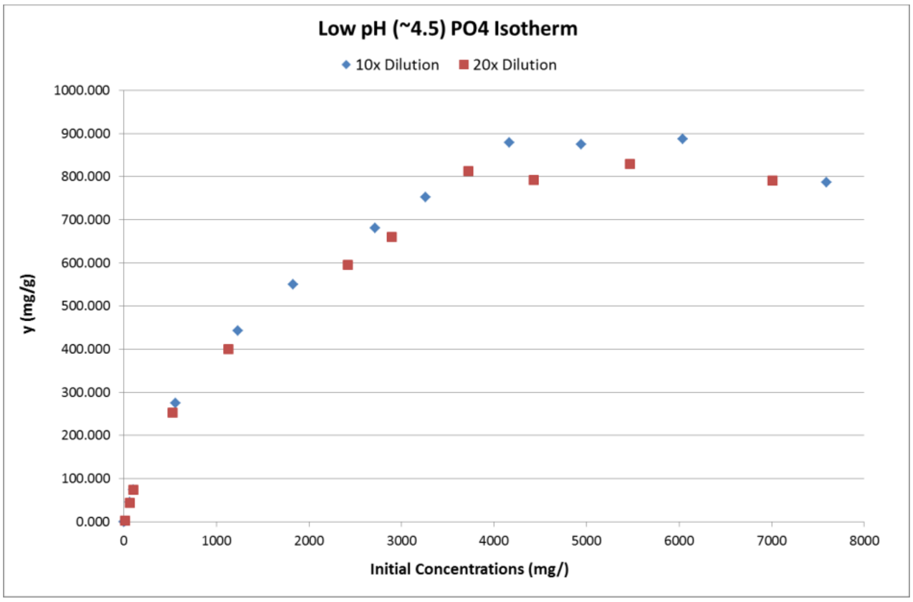


Figure 46 – Example of an isotherm plot showing the amount of phosphate removed for different initial concentrations under different experimental conditions.

Several core experiments were also completed using secondary treated effluent that was sampled from Scaynes Hill WwTW (Fig. 47). These core experiments were carried out in order to allow for a comparison to be made between the actual effluent breakthrough curves and synthetic ones using laboratory solutions. The nitrate breakthrough curve during the effluent core experiments is seen to have the same characteristic abrupt shape as during the sodium nitrate core experiments. The effects of dispersion were more clear during these effluent tests than the sodium phosphate experiments, with the breakthrough occurring before one pore volume of effluent had been inject at 0.8 0.93 and 0.82 pore volumes for the three effluent core experiments. Modelling of these tests using the co-efficient of hydrodynamic dispersion derived using the laboratory solution experiments indicates that these values are suitable for modelling the behaviour of nutrient contaminants in real effluent.

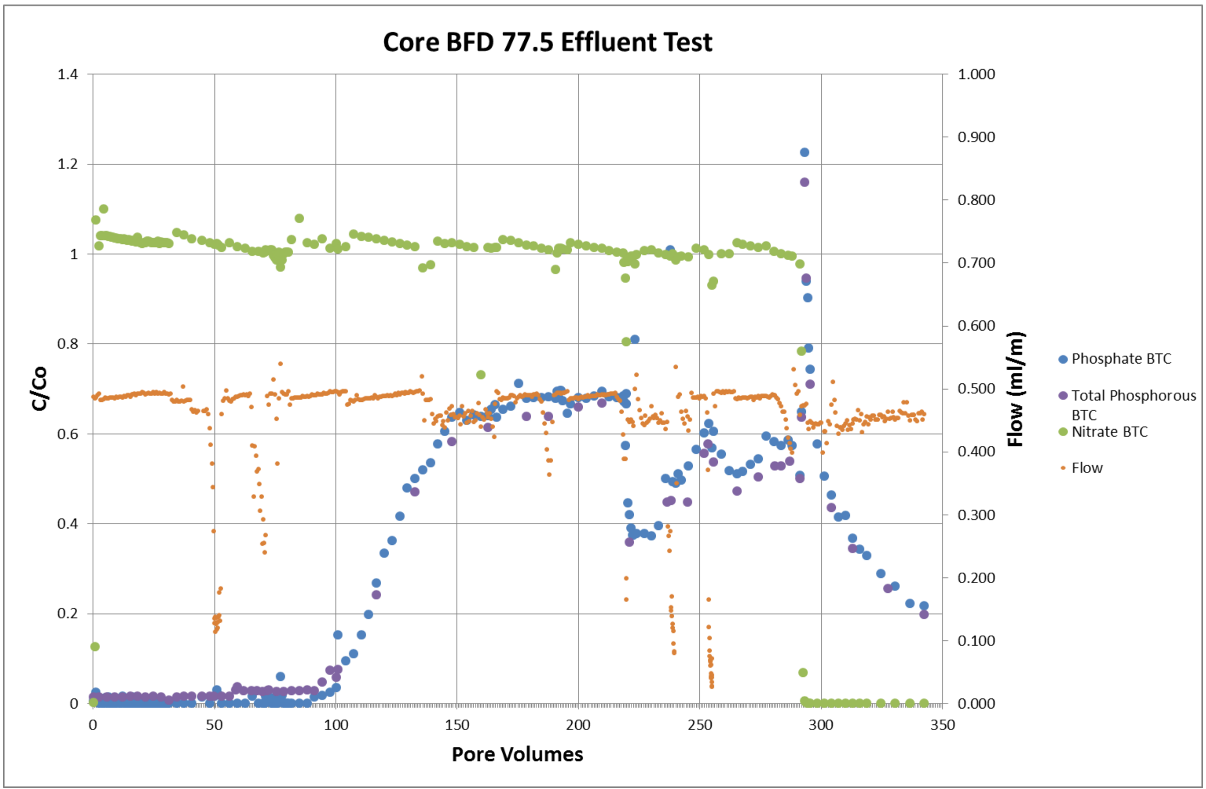


Figure 47 - Example of a core flow and reaction test using real water treatment works effluent. Variations in concentration and flow in these experiments are a result of clogging of the core pore space by suspended particualtes.

The phosphate breakthrough curves obtained during the effluent core experiments are seen to have the same phases of phosphate removal (total and partial) as the sodium phosphate core experiments. The chalk matrix has a lower capacity to remove phosphate in the effluent than compared to the sodium phosphate solution. The reasons for the reduced phosphate removal capacity are thought to be due to the presence of fluoride in the treated effluent, which could be competing with phosphate for mineral surface sites during the chemisorption/precipitation process.

Nutrients are not the only compounds of concern in the potential contamination risk from treated effluent dispersal, or from changing precipitation regimes on catchment recharge areas. Initial experiments have been carried out to assess the transport of the pesticide atrazine (a polar organic molecule) and bacteriophage viruses (which may be used as indicators for contamination by human faecal bacteria) through the chalk matrix. These experiments are still being analysed, but examples of results are given in Figure 48. Atrazine in this case reaches the initial concentration after approximately 2 pore volumes injected, and is only fully removed from the core after pumping of a further 4 core volumes during the displacement phase. This implies that although atrazine is largely behaving conservatively during groundwater flow, there is some dispersion and retention of the compound with in the pore network.

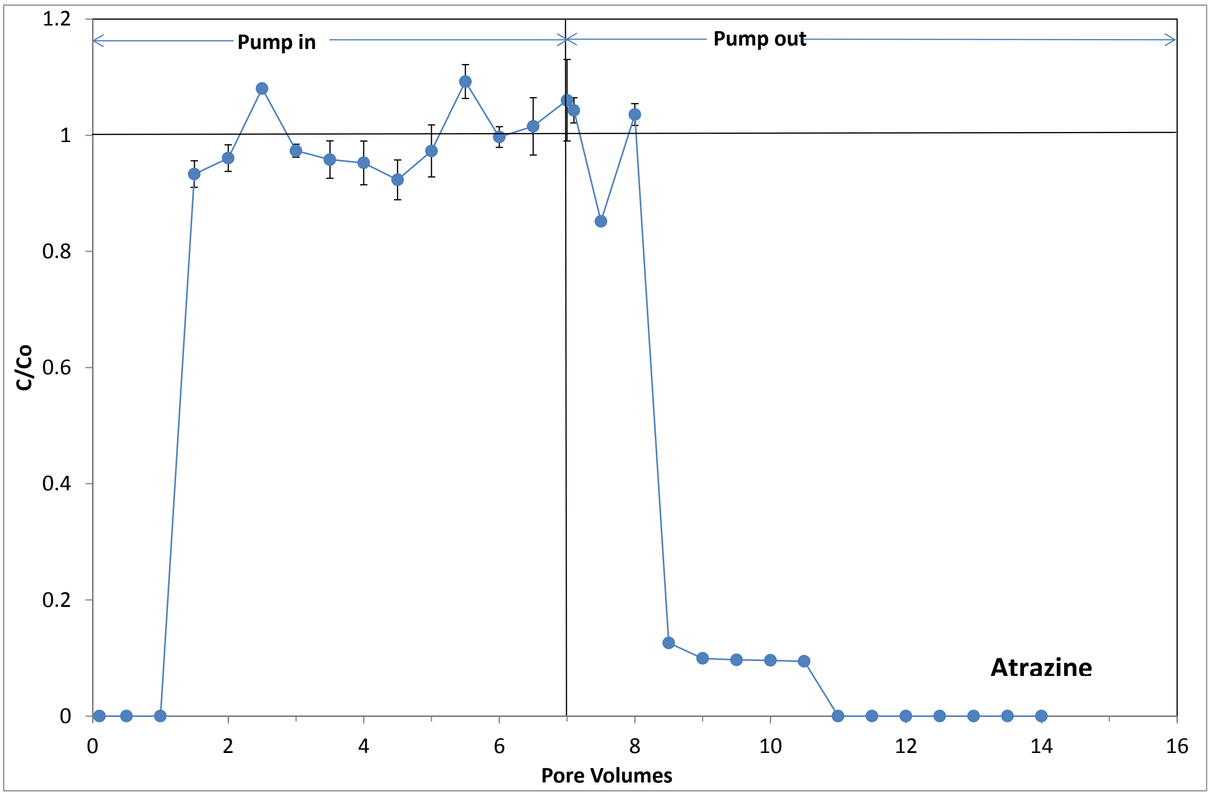


Figure 48 – Atrazine injection and dispersal test.

Field Experiments

The characterization of the mobility, distribution and retention of contaminants requires the performance of field tracer tests that consists in injecting a given volume of chemical in the aquifer and measuring the evolution of its concentration with time at an outlet, such as a pumped borehole. These tests were the focus for this Work Package at Ploemeur. The measurement of these breakthrough curves enables estimating the distribution of transfer times of chemical elements transported in groundwater flow. A series of tracer experiments were performed in 2011 on the Ploemeur site (Fig. 49) under various flow configurations, including dipole, convergent and push-pull tests. Two boreholes, B1 (83 m deep) and B2 (100 m deep), which are 7 m apart, were used. A double-packer system was designed and installed in B1 at 50 m depth to inject tracer into a single fracture. Results show the existence of very long transfer times that are related to tailing in the breakthrough curves, i.e. the fact that full recovery of the tracer takes a very long time. In the example of Figure 49 in dipole flow configuration, where the tracer is injected in one borehole and pumped in other boreholes under the same injection and pumping rates, the peak of tracer arrives after about 30 minute but full recovery is not obtained after 24 hours. Results also show that such tailing strongly depends on the flow configuration. For instance, the recovery is much faster in push-pull flow configuration, where the tracer is injected and recovered in the same borehole (Fig. 49). We are currently interpreting these results in order to define the most relevant model of contaminant mobility at the Ploemeur site.

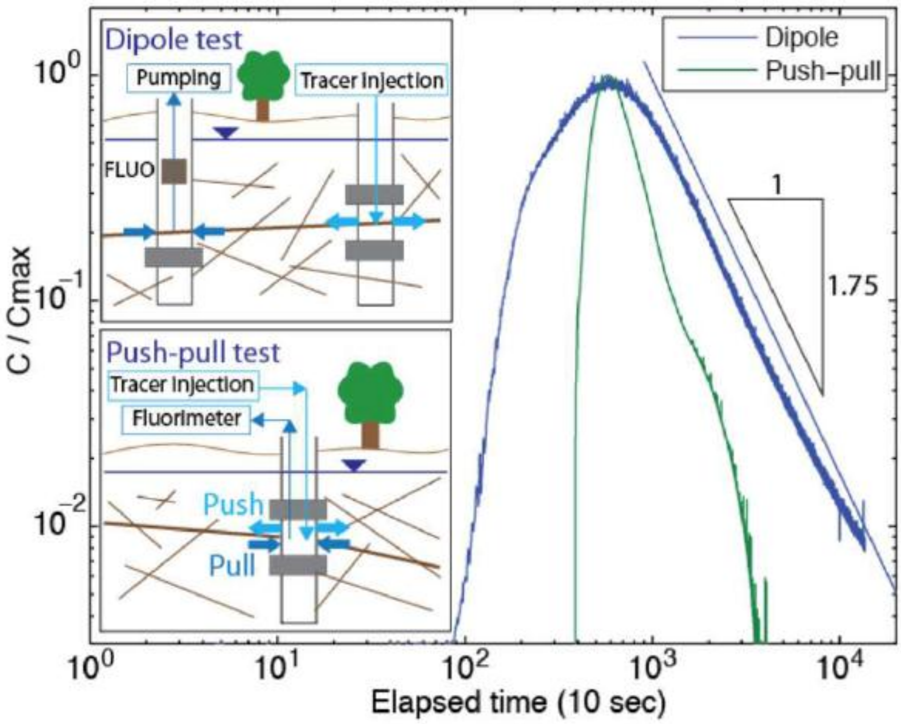


Figure 49 - Evidence of breakthrough curve tailing from a dipole tracer test (blue line), and indication of lack of tailing from a push-pull test (green line). Inset: illustration of dipole and push-pull tracer tests using a double-packer system.

Analogue modelling

The characterization of solute dispersion, and related processes such as mixing and reaction, is essential in many environmental applications. The developed setup provides the first experimental images of the spatial distribution of flow velocities, concentrations and reaction rates at the pore scale. Experimental set-up is based on a two-dimensional cell built by soft lithography. It allows a dynamic 2D visualization of the flow (single or multiphase) and transport processes (dispersion, mixing, reaction). The injection system developed is designed for a precise control of the fluid and tracer injection. The transport of pollutants between the soil surface and subsurface water bodies mainly takes place under a partially-saturated condition. While these questions have been mainly addressed based on column experiments (mostly 1D setup), our 2D experimental setup provides the full spatially-resolved information necessary to study the coupling of flow and transport in multiphase flows, at the pore scale (Fig. 50).

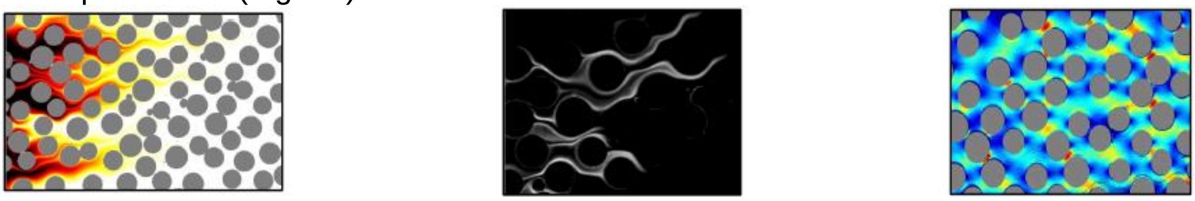


Figure 50 - Field concentration of a dyed solution. Left - Reaction. Light emitted by a chemiluminescent reaction at the front between two reactants, one displacing the other. Centre - Flow structure. Right - Field flow velocity obtained by particles tracking.

Water fluxes and their variation on biogeochemical processes (and especially denitrification) have been studied through an experimental device. The experiment allows monitoring water nitrate concentration flowing through plastic tubing (acting as carbon source) with different velocities. First the results show nitrate degradation with similar output concentration whatever the water velocity (and consequently whatever the total volume passed through the tubing). This stage seems to be biologically-controlled. Then nitrate concentrations reach a law which is velocity-dependant. In that stage a physical control is suspected: water velocity limits the nitrate residence time in tubing and consequently the diffusion process through biofilms. In the third stage, nitrate concentration increases. The end of nitrate reduction process could be due to an inhibition from reaction end-products (Fig. 51).

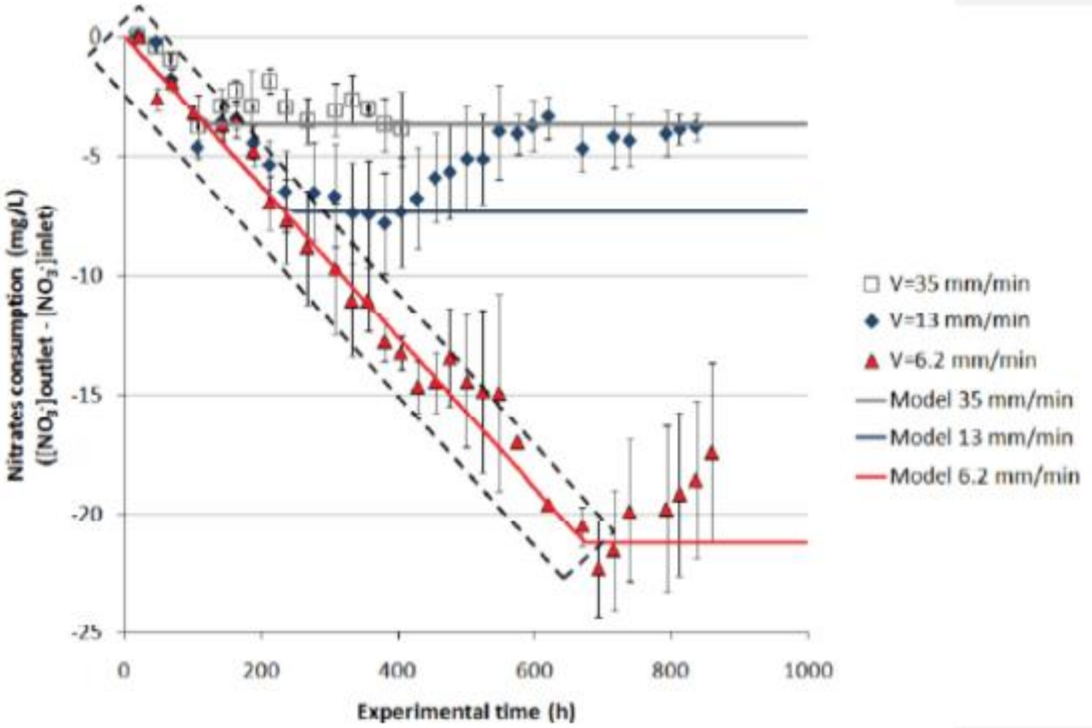


Figure 51 - Denitrification processes observed in laboratory for different flow rates.

2.4 Work Package 3 Risk Assessment and management of groundwater resources.

Numerical model of the Ploemeur experimental site

Groundwater resources in crystalline rock are typically associated with the weathered zone and regional sub-vertical faults that are well connected to the surface. However, some sub-horizontal and shallowly dipping fractured zones can also be highly-productive aquifers. During the project, numerical simulations of a conceptual hydrogeological model have shown that the flow to such strongly transmissive fractured zones is controlled by their transmissivity or by their deepening structure. While leakage through the overlying rock units is generally the limiting factor, recharge always occurs at least close to the outcrop of the fractured zone where the overlying rock is thinner and guarantees the availability of some groundwater. At small dip angles, recharge extends spatially and the flow within the fractured zone may even become the limiting factor when the hydraulic conductivity of the overlying rock is not less than two orders of magnitude smaller than the fractured zone transmissivity. This is precisely the case of the Plœmeur aquifer where groundwater in a shallowly dipping fractured zone is used as the source of water supply for a nearby city of 20,000 people. Simulation results (Fig. 52) show that the fractured zones may represent potential aquifers under a large variety of hydrogeological conditions. Aquifers in shallowly dipping structures differ strongly from those located in regional subvertical fault zones in terms of flow patterns, and thus supposedly in terms of management of the groundwater resource. They are more local than regional in scale, and consequently do not require regional fracture connectivity. The leakage through the overlying rock unit enhances water quality. Finally, we argue that the potential widespread occurrence of these alternative and possibly less accessible resources should promote the development of appropriate identification methods.

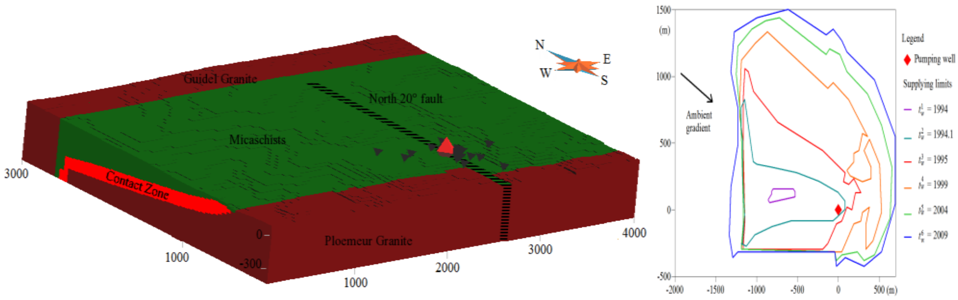


Figure 52 Left: Conceptual illustration of the numerical model of the Ploemeur site, right : predicution of the supplying limits as a function of groundwater age.

Analysis of past climates

Paleocoastlines and paleotopography were reconstructed from local studies of the Armorican basement and from eustatic sea-level fluctuations. Three major transgressions were identified, the oldest being Zanclean (~4.5Ma) with sea level +90m asl, the second Piacenzian (~3Ma) with sea level +60m asl and the most recent Gelasian (~2Ma) with sea level +30m asl. Zanclean and Piacenzian paleocoastlines are distributed around the three domains of higher elevation. The paleocoastline of the last Gelasian transgression is distributed along the current coastline and slightly inland. Only three zones present chloride concentrations below 40mg/L. These correspond to the three domains of higher elevation above 200m and to the area above the higher Zanclean paleocoastline altitude of +90m asl. Thus, the distribution of chloride concentrations is in good agreement with the paleocoastlines. The well network investigated covers the whole Armorican basement and includes more than 1800 drillings with an average depth of approximately 40m. Chemical records, such as chloride or nitrate concentrations, are available for each drilling. 12 sites presenting moderately saline fluids were subjected to further geochemical analysis. Chemical records, such as chloride or nitrate concentrations, are available for each drilling. We first preprocessed the database of 1874 chloride measurements and removed the “abnormal” values (i.e. non representative of natural conditions). Wells close to a potentially polluted site (industrial estate, garbage dump, mill pond…), wells less than one kilometer from the current coastline and wells for which the variability was too high (standard deviation of Cl concentration higher than 30%) were excluded (716 points, 38% of the total) (Fig. 53).

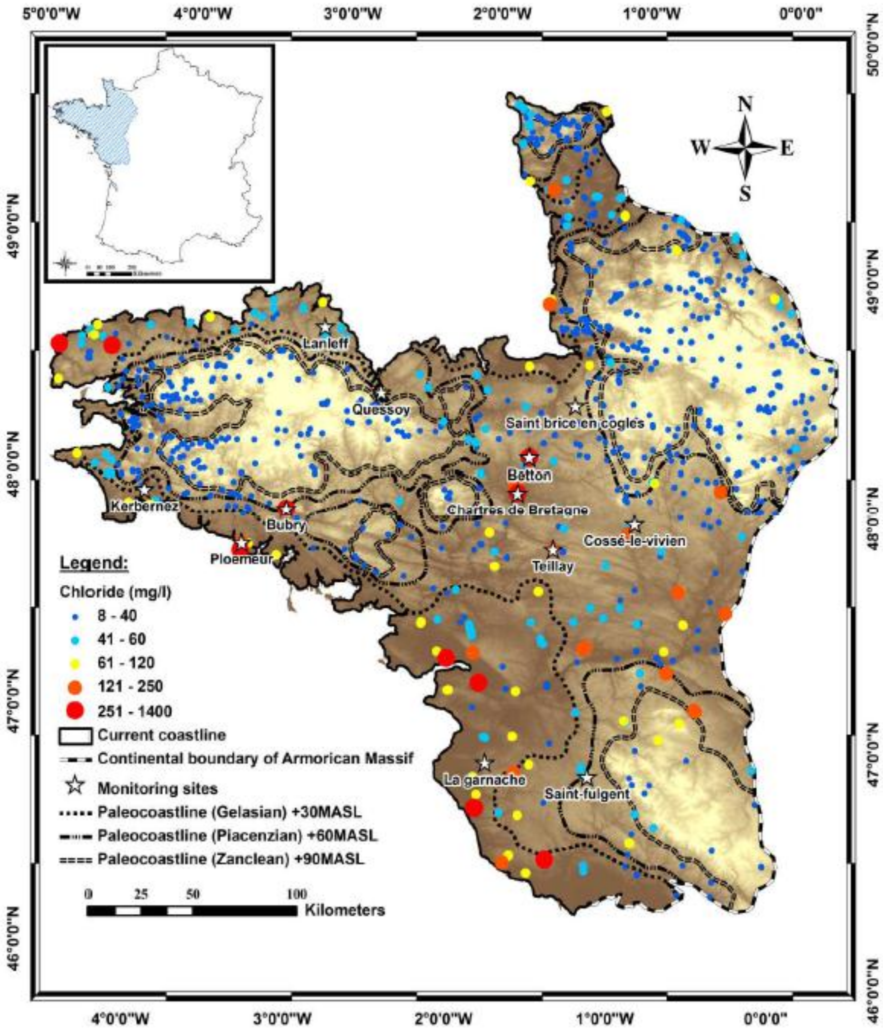


Figure 53 Chloride concentration and paleocoastlines of 3 major transgressions: Zanclean ≈ 4,5Myr, Sea level +90m asl, Piacenzian ≈3Myr, Sea level +60m asl, Gelasian ≈ 2Myr, Sea level +30m asl.

Modelling climate change impacts on groundwater recharge and quality.

In the Brighton area full deterministic modelling of water levels incorporating large scale aquifer heterogeneity was implemented as a commercial project by one of the project partners (Southern Water) during the progress of the CLIMAWAT program. Data from the FLOOD1 and CLIMAWAT programmes of aquifer hydraulic property determination, and from the long term EU-RDF INTERREG funded monitoring under both programs was incorporated into the conceptual model, and used in model validation (see Evidence of Deliverables CD). This work was presented at the CLIMAWAT UK End Users Meeting.

Because of this an alternative approach was used in the Patcham catchment, based on collaborative work with the University of Rennes. The obvious annual periodicity in water level records in the UK suggests the possibility of the application of a periodogram approach to the analysis of effective rainfall and ground water level interactions (e.g. Almedeij & Al-Ruwaih, 2005). However a full spectral analysis approach can represent more complex interactions of magnitude and phase properties provided data of sufficient resolution is available. The records from the Patcham catchment were analysed using both frequency domain and time domain approaches, and the resulting transfer functions used to predict water levels from predicted future rainfall patterns. The use of a frequency domain approach allows the application of transfer functions based on a range of models of aquifer response to rainfall. These include a Linear model (represents the average saturated zone thickness as a function of time by ignoring spatial variation of the water level), a Dupuit model (assumes horizontal flow lines throughout the aquifer and that the slope of the water table represents the hydraulic gradient) and models that can account for the dual permeability behaviour of aquifer like the chalk where this behaviour is having a marked impact on aquifer behaviour.

The input data for this process was taken from site monitoring program. Continuous readings of groundwater level every 15 minute have been taken at North Heath Barn over the whole study period of 7 years. Rainfall and evapotranspiration data were taken from the meteorological monitoring station at North Heath Barn. Where these did not cover the entire monitoring period data from other sources was used, with careful correlation in order to ensure consistency of the data sets. Evapotranspiration was calculated using the Turc method to derive the potential effective rainfall for the period. Account was also taken of the development of a significant water deficit during periods of high evapotranspiration. The results of the frequency domain analysis of the data show a reasonable relationship to a linear reservoir model (Fig. 54) rather than the Dupuit or dual permeability models.

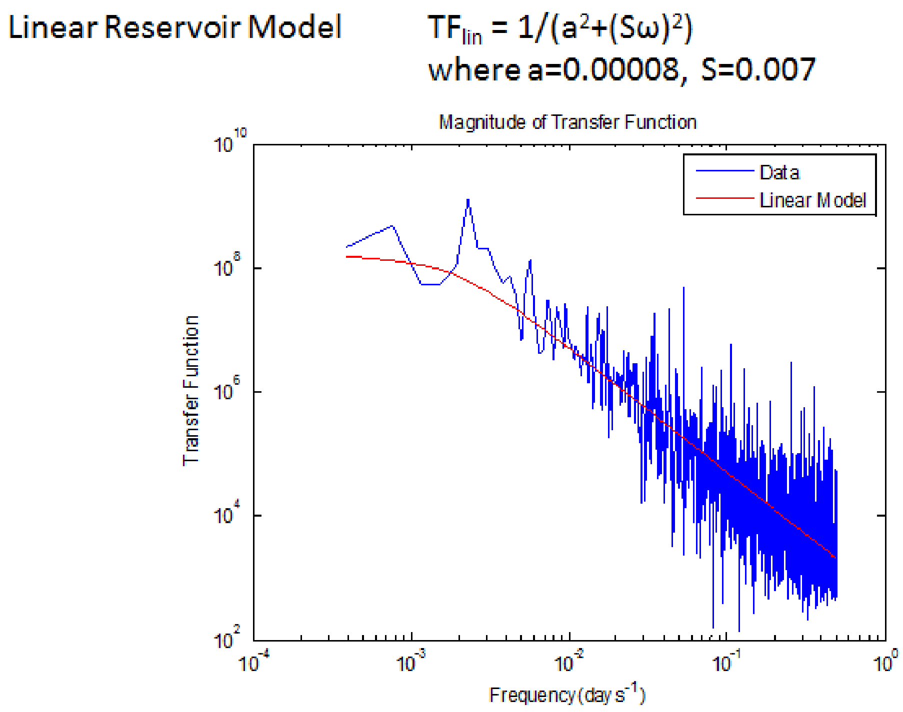


Figure 54 Comparison of frequency domain analysis of the North Heath Barn water level record with the linear aquifer model.

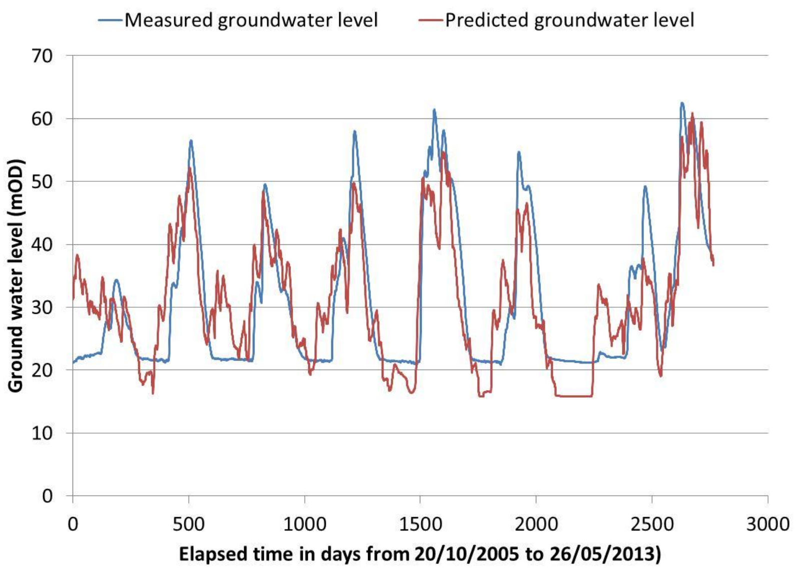


Figure 55 – Comparison of predicted groundwater levels calculated with a frequency domain transfer function using rainfall and evapotranspiration records with the actual groundwater levels at North Heath Barn.

The transfer function resulting from this approach was then applied to the effective precipitation input data in order optimise the analysis, and to test for the applicability of the approach. It can be seen in Figure 55 that the approach reproduces high water levels with a reasonable degree of accuracy. During recession periods water levels are lower than actual, reflecting geological control on the groundwater minimum at North Heath Barn. The transfer function was then applied to predicted rainfall data for future scenarios. The UKCP09 Weather Generator provided statistically equivalent and stationary daily time series at a 5km resolution consistent with the underlying 25 km resolution climate projections. Output data sets from this model were obtained through the University of East Anglia and are the same as those used for process based modelling using HYDRUS 1D. The data sets produced are for one location, one 30-year time period (1960-1990 reference period, 2050 - 2080, 2080-2110), and one UKCP09 green house gas emission scenario (low, medium and high). The analysis included 1000 separate 100 year long self consistent data sets for each scenario amounting to a total of over 100,000 years of daily data (700,000 years of data for all 6 future scenarios plus one control data set). The probability of rainfall exceeding certain daily values from this approach is compared with the current probability in Figure 56.

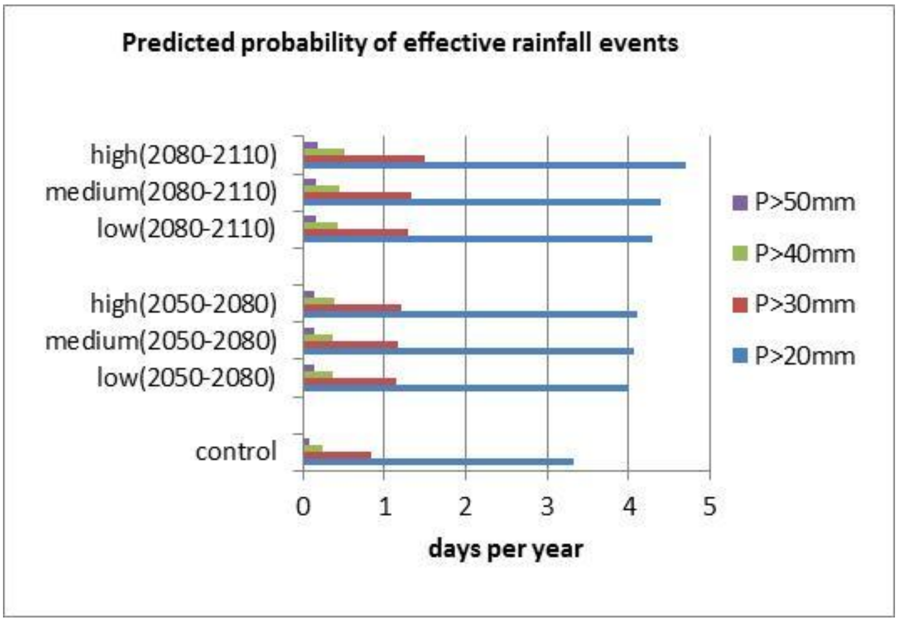


Figure 56 - Summary of effective rainfall exceedence probability Under all emissions scenarios the probability of high intensity rainfall events increases.

A more detailed examination of the average annual effective rainfall distributions indicated that, although total rainfall did not vary much beyond 400-410mm per year, a more progressively significant proportion of the effective rainfall occurred during the months of November, December, January and February (~17% for 2050-2080 and ~25% for 2080-2110) when the aquifer is most likely to be saturated and susceptible to ground water induced flooding.

The predicted ground water level data were converted into probability charts and then were used to calculate the probability of exceedence of a particular level. Inspection of the predicted groundwater level exceedence probability charts enabled a comparison of the increased likelihood of groundwater induced flooding if future predictions are compared to the control period. For both future time periods the higher greenhouse gas emission scenarios lead to a significantly higher probability of groundwater induced flooding and this is more severe for the period 2080-2110. More details on these predictions are available in the report on the Deliverables CD.

Modelling of Future groundwater recharge using HYDRUS 1-D.

In addition to the above frequency domain analysis approach a process based recharge model was applied to the Patcham catchment in order to further assess the impacts of future climate change (Fig. 57). A climate scenario approach based on GCM predictions was extended by combining the GCM ensemble predictions with a physically-based model that uses the Richard's equation, namely the hydrological model HYDRUS-1D (). Daily precipitation and potential evapotranspiration data derived from UKCP09 climate projections for the 2050s and 2080s under low, medium and high gas emissions scenarios which equate to the SRES B1, A1B and A1FI storylines for future gas emissions respectively (IPCC, 2007) were used as an atmospheric forcing for a HYDRUS-1D model of the Chalk unsaturated zone. The same predictions were used for the frequency domain model above.

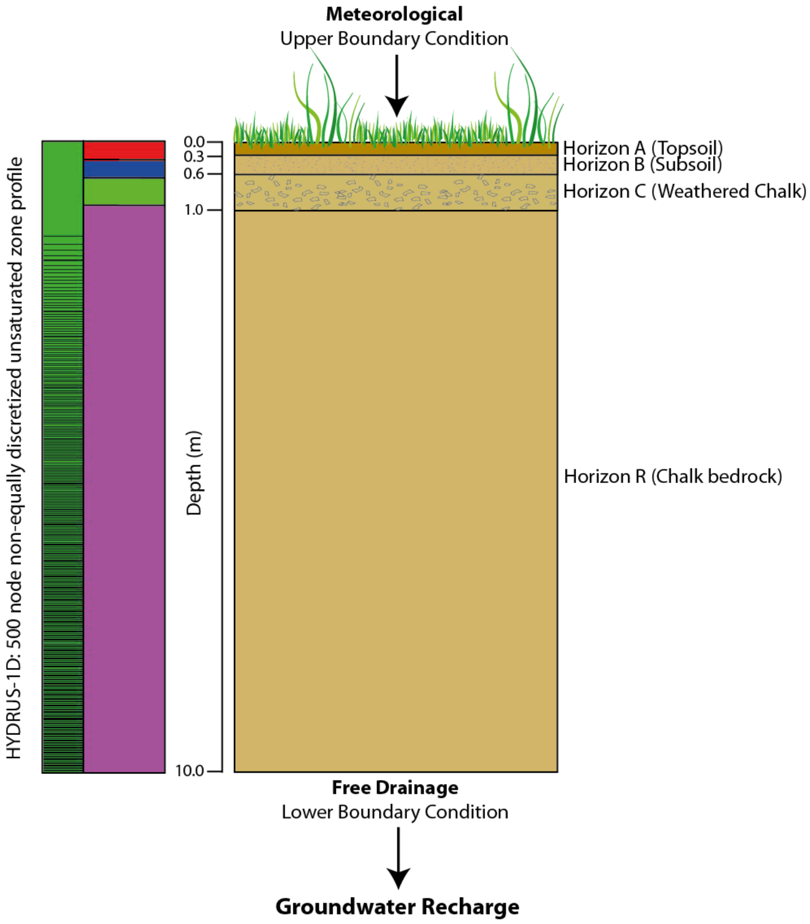


Figure 57 Schematic diagram of the Patcham Chalk unsaturated zone (CUZ) profile implemented in HYDRUS-1D. The column was non-equally discretized with 500 nodes (green lines), with finer discretization towards the upper horizons.

Validation of the HYDRUS-1D model utilised historical daily meteorological data from weather stations situated within or close to the Patcham catchment for a baseline period of 1961-1991. These data were obtained from the British Atmospheric Data Centre (BADC) Met Office Integrated Data Archive System (MIDAS) for land surface observations. The 31-year baseline period (1961-1991) simulation using measured climatic data from the Patcham catchment and surrounding areas resulted in a mean annual groundwater recharge value of 412 mm $year^{-1}$, with a minimum of 319 mm $year^{-1}$ in 1973 and a maximum of 445 mm $year^{-1}$ in 1987.

Groundwater recharge was modelled for low, medium and high gas emissions scenarios that equate to the SRES B1, A1B and A1FI storylines for future emissions respectively (IPCC, 2007). Future time periods of the 2050s and 2080s were selected for analysis and each 100-year hydrological simulation was run for 1000 realisations to provide representative future groundwater recharge for the given decade under the prescribed gas emissions scenario. From the 1000 realisations of each gas emissions scenario for the 2050s and 2080s, the arithmetic mean, standard deviation, as well as minimum and maximum groundwater recharge values were calculated. The results of the HYDRUS-1D simulations using UKCP09 probabilistic climate data showed that under a high gas emissions scenario, groundwater recharge for the Patcham Chalk aquifer would be reduced by 8.1% during the 2080s. Under a low gas emissions scenario recharge would be decreased by 5.3% by the 2050s but would not decrease significantly further by the 2080s, maintaining a 5.4% decrease in recharge to the Chalk aquifer under a low gas emissions scenario (Fig. 58, 59). Hence these results suggest that reducing gas emissions now would help prevent a cumulative decrease in groundwater recharge and thus mitigate the impact of climate change on groundwater resources in South East England. A particular challenge will be the need for policy makers, regulators and water resource managers to respond to the challenge of more persistent drought events of 3-6 years in a representative 100-year period becoming a possible feature in the 2050s and 2080s under both medium and high gas emissions scenarios.

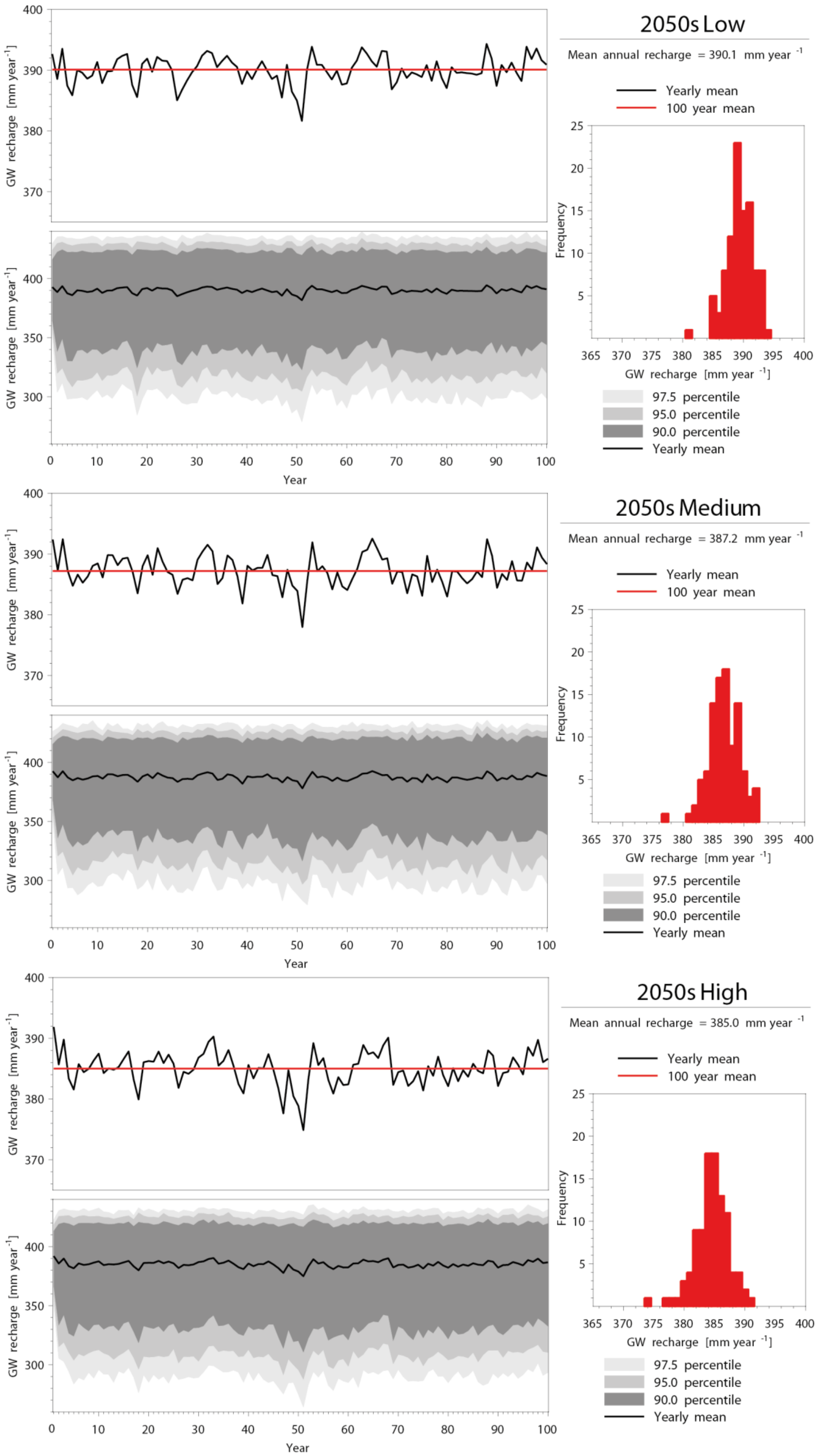


Figure 58 Annual and 100-year mean groundwater recharge [mm year^{-1}] for the Patcham catchment for the 2050s baseline, under a low, medium and high gas emissions scenario.

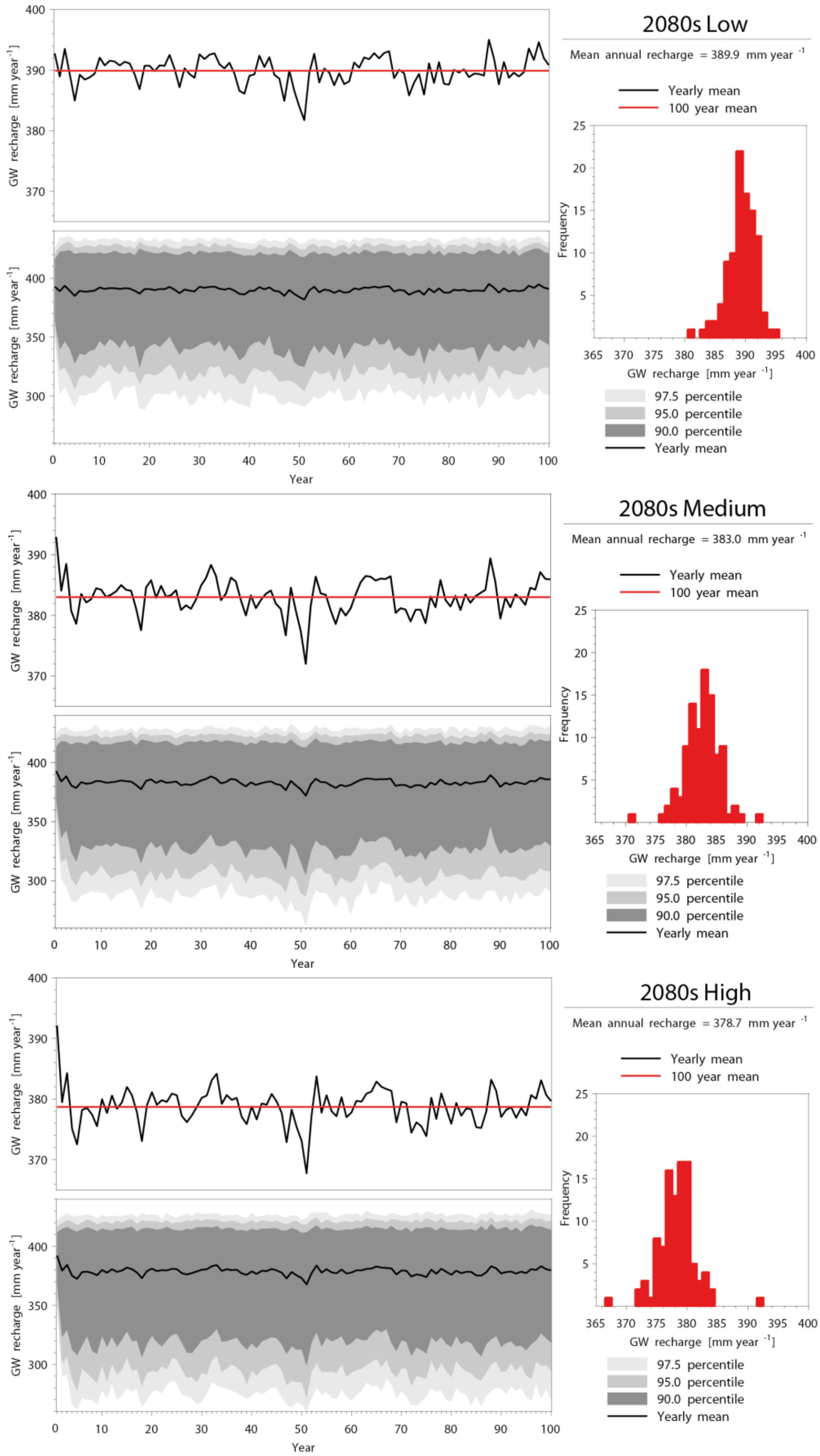
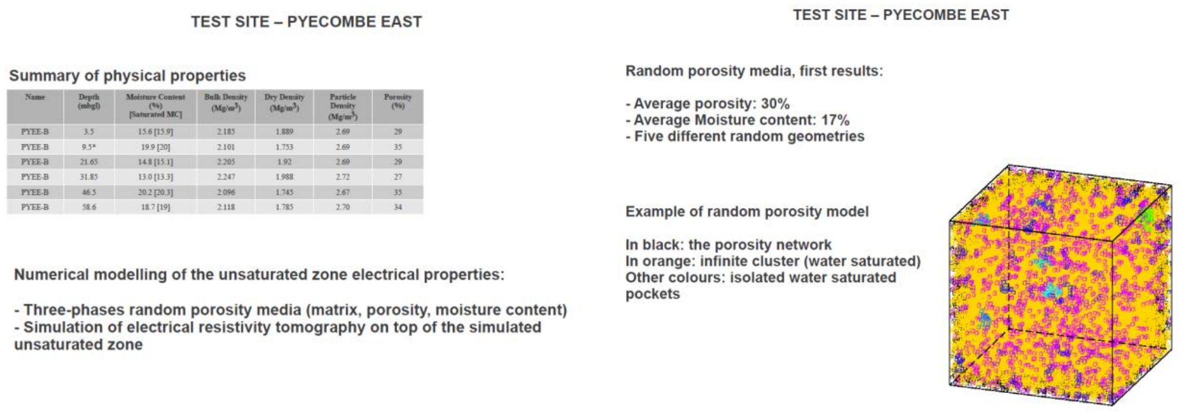


Figure 59 Annual and 100-year mean groundwater recharge [mm year-1] for the Patcham catchment for the 2080s baseline, under a low, medium and high gas emissions scenario.

Modelling and Geophysical Properties of 3-phase system.

The Brest team were given the hydrological data of the Brighton sites in the fall 2010 and they have studied with the Rennes team the available data for the Ploemeur site. Synthetic models have been produced to study the effect of saturation or moisture content in the undersaturated zone on geophysical data of the type acquired in the field (Figure 60).



Name	Depth (mbgl)	Moisture Content (%) [Saturated MC]	Bulk Density (Mg/m^3)	Dry Density (Mg/m^3)	Particle Density (Mg/m^3)	Porosity (%)
PYEE-B	3.5	15.6 [15.9]	2.185	1.889	2.69	29
PYEE-B	9.5*	19.9 [20]	2.101	1.753	2.69	35
PYEE-B	21.65	14.8 [15.1]	2.205	1.92	2.69	29
PYEE-B	31.85	13.0 [13.3]	2.247	1.988	2.72	27
PYEE-B	46.5	20.2 [20.3]	2.096	1.745	2.67	35
PYEE-B	58.6	18.7 [19]	2.118	1.785	2.70	34

Figure 60 - ***Conversion of hydrological data into electrical resisitivity model. The conversion is based on a model verifying the percolation laws.***

Figure 61 shows some relationships between resistivity and phases (matrix, water clay).

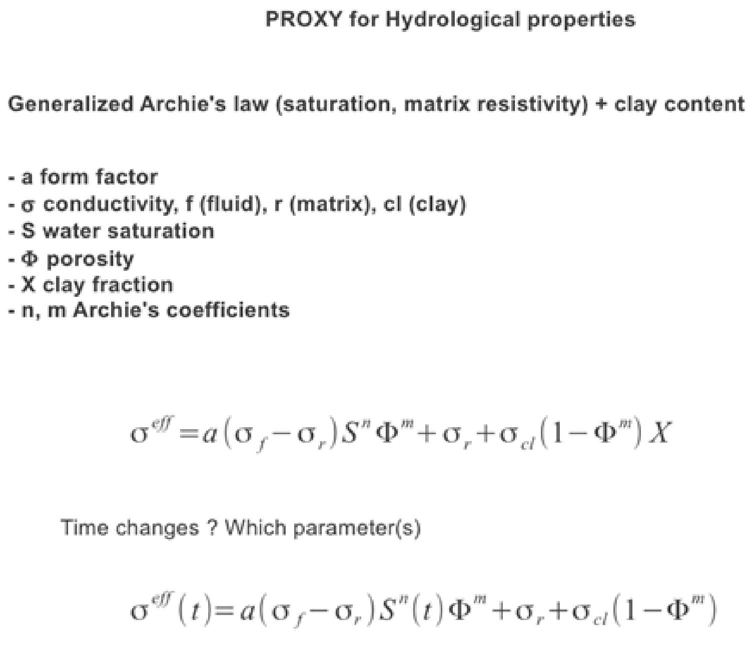


Figure 61 ***Generalized Archie's law***

Using this relationship and results from the data analysis between the 2011 and 2012 sections (see above), some estimate of the saturation may be obtained (Figure 62):

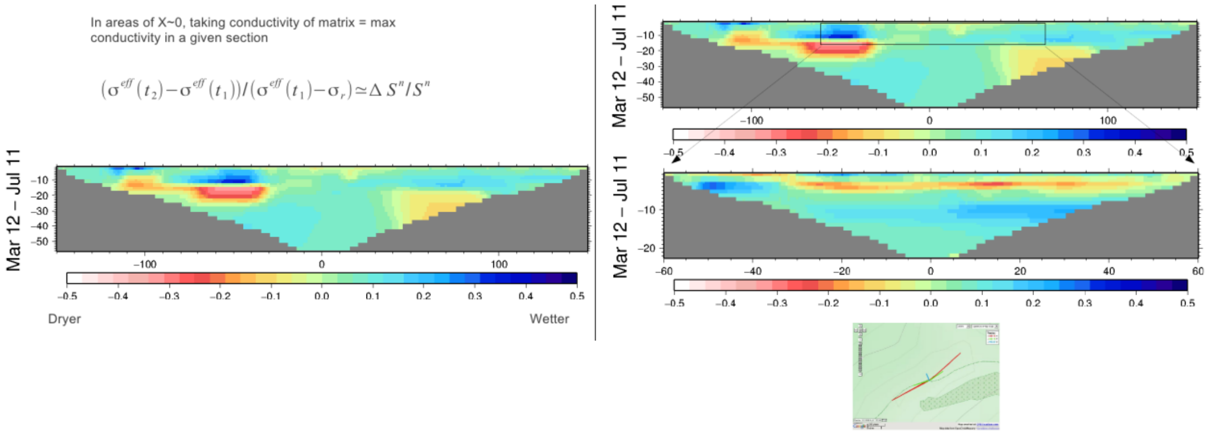


Figure 62 *Calculation of the variation in saturation from observed variation sin resisitivity at Pyecombe.*

The technique was applied to all data and models of saturation versus time were obtained. This work formed the basis of an MSc thesis (Le Texier, Lena, Etude des processus d'infiltration de la zone vadose à partir de l'imagerie géophysique: projet CLIMAWAT, master 1, 2013, Brest).

Modelling of climate change impacts on groundwater in Brittany.

The distribution of groundwater fluxes in aquifers is strongly influenced by topography, and organized between hillslope and regional scales. In order to assess the impact of climate change on groundwater resources, we investigated the compartmentalization of aquifers at the regional scale, and the partitioning of recharge between shallow/local and deep/regional groundwater transfers. A finite difference flow model was implemented (Fig. 63a) and the flow structure was analyzed as a function of recharge (from 20 to 500 mm/yr), at the regional-scale (1400 km2), in 3-dimensions, and accounting for variable groundwater discharge zones; aspects which are usually not considered simultaneously in previous studies. The model allows visualizing 3D circulations, as those provided by Tothian models in 2D, and shows local and regional transfers, with 3D effects (Fig. 63b). The PDF of transit times clearly show two different parts, interpreted using a two compartment model, and related to regional groundwater transfers and local groundwater transfers. The importance of each process is strongly influenced by the total recharge rate and the spatial distribution of discharge zones, which control the length of groundwater pathways. Results show that, while the absolute recharge rate feeding the 'regional' compartment decreases with total recharge, the proportion of total recharge feeding this compartment increase. The volume associated to the regional compartment is calculated from the exponential part of the two-compartment model, and is nearly insensitive to the total recharge fluctuations. This methodology constitutes an efficient methodology to segregate and quantify local and regional fluxes.

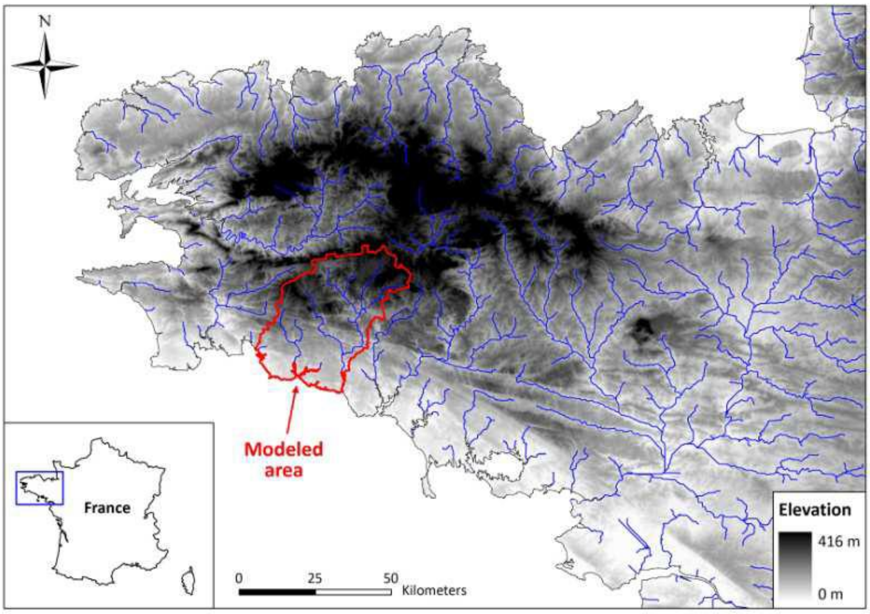


Figure 63a View of the modelled area at the scale of the 'Brittany' region.

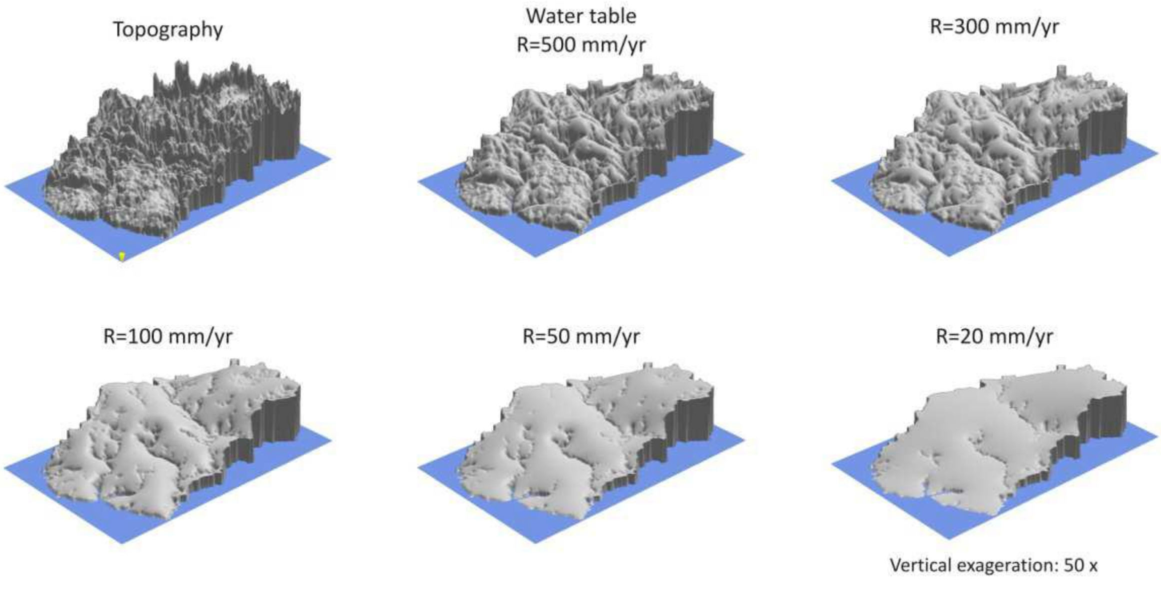


Figure 63b - Evolution of groundwater levels as a function of recharge

In order to obtain a regional assessment of Brittany region groundwater resources and their potential sensitivity to climate change, a series of investigations were undertaken on different sites at regional scale. In particular, the Saint Brice en Cogles site corresponds to a deep crystalline aquifer situated at about 55km north east of Rennes. It is located in a similar geological setting as the Ploemeur site but in a different geographic and climatic context. Thus, it allows obtaining complementary data for assessing recharge mechanisms and climate change effect, and it provides a better representativeness of hydrogeology at regional scale. These data will be included into the modeling approach to characterize and quantify, at the regional scale, groundwater circulations in deep and shallow aquifers, in function of recharge conditions, topography, and surface - subsurface interactions.

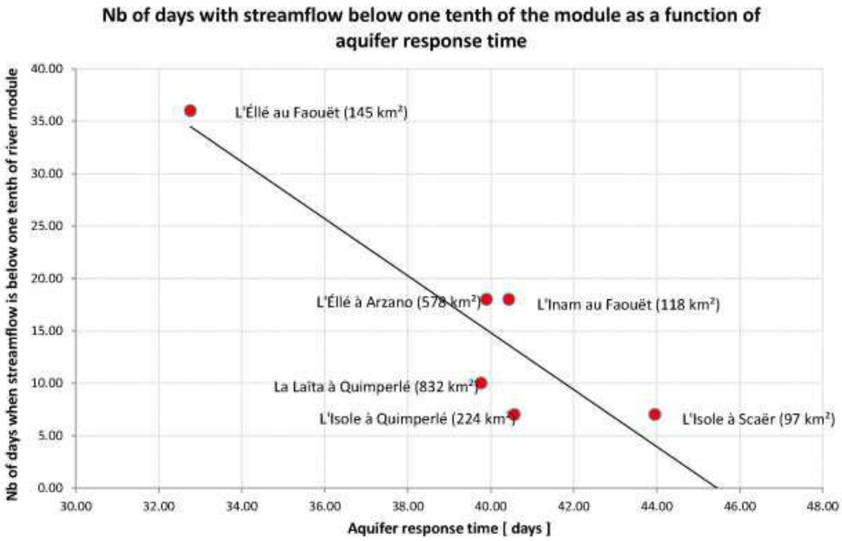


Figure 64 - Number of days a year when streamflow is 10 times smaller than river module.

The Brittany region has created a working group focusing on minimum river streamflow ensuring sufficient water quality and quantity for biological life, with a specific focus on crystalline context. This working group is called CRESEB (Centre de Ressources et d'Expertise Scientifique sur l'Eau de Bretagne, http://www.creseb.fr/) and gathers stakeholders, water management associations, state experts and researchers. CNRS is supporting the working group with the estimation of mass balance at watershed scale and river discharge considering both impacts of water management and climate change to water quality and ecological/biological preservation issues. Ecological risks are maximal when river discharge is minimal, i.e. during dry periods, when river discharge is reduced to aquifer discharge, or baseflow. Knowledge of aquifer characteristics is here of prior importance. Figure 64 shows the number of days a year when streamflow is 10 times smaller than river module, a critical stage. It is compared to aquifer response time, which underlines how long an aquifer might release water with no new water influx (precipitation). Physically, it is directly related to aquifer size, porosity and transmissivity. In an homogeneous context, aquifer response time is essentially controlled by its size, because of the ability of large watershed to catch deep water circulation, on contrary to smaller watersheds. In Brittany, small watersheds (Isole river in Scaer, 97 km2) might have response time around 40 days, ensuring sufficient water storage and release during dry periods, similar to large watersheds (Laita river in Quimperle, 832 km2). This underlines the direct impact of the highly heterogeneous hydrogeological context. Local discharge of deep groundwater system might also be suspected. Three basins have been selected for pilot studies, ranging from natural (Odet watershed), lightly anthropized (Elle, Isole Laita watershed) to heavily antrhopized (Rance watershed).

Effluent dispersal site design considerations.

The results from the core experiments indicate that nitrate is behaving as a non-sorbing solute when it migrates through the chalk matrix. Under certain conditions it is reported in the literature that denitrifcation can occur in both the unsaturated and saturated zone, when there are the presence of denitrifying bacteria and suitable electron donors (Buss et al., 2005; Rivett et al., 2007). Denitrification by microbial action can only occur where there are sufficient openings (fractures/ fissures) in the chalk to allow microbial colonisation to occur. As the laboratory experiments used solid chalk cores only, the small size of the chalk pores and pore throat openings, which are less than that of bacteria, would have prevented the colonisation of the core sample so that no microbial denitrification would have been possible. Phosphate is initially total removal phase and partially removed after a certain period of discharge which is dependent on flow rate and phosphate concentration.

When considering the suitability of using treated wastewater as a source for ASR and discharging treated effluent to ground in unconfined chalk catchments, there is the potential for nitrate and phosphate present in the treated effluent to reach the groundwater body, which presents a potential pollution risk. Assuming matrix flow is the only transport mechanism present through the chalk unsaturated zone (Fig. 65A), it is possible to estimate the period of discharge before nitrate and phosphate reach the unsaturated zone (Fig. 66A). The nitrate core experiments have shown that little dispersion is occurring at the front of the nitrate plume and that the main transport mechanism is advection. From this it can be assumed that nitrate is moving at the same rate as the downward migration of the dispersed effluent. For phosphate a total removal phase exists, which will result in certain number of pore volumes of total removal before any phosphate is expected to be seen at the bottom of the unsaturated zone/groundwater body. The hydraulic loading rate (HLR) of the effluent dispersal site is the volume of dispersed effluent disposed of per day (m^3/d) divided by the area (m^2) in which it is dispersed over to give the HLR in m/d. A range of design and operational hydraulic loading rates are referenced in existing literature and these were used in preparing the transport time diagrams.

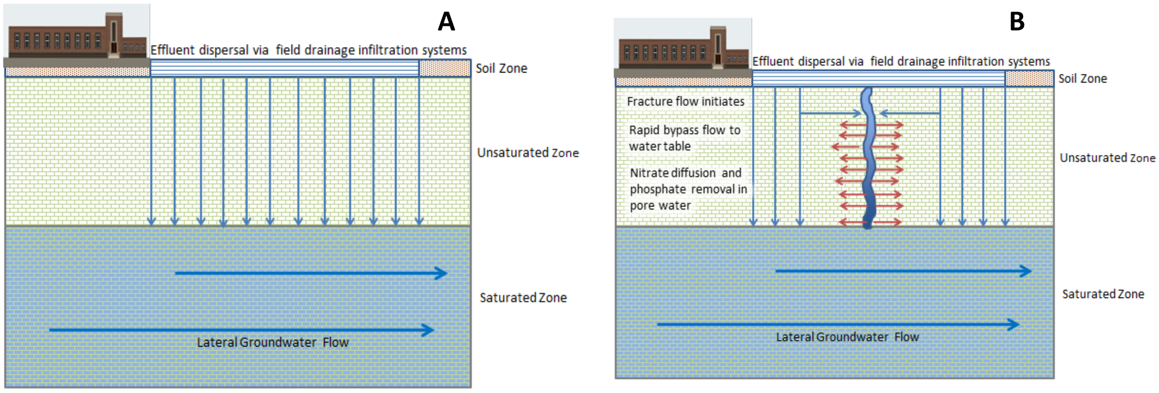


Figure 5 – (A) Conceptual model for unsaturated zone matrix only flow from a waste water treatment works. (B) Conceptual model for unsaturated zone matrix and fracture from a waste water treatment works.

Figure 66A shows that there is an estimated range of between 0.1 and 5 years of discharge periods before nitrate is likely to reach the unsaturated zone with the range of unsaturated zone thicknesses (5-40m) and HLR's (0.0017-0.2m/d). Figure 66B shows the periods of discharge before phosphate is likely to reach the groundwater table assuming flow is through the matrix only. The periods of discharge can be seen to be substantially longer than that for nitrate, which reflects the total phosphate removal phase that occurs when the effluent is initially discharged to the chalk matrix.

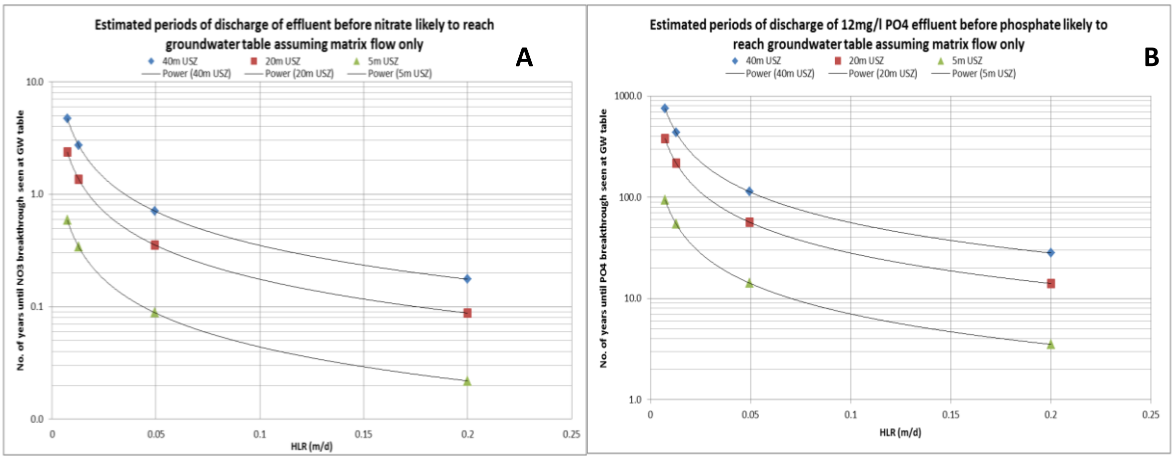


Figure 66 – Results of calculations of discharge period before effluent derived phosphate reaches the water table.

These estimates are based on the migration of treated effluent through the chalk matrix only and assume that no fracture or bypass flow occurs. It is likely that fissure flow will initiate if the recharge rate is greater than the hydraulic conductivity of the chalk matrix (Price et al., 1993; Fig. 66B). The measured hydraulic conductivities for the chalk matrix range 1 – 5 x10^{-3} m/d (Price et al., 1993) and as the HLR's range 0.007-0.2m/d it is likely that fracture flow will initiate, especially during periods of rainfall. When fracture flow initiates there will be bypass flow of the effluent containing nitrate and phosphate to the groundwater table. Once the nitrate and phosphate present in the treated wastewater has reached the saturated zone, it is predicted that mixing with fresher groundwater will result in both dilution and dispersion in the direction of the groundwater flow. Whilst it is expected that nitrate will behave as a non-sorbing solute with little reduction occurring in the saturated zone apart from in certain circumstances when there is the presence of denitrifying bacteria and suitable electron donors (Buss et al., 2005; and Rivett et al., 2007) phosphate will be readily removed by the chalk matrix. Overall, phosphate has the potential to mineralised out of the system by interaction with the aquifer skeleton, whilst nitrate is likely to be dispersed and diluted below the water table, and in favourable circumstances may be removed by denitrifying bacteria.

2.5 Work Package 4 – Dissemination and Communication

A bilingual website was established early in the project, and will currently remain as a publically available site for a further 2 years (http://www.climawat.info). The site includes basic information on the project, advertises the support of the EU-RDF and gives information on the partner organisations. The site also has a password protected partners section, which includes monitoring data from the project, and the presentations from each of the project progress meetings. This area is accessible to all partners, the supporting organisations and the INTERREG office and audiors. In additional the programme and all presentations from the UK End Users meeting are available on the site, as are the information leaflets disseminated at the French End Users meeting. The UK site also includes a publically accessible GIS site for communicating some of the results of the project. The French site includes a link to the H+ data base site. This is the site of the French National Hydrogeological Network (hpus.ore.fr) which includes the Ploemur site, and the data and results acquired during the CLIMAWAT project are represented on the website of the network.

Progress meetings have taken place throughout the project with attendance by representatives of supporting and other end user organisations. A UK end users meeting was organised on the 17th September 2013, and was attended by 42 delegates including representatives of UK water companies (Southern Water; South East Water; Thames Water; Anglian Water), the UK Environment Agency, consultancy companies (Tapajos Ltd; Affinity Water; AMEC; Atkins Global) and the general public (University of Brighton students; Patcham & Hollingbury Conservation Association). The French Enduser meeting took place during the "Carrefour des Gestions Locales de l'Eau" which is a sort of trade fair dedicated to water. It was held on the 29th and 30th of January in Rennes and had ~8,000 visitors. The CLIMAWAT project held a stand with the association Eco-Origin (Chamber of Commerce and Industry of Brittany) which represents the administration, schools and firms acting in eco-technology. During this meeting the visiting people included the stakeholders, company engineers interested in water management and treatment. Leaflets presenting CLIMAWAT and its principal outcomes were distributed as well as flyers on particular techniques or results. These are available on the evidence of deliverables CD.

Conference presentations have taken place throughout the project. These include:

French International Association of Hydrogeologists	Oral Presentation L. Aquilina	25th May 2010
Goldschmidt Conference in Knoxville, Tenesse, USA	Poster and oral presentation, Rennes Team	13-18th June 2010
7th Annual International Symposium on Managed Aquifer Recharge (ISMAR 7)	Poster presentation P. Tarits.	7-9th October 2010
Festival des Sciences, Rennes	Conference session T. Le Bourgne; O. Bour	19th October 2010
European Geosciences Union	3 Poster presentations R. Phillips, Rennes Team	5th April 2011
What's New in Hydrogeology?	Poster presentation L. Gumm	4th July 2011
American Geophysical Union	10 Poster presentations	5-9th December 2011

	Rennes Team	
European Geosciences Union	5 Poster presentations Rennes Team, R. Phillips	22-27th April 2012
Geological Society of London Water Futures	Oral Presentation M. Smith	6-7th March 2012
American Geophysical Union	3 Poster presentations Rennes Team	9-13th December 2012
European Geosciences Union	2 Poster presentations Rennes Team	2013
American Geophysical Union	9 Poster presentations Rennes Team	2013

A number of peer reviewed Journal Articles have already been published. These include:

Characterizing groundwater flow and heat transport in fractured rock using fiber-optic distributed temperature sensing	T. Read, O. Bour, V. Bense, T. Le Borgne, P. Goderniaux, M.V. Klepikova, R. Hochreutener, N. Lavenant, and V. Boschero	GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 1–5
Numerical modeling of the productivity of vertical to shallowly dipping fractured zones in crystalline rocks	S. Leray, J.-R. de Dreuzy, O. Bou, E. Bresciani	Journal of Hydrology 481 (2013) 64–75
Reaction chain modelling of denitrification reactions during a push–pull test	A. Boisson, P. de Anna, O. Bour, T. Le Borgne, T. Labasque, L. Aquilina	Journal of Contaminant Hydrology 148 (2013) 1–11
New understanding of deep unsaturated zone controls on recharge in the Chalk: a case study near Patcham, SE England	H. K. Rutter, J. D. Cooper, D. Pope & M. Smith	Quarterly Journal of Engineering Geology and Hydrogeology 2012, v.45; p487-495
A methodology for using borehole temperature-depth profiles under ambient, single and cross-borehole pumping conditions to estimate fracture hydraulic properties	Maria V. Klepikova , Tanguy Le Borgne, Olivier Bour, Philippe Davy	Journal of Hydrology 407 (2011) 145–152
Nitrate dynamics in agricultural catchments deduced from groundwater dating and long-term nitrate monitoring in surface- and groundwaters	L. Aquilina, V. Vergnaud-Ayraud, T. Labasque, O. Bour, J. Molénat, L. Ruiz, V. de Montety, J. De Ridder, C. Roques, L. Longuevergne	Science of the Total Environment 435–436 (2012) 167–178
Temporal evolution of age data under transient pumping conditions	S. Leray, J.-R. de Dreuzy, L. Aquilina, V. Vergnaud-Ayraud, T. Labasque, O. Bour, T. Le Borgne	Journal of Hydrology 511 (2014) 555–566
Hydrological behavior of a deep sub-vertical fault in crystalline basement and relationships with surrounding reservoirs	C. Roques, O. Bour, L. Aquilina, B. Dewandel, S. Leray, JM. Schroetter , L. Longuevergne, T. Le Borgne, R. Hochreutener, T. Labasque, N. Lavenant, V. Vergnaud-Ayraud, B. Mougin	Journal of Hydrology 509 (2014) 42–54
Investigating the respective impacts of groundwater exploitation	Antoine Armandine Les Landes, Luc Aquilina, Jo De Ridder, Laurent Longuevergne,	Journal of Hydrology 509 (2014) 367–378

and climate change on wetland extension over 150 years	Christian Pagé, Pascal Goderniaux	
Conditioning of stochastic 3-D fracture networks to hydrological and geophysical data	Caroline Dorn, Niklas Linde, Tanguy Le Borgne, Olivier Bour, Jean-Raynald de Dreuzy	Advances in Water Resources 62 (2013) 79–89
Temporal and spatial scaling of hydraulic response to recharge in fractured aquifers: Insights from a frequency domain analysis	Joaqu_ın Jim_enez-Martınez, Laurent Longuevergne, Tanguy Le Borgne, Philippe Davy, Anna Russian, and Olivier Bour	WATER RESOURCES RESEARCH, VOL. 49, 1–17, doi:10.1002/wrcr.20260, 2013
Inverse modeling of flow tomography experiments in fractured media	Maria V. Klepikova,Tanguy Le Borgne, Olivier Bour,and Jean-Raynald de Dreuzy	WATER RESOURCES RESEARCH, VOL. 49, 1–11, doi:10.1002/2013WR013722, 2013

This report will also be made available via the public website.

3. Achievements of Deliverables and related indices

The deliverables for each work package and the evidence of achievement are listed in the Appendix. All major deliverables have been met. The documentary evidence of each deliverable has been provided on the accompanying CD, and individual items will be linked to the project website as and when they have undergone peer review and been published. The only deliverable not listed in the Appendix is that pertaining to Cross Border exchange. The deliverables under this heading in the original project proposal are given as:

Stage 1 (0-6 months)
University of Brest will carry out about 15 days field work at the Patcham site, UK; five members of staff (3 academic staff, 1 Postdoc and 1 training student)
University of Brighton will carry out about 7 days field work at the Ploemeur site, France; five members of staff (4 academic staff and 1 research assistant)
University of Rennes 1 and CNRS will carry out about 7 days field work at the Patcham site, UK; four members of staff (2 academic staff, 1 Postdoc and 1 PhD student)
University of East Anglia will carry out about 2 days field work at the Patcham site, UK; two members of staff (1 academic staff and 1 PhD student)
Stage 2 (7-12 months)
University of Brest will carry out about 15 days field work at the Patcham site, UK; five members of staff (3 academic staff,1 Postdoc and 1 training student)
University of Brighton will carry out about 5 days field work at the Ploemeur site, France; four members of staff (3 academic staff and 1 research assistant)
University of Rennes 1 and CNRS will carry out about 7 days field work at the Patcham site, UK; three members of staff (2 academic staff and 1 Postdoc)
University of East Anglia will carry out about 2 days field work at the Ploemeur site, France; two members of staff (1 academic staff and 1 PhD student)
Stage 3 (13-18 months)
University of Brighton will carry out about 3 days field work at the Ploemeur site, France; four members of staff (3 academic staff and 1 research assistant)
University of Rennes 1 and CNRS will carry out about 3 days field work at the Patcham site, UK; two members of staff (1 academic staff, 1 Postdoc)

Stage 4 (19-24 months)
Two members of staff from CNRS (1 academic and 1 postdoc) will perform laboratory training for three days at the University of Brighton)
Stage 5 (24-30 months)
University of Brest will carry out about 15 days field work at the Patcham site, UK; five members of staff (3 academic staff,1 Postdoc and 1 training student)
University of Brighton will carry out about 7 days field work at the Ploemeur site, France; four members of staff (3 academic staff and 1 research assistant)
University of Rennes 1 and CNRS will carry out about 7 days field work at the Patcham site, UK; four members of staff (2 academic staff, 1 Postdoc and 1 PhD student)
University of East Anglia will carry out about 7 days field work at the Ploemeur site, France; two members of staff (1 academic staff and 1 PhD student)

The cross border exchanges achieved are:

Stage 1 (0-6 months)	Date
University of Brest attended 2 day inception meeting at Brighton (2 members of staff).	15/6/2010
University of Rennes/CNRS attended 2 day inception meeting at Brighton (2 members of staff).	15/6/2010
Stage 2 (6-12 months)	
University of Brighton attended 3 day meeting in Rennes, including 1 day field visit (4 members of staff).	21-22 /2/2011
University of East Anglia attended 3 day meeting in Rennes, including 1 day field visit (2 members of staff).	21-22 /2/2011
Stage 3 (12-18months)	
University of Rennes student carried out exchange visit at the University of Brighton for 2 months.	2/5-30-6/2011
University of East Anglia carried out 5 days of field work in the Ploemeur catchment (1 member of staff)	6/2011
University of Brest carried out 5 days of field work in the Patcham catchment (2 members of staff)	7/2011
University of Rennes carried out 5 days field work in the Patcham catchment (3 members of staff).	11-15 /4/2011
Stage 4 (18-24 months)	
Univeristy of Rennes attended 2 day meeting and field visit at the University of East Anglia (5 staff)	17-18 /10/2011
Univeristy of Brest attended 2 day meeting and field visit at the University of East Anglia (3 members of staff)	17-18 /10/2011
Stage 5 (24-30 months)	
University of Brest carried out 5 days of field work in the Patcham catchment (2 members of staff)	25-30/ 3/2012
University of East Anglia carried out 11 days of field work in the Ploemeur catchment (2 members of staff)	27/2-9/3/ 2012
University of Brighton attended 2 day meeting at the Univeristy of Brest (3 staff).	9-10/5 /2012
University of East Anglia attended 2 day meeting at the University of Brest (3 staff).	9-10/5 /2012
Stage 6 (30-36 months)	
University of Brest carried out 3 days field work in the Patcham catchment (3 staff).	27/11-1/12 2012

University of Rennes attended 2 day meeting at the University of Brighton (6 staff).	28-29/11 /2012
University of Brest attended 2 day meeting at the University of Brighton (3 staff).	28-29/11 /2012
Stage 7 (project extension)	
University of East Anglia carried out 6 days of field work in the Ploemeur catchment (2 members of staff)	24-29/06/2013
University of Brighton attended 2 day meeting at the University of Rennes (3 staff)	12-13/6 /2013
University of East Anglia attended 2 day meeting at the Univeristy of Rennes (2 staff)	12-13/6 /2013
University of Rennes attended 1 day UK end users meeting in Brighton (4 staff)	17/9 /2013
University of Brest attended 1 day UK end users meeting in Brighton (2 staff)	17/9/2013

National teams also attended the meetings in their home nations without cross-border exchange. In addition to the physical exchanges noted above close collaboration was needed for:

- Two further campaigns of CFC-SF6 analyses of groundwaters in the Patcham catchment by the University of Rennes. For these campaigns University of Brighton staff were trained in sampling techniques using sample vessels supplied by the University of Rennes.
- Extended collaboration between the University of Rennes and the University of East Anglia over the DTS analysis of fracture hosted flow which has lead to several publications.
- Participation of Joaquin Jimenez-Martinez (Universite de Rennes 1) providing support regarding the frequency domain analysis on the predicted effect of climate change on ground water levels within the chalk aquifer to the north of Brighton, UK, by D.J. Pope (University of Brighton).

The program of cross border exchange did not perfectly follow the original proposal because of changes to staffing during the course of the project, evolution of the work packages (TDEM geophysics was tested and ruled out as ineffective for this program; DTS sensors were introduced as an aspect of the program), and training of staff early on in the program which meant it was more effective for the University of Brighton team to carry out sampling for CFC-SF6 analyses, than for further visits by the University of Rennes team.

4. Difficulties encountered.

Two main difficulties were encountered during the course of the programme. The first was that early on in the programme the project co-ordinator (Dr. Salima Baraka-Lokmane) resigned from her post at the University of Brighton. Dr. Martin Smith took over as project co-ordinator. This required some adjustment of workloads and changes in staff time contributions at the University of Brighton. The second major issue was that the program was initially costed at an exchange rate of EURO1.6 to £1. The actual exchange for the majority of the duration of the program was ~EURO1.1 to £1. This meant that the UK partners budgets were significantly under-spent relative to the original project budget. This was accommodated by changes to the budget within individual partners, and transfer of available budget between UK and French partners.

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Appendix – Mapping of deliverables to evidence.

WP1.1: Quantification of Groundwater Fluxes 2010-04-01 2012-12-31	
Deliverable	**Evidence**

Production of GIS maps and datasets	**1.1.1, 1.1.2**
Presentation ofGeomorphological and geological site maps	**1.1.1, 1.1.2**
Dissemination to all project partners of GISs based on both monitoring sites, incorporating geomorphology, geology and soil/rock mass properties	**1.1.1, 1.1.2, 1.1.3, 1.1.5, 1.1.6, 1.1.9**
Geophysical simulations based on realistic 3D saturated and unsaturated zones of fractured aquifers with time varying physical and chemical conditions	**1.1.5, 1.1.6**
3D geophysical models at the appropriate scale (from mm to metres or more)	**1.1.5, 1.1.6**
Production of hydrodynamic parameters of the chalk and granite aquifers	**1.1.7, 1.1.8, 1.1.11, This report**

Work Package 1.2 Local-Scale and Regional-Scale recharge mechanisms with climate change	
Deliverable	**Evidence**
Report on the interaction of recharge with groundwater quality, and hence models of Changing groundwater quality with changing climatic effects	**1.2.1, 1.2.2,This report**
Publication of guidelines for using the combined measurement of groundwater ages	**1.2.11**
Results of second season monitoring and correlation between flow/recharge	**1.2.2, 1.2.3**
Development of a better understanding of the percolation mechanisms from the unsaturated to saturated zones	**4.1, 4.2, 1.2.4, 1.2.5, 1.2.6, 1.2.7**
Report on detailed correlations between chemistry, precipitation and recharge	**1.2.2, 1.2.10 This report**

Work Package 2.1: Water quality and long-term effects of artificial groundwater recharge using treated waters	
Deliverable	**Evidence**
Agreement and publication of analytical protocols for chemical analyses	**2.1.1**
Report on correlation of changes in water chemistry with climatic conditions and flow processes in the aquifers	**1.2.2, 2.1.4**
Determination of the standard to which treatment is required for the injected sewage water	**2.1.2**
Report on prediction of the long term evolution of groundwater quality, under different water management and climate change scenarios including assessment of the water quality in the long term future (25	**2.1.3, This report**

and 50 years)	

Work Package 2.2 Mobility, distribution and retention of contaminants	
Deliverable	**Evidence**
Report on the mobility and retention mechanisms of fertilisers and micro-organisms on the fracture surfaces of the rock formations (chalk and granite)	**2.1.2, 2.2.1, 2.2.2**
Report on the mobility and retention mechanisms of fertilisers and micro-organisms in the porous network of the rock formations (chalk and granite)	**2.1.2, 1.2.3, 2.2.1, 2.2.2**

Work Package 3 - Risk Assessment and management of groundwater resources	
Deliverable	**Evidence**
Process-based geochemical flow and transport model, which includes detailed structural characterisation of the aquifer using geophysics and geology	**2.1.2, 1.1.10, 3.3, 3.5**
Numerical model which simulates the impact of climate change on groundwater recharge, quantity and quality and validation against physical and chemical data from the other work packages	**3.1, 3.2 , 3.3, 3.4**
Guidelines for aquifer management in response to changing climate and contaminant loadings	**2.1.2, This report**

Work Package 4 – Dissemination and Communication	
Active, bilingual, project website uploaded advertising the project and INTERREG support	**http://www.climawat.info**
Progress summary on public website	**http://www.climawat.info**
Presentation of results at conferences	**4.1-4.5**
Production of reports	**WP1-WP3 above; this report**
Final end users conference UK	**4.6-4.9**
Final end users conference France	**4.10-4.17**
Production of journal papers	**4.18-4.29**