APPENDIX 1

Extended Technical Summary

Background

This report describes the conceptual and numerical development of the Wessex Basin recharge, runoff and groundwater model which was completed in February 2010. The model was extended westward to cover the whole Basin including the catchments of the Dorset Stour, Piddle and Frome from a study area which initially focused on the catchment of the Hampshire Avon where EU Habitats Directive investigation drivers were more urgent (Council of European Communities 1992).

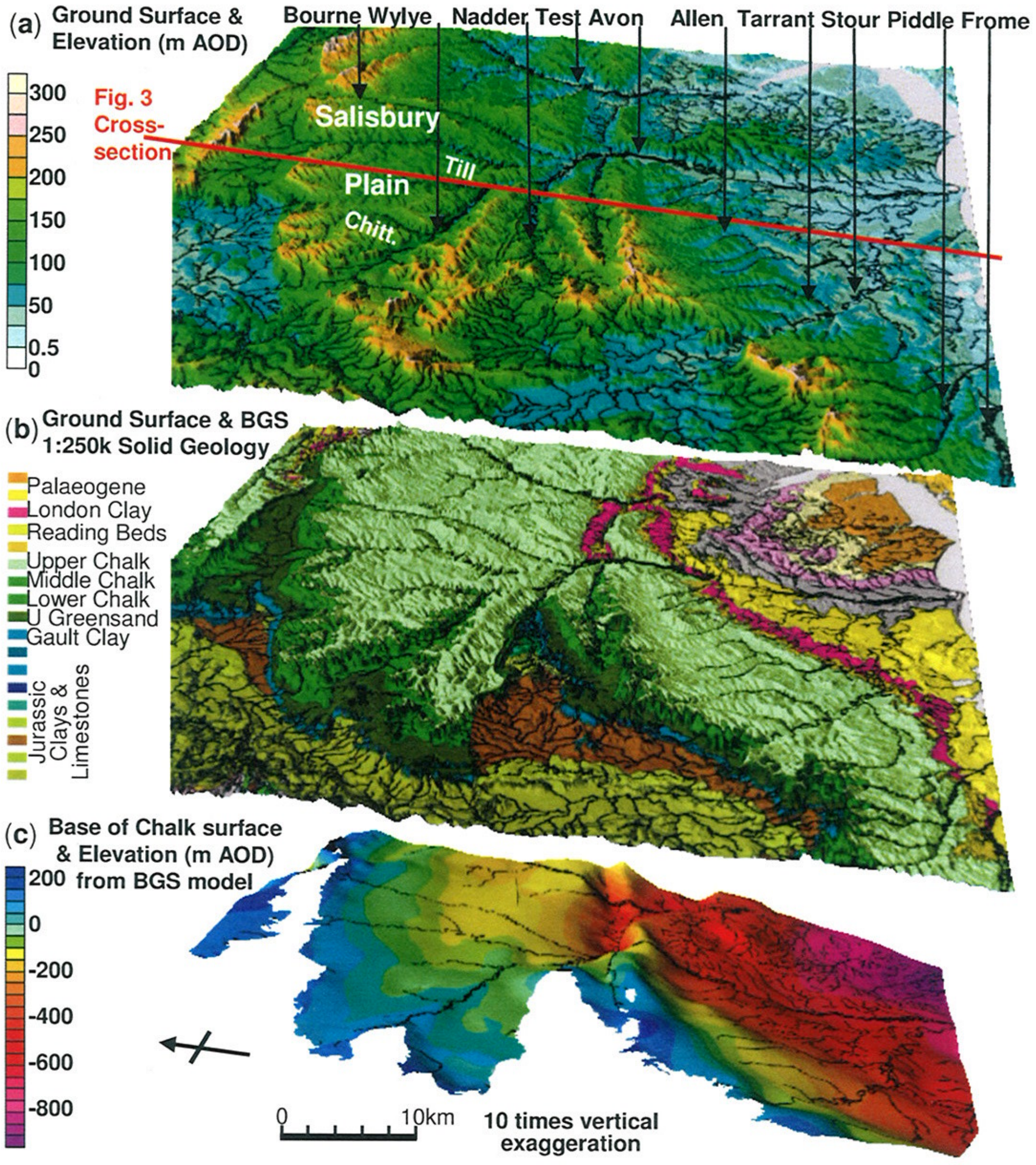
This extended summary provides a standalone illustrated overview of all the main phases of work. It describes the main features of the conceptual understanding of the Chalk aquifer system including the relationships between stratigraphy, topography, groundwater flow and the development of transmissivity – particularly through the secondary dissolution of fissures. Bed parallel fissuring is often most marked above lower permeability marl or hardground horizons. The challenges of translating this understanding into a time variant, gridded numerical model are considered with a brief account of the alternative model designs which were trialled and the subsequent refinement process. After being accepted as 'fit for purpose', subject to caveats which are set out in the main report, the model has been extensively used for predictive scenarios. Examples of the impacts of groundwater abstraction predicted by the model for two public water supply sources are provided towards the end of this summary, before conclusions are pulled together and recommendations for future development are made.

Many of the conceptual and numerical model features discussed here are summarised from Hampshire Avon reports for the Environment Agency (Entec 2005) which, in turn, built on the understanding established in previous modelling studies of three sub-catchments – the Bourne and Nine Mile River (Environment Agency 2004), the Wylye (Komex 2004) and the Lower Avon and Dorset Stour (Water Management Consultants 2004). The model was built by Entec on behalf of the Environment Agency with significant contributions from experienced Agency hydrologists and hydrogeologists. Wessex Water provided active support and technical steer and a representative from Bournemouth and West Hampshire Water was also involved in the initial Hampshire Avon study. Mott MacDonald provided technical review throughout.

This summary has been adapted from two papers (Soley *et al.* 2010a & 2010b) which are going through the process of peer review for inclusion in a Geological Society Special Publication entitled "Regional Groundwater Resource Modelling in the UK: A Case History".

Topography, stratigraphy, structure and saturated aquifer formations

The Wessex Basin model area includes the surface and groundwater catchments drained by the Rivers Frome, Piddle, Dorset Stour, and Hampshire Avon (ES Figs. 1(a)). The topographic form of the dominantly rural landscape (ES Fig. 1(a)) reflects the outcrop (ES Fig. 1(b)) and structure (ES Fig. 1(c)) of



ES Fig. 1. Eastward looking mapped projections, surfaces and drainage of the Wessex Basin model area illustrating the relationships between (**a**) scarp and dip slope topography and the river network; (**b**) the outcrop of the main aquifer formations, and the aquicludes which underlie and confine the groundwater system; and (**c**) the folded and faulted geological structure apparent in the base of the Chalk surface from the BGS geological model.

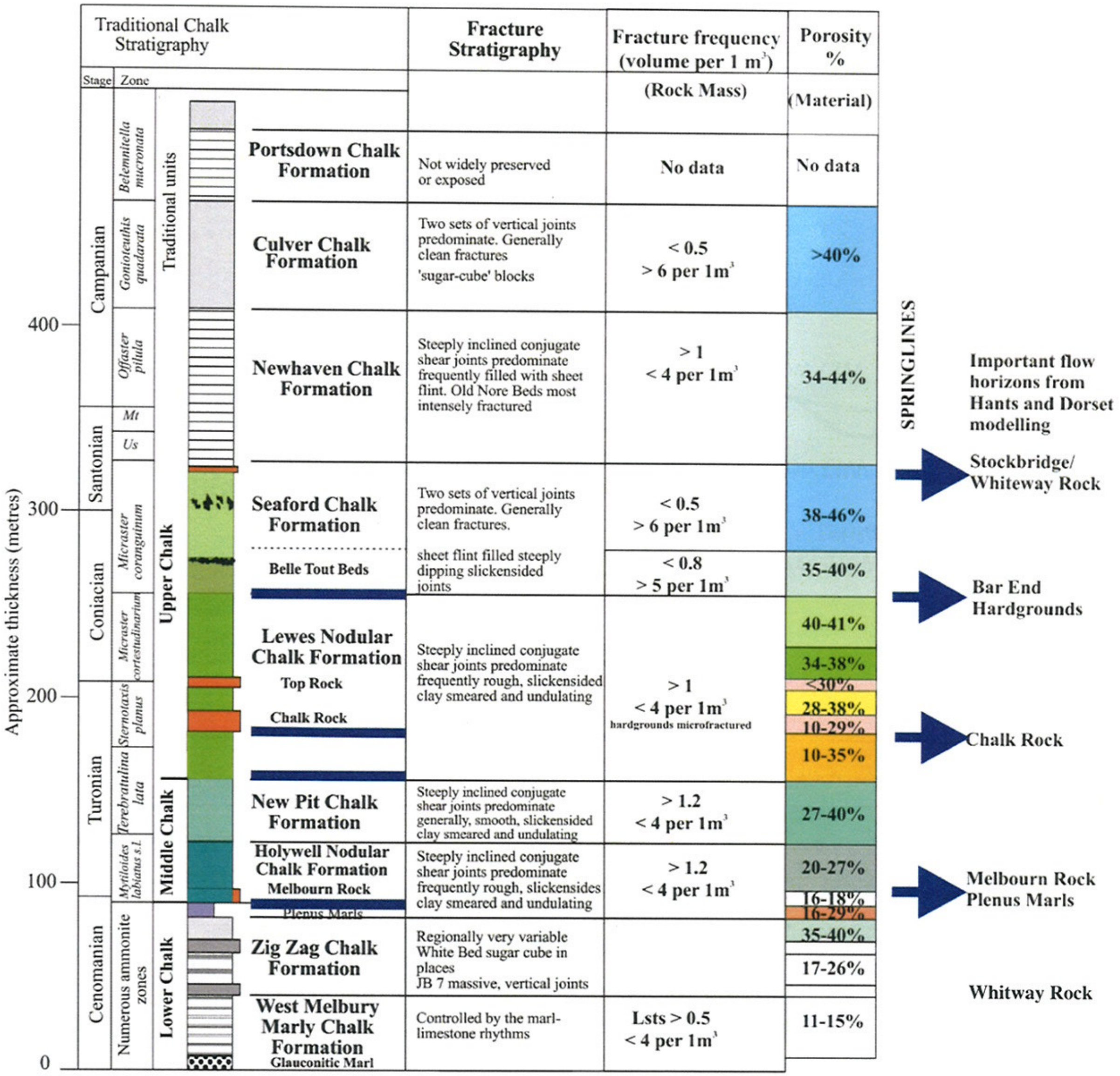
the solid geological formations. Superficial deposits are thin or absent on the interfluves, but include river terrace gravels and alluvium around the main rivers. The principal groundwater system aquifers are the Upper Greensand, Chalk and Reading Beds (now re-named the West Park Farm Member) and these are bounded by the underlying Gault Clay (mapped in blue on ES Fig. 1(b)) and the confining London Clay (mapped in pink).

These strata are gently folded into an open syncline beneath Salisbury Plain which has a shallow eastward plunge (ES Fig. 1(c)). A series of anticlines bring the older Upper Greensand and lower Chalk formations to outcrop beneath the Upper Avon, the Wylye and the Nadder. Much of the upper reaches of the Nadder and the Stour drain the less permeable underlying Jurassic clay and limestone formations. The dip steepens towards the south east beneath the middle reaches of the Avon and the Stour, tributaries of the Stour including the Allen and the Tarrant, and beneath the upper half of the Piddle and Frome catchments. The lower reaches of all these rivers flow over the clay, silt and sand formations of the Palaeogene which support minor shallow groundwater flow systems isolated from the regionally significant underlying aquifers by the London Clay. The base of the Chalk is brought abruptly to the surface again by the Purbeck monocline along the Jurassic Dorset coast - just to the south of the area shown in ES Fig. 1 - where all the Cretaceous formations are present in a narrow vertically dipping outcrop. The new BGS 1:50,000 maps show that, as well as these folds and broad basinal structures, the Chalk is also extensively faulted.

Outcrops of the lower Chalk formations commonly form topographic scarp features, hills or ridges above the more flat lying Upper Greensand valleys (ES Figs. 1(a) and (b)). The drainage network over the Chalk is very sparse in comparison with the Jurassic and Palaeogene catchments, but valleys typically extend well upstream of mapped water courses. These are dry for most of the time, flowing only during winter when groundwater levels rise to overflow into more extensive 'winterbourne' reaches.

A BGS structural model providing a three dimensional interpretation of the elevations of the new stratigraphic formations (ES Fig. 2) was an essential building block of the Wessex Basin conceptualisation. ES Fig. 3 is a north – south cross section through these formations and includes the inferred elevations of three horizons which, in different parts of the Wessex Basin, are associated with significantly enhanced fissure flow into abstraction wells, as well as with locations of river flow loss and spring discharge.

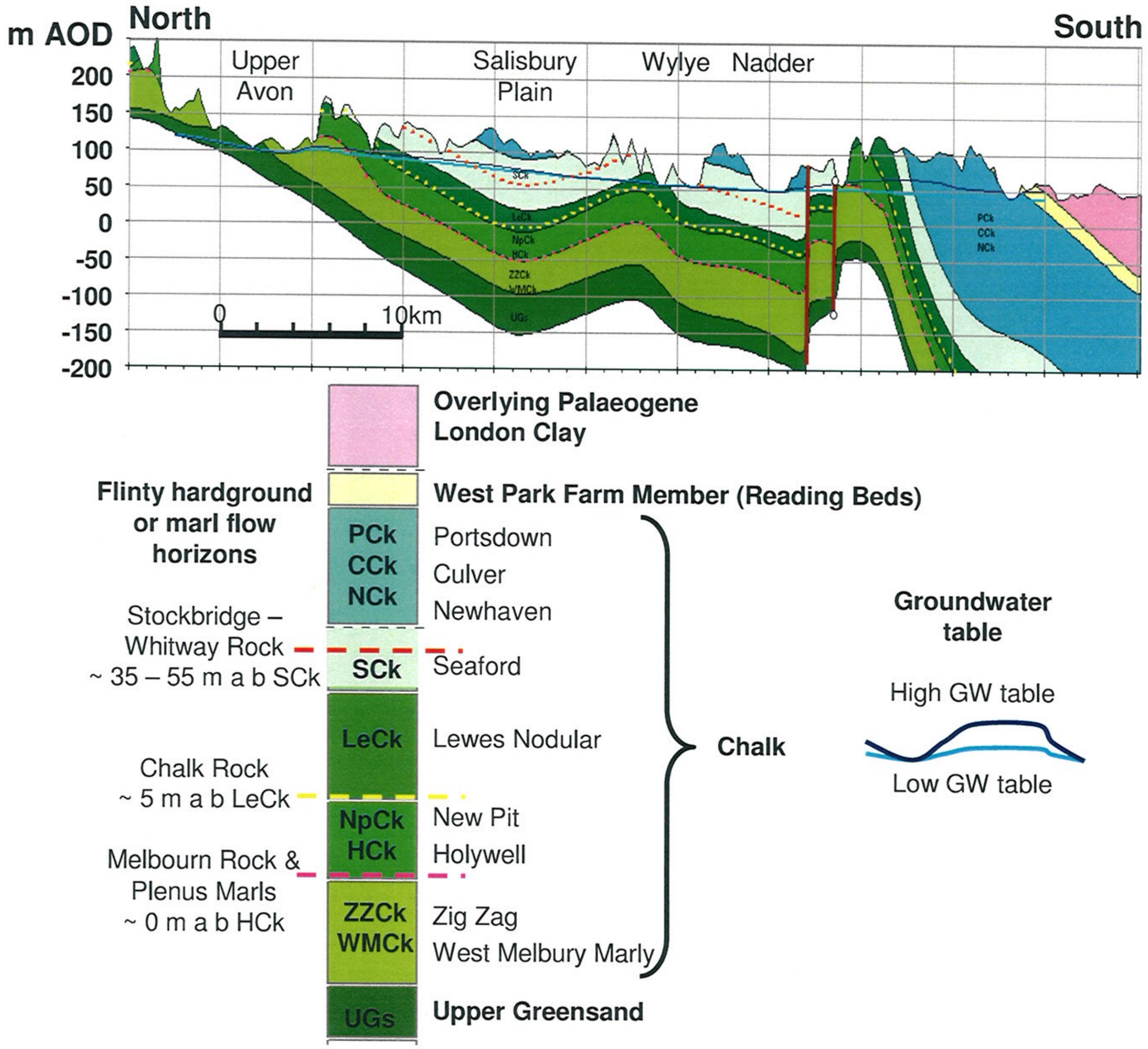
These three horizons are the Melbourn Rock and Plenus Marls at the base of the Holywell Chalk, the Chalk Rock, and the Whitway Rock (which is also called the Stockbridge Rock further east) – as



ES Fig. 2. Chalk lithological and fracture stratigraphy showing some of the key horizons associated with enhanced groundwater fissure flow and spring lines from the Hampshire and Dorset modelling areas.

shown on ES Fig. 2. Other notable zones of preferential permeability development also occur around the top of the Lewes Chalk. It should be emphasised that secondary bed-parallel or fracture related fissure transmissivity may be developed in most parts of the Chalk sequence, depending on the history of active groundwater flow, but the horizons noted are often considered to be particularly important.

Observed groundwater levels were contoured for periods representing minimum (drought) and maximum (wet winter) conditions, and these surfaces are included on ES Fig. 3. It is apparent that the aquifer formations saturated at the groundwater table are often not the same as those mapped at outcrop beneath interfluve areas where unsaturated depths can be over 50 m.

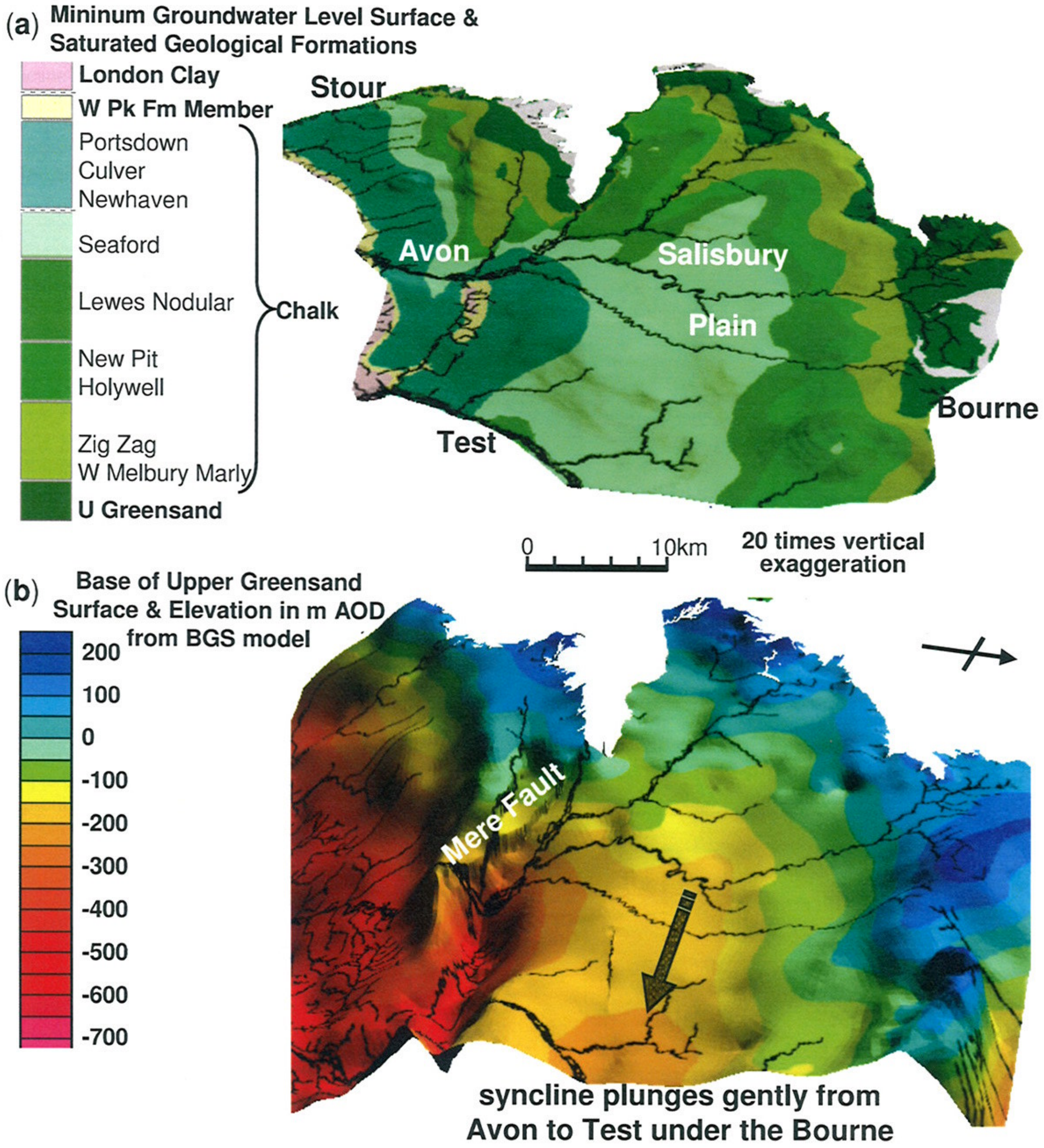


ES Fig. 3. A north – south cross section through the Wessex Basin along a line shown in Fig. 3(a). The folded and faulted new Chalk lithostratigraphic formation elevations and inferred hardground and marly horizons are based on the BGS structural model. High and low groundwater levels are drawn from hand contoured observations and river discharge elevations. Unsaturated depths may be over 50 m beneath interfluves so that formations saturated at the water table are different from those mapped at the surface.

By intersecting contoured groundwater levels with the stratigraphic model surfaces, a 'water table geology' map can be developed, as shown in ES Fig. 4(a) for the minimum groundwater level period. Such maps are helpful for the development of numerical model parameterisation because, whilst there are many local exceptions, the formations do have distinctive general characteristics. Both the Upper Greensand and West Park Farm Member have a higher specific yield (ranging from 5 to 20%) than the Chalk (typically between 0.5 to 2%). They are also typically less transmissive.

The lower Chalk formations tend to be marlier than those further up the sequence such that secondary developed permeabilities are often lower, and groundwater flow across bedding is more restricted in comparison with bed-parallel flow.

ES Fig. 4(b) shows the Upper Greensand surface and elevation from the BGS geology model and includes the projected lines of the rivers. This is a westward looking view of part of the Wessex Basin which is presented in an eastward view in ES Fig. 1. A shallow syncline is again seen to be plunging gently eastward beneath the Avon and Bourne which drain Salisbury Plain towards the Test.



ES Fig. 4. (**a**) A westward looking 'water table geology map' of saturated Upper Greensand, Chalk and West Park Farm Member formations within part of the Wessex Basin, projected onto the mimimum groundwater level surface. The main rivers discussed in the text are labelled. (**b**) The underlying geological structure from the BGS model indicated by the base of the Upper Greensand. A shallow dipping syncline beneath Salisbury Plain plunges gently beneath the Avon and Bourne towards the Test. The structure dips more uniformly towards the south east beneath the lower reaches of the Avon, the Stour and its tributaries.

Development of hardground flow horizons and winterbournes

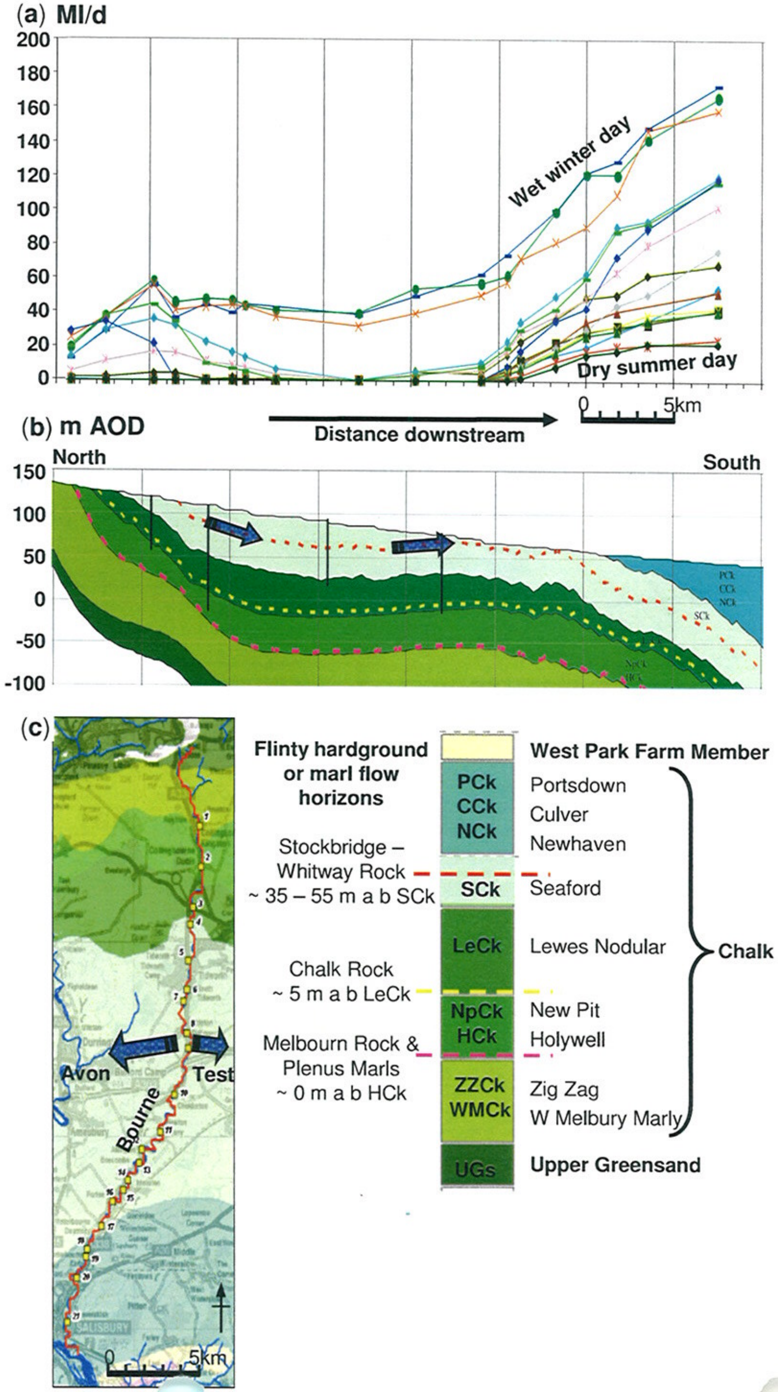
The significance of enhanced transmissivity development and groundwater flow associated with hardgound horizons is illustrated by the spatial and temporal variation of flows gauged down the River Bourne (ES Fig. 5(a)). As its name suggests, only the lower reaches of the river have perennial, year-round flow. For much of the time, flow accreting to its headwaters is lost so that there is no water in its middle reaches. The whole river only flows during wet winter months when recharge and groundwater levels are highest.

This behaviour is explained (Environment Agency 2001 and 2004) by the relatively high elevation of the Bourne in comparison with the more deeply incised River Avon to the west, and River Test to the east, and by the significant transmissivity associated with fissure flow around the Whitway Rock horizon (ES Fig. 5(b)). The Salisbury Plain syncline brings this horizon to outcrop in the bed of the upper reaches of the Bourne where flow is lost and also returns it close to the surface further down gradient – where perennial flow is established. The intersection of structure, topography and drainage therefore provides a route for water to enter, flow through, and leave this horizon which has developed significant bed-parallel transmissivity because it is harder for water to flow across it. Geophysical logging of the abstraction boreholes next to the Bourne confirm that the Whitway Rock is an important flow horizon, but the loss of flow in the middle reaches is mostly a natural feature of the hydrogeology.

During low groundwater level periods, much of the water leaking into the Whitway Rock 'underdrain' flows parallel with strike to discharge at a lower elevation into the Avon to the west, or into tributaries of the Test in the east (ES Fig. 5(c)). For this reason, the groundwater catchment to the Bourne differs significantly from its topographic catchment, and also moves with time according to recharge and groundwater level conditions.

Such 'underdrainage' is less likely to be associated with the Chalk Rock beneath the Bourne because ES Fig. 5(b) shows that, being deeper than the Whitway Rock, the syncline does not bring it closer to the surface again in this location – there is 'nowhere for the water to flow to' in the south (Environment Agency 2001 and 2004). However, on the west side of the Avon, the Chalk Rock is shallower and ES Fig. 3 shows that it outcrops on both the up-gradient northern margins of Salisbury Plain, and on the down gradient side, in the Wylye Valley (and it's tributaries, the Chitterne and Till – located on ES Fig. 1(a)). West of the Avon, therefore, the most important flow horizon is the Chalk Rock – responsible for regionally significant flows across surface catchment divides, a significant inflow horizon in abstraction boreholes, and associated with spring discharges into the lower reaches of the Chitterne and Till.

The Whitway Rock occurs above the water table further west but, like other similar horizons, it may still be associated with enhanced fissuring and the lateral movement of recharge down dip within the unsaturated zone.



ES Fig. 5. (**a**) Spot flows gauging survey results for the River Bourne demonstrating its 'winterbourne' character. For much of the time flow is lost from its upper section such that the middle reaches are dry. (**b**) The geological cross section drawn along the line of the river indicates that enhanced fissure transmissivity and 'underdrainage' associated with the Whitway Rock horizon helps to explain this behaviour, and the syncline structure evident in Fig. 5 (b) returns of some of the water to the lower perennial reaches of the river. (**c**) Map of the River Bourne with arrows to show that during the summer, some of the Whitway Rock water flows along the axis of the syncline towards the lower level River Avon to the west and River Test to the east.

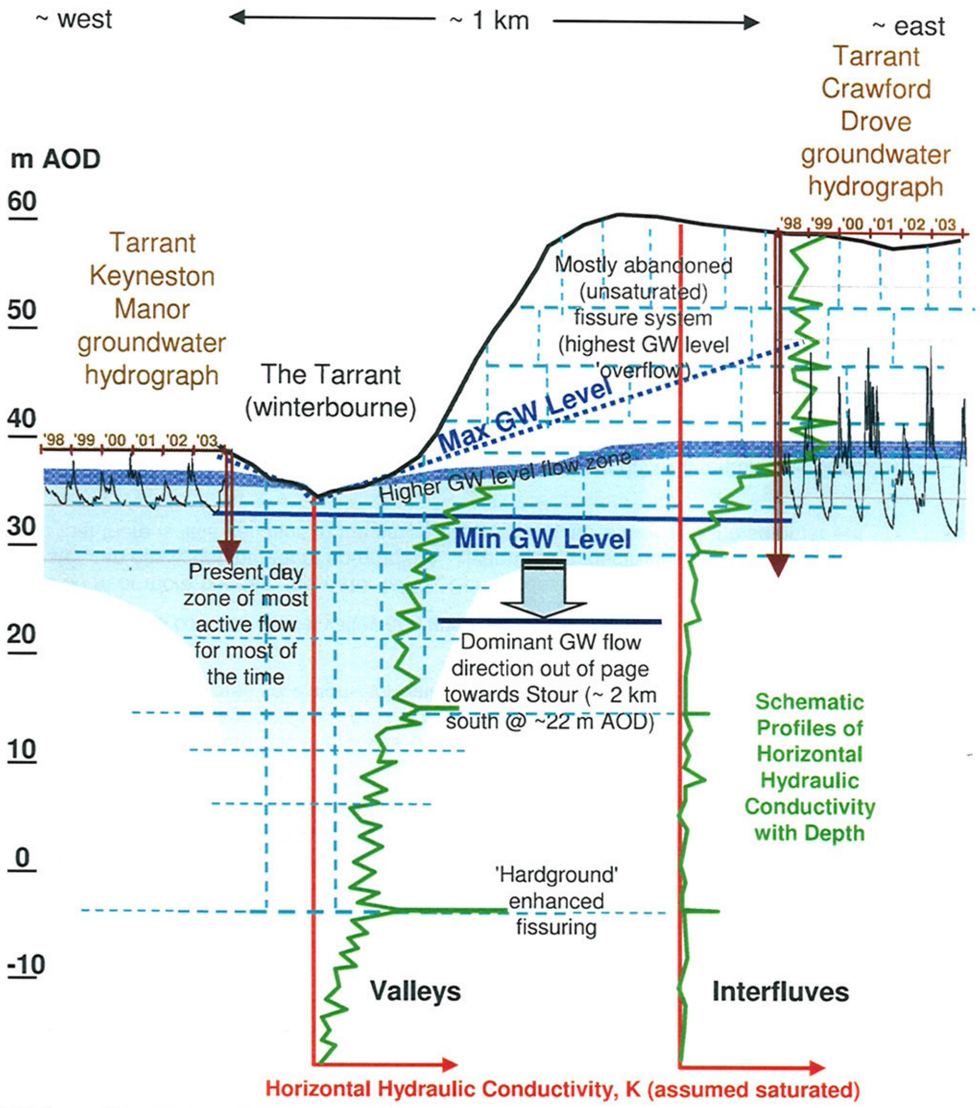
Recharge, unsaturated zone flow, and interfluve – valley contrasts in hydraulic conductivity profiles

Further to the south and west, the Chalk dips more uniformly south-eastwards, beneath the confining Palaeogene. So around the middle reaches of the Avon, the Stour, and its tributaries the Allen and Tarrant, hardground flow horizons, although locally important, have not developed over such large areas to cross surface water catchments. Chalk transmissivity is extremely variable. Some boreholes drilled may be totally dry, whereas others nearby intersect high yielding fissures. However, some general contrasts between interfluve and valley locations are apparent which relate to the development of secondary fissure permeability through dissolution and the history of groundwater flow.

ES Fig. 6 is a cross section drawn from an observation borehole next to the Tarrant – a winterbourne valley labelled on ES Fig. 1(a) – to an interfluve observation borehole approximately 1 km to the east. Both these groundwater level records include the five year period plotted from 1998 to 2003 during which data loggers were fitted to capture short term fluctuations. Water levels in both boreholes fall to roughly the same minimum elevation – just below the bed of the Tarrant (so that it is losing flow, or is dry). During such summer and autumn periods, the dominant gradient is southward – towards the main River Stour. The bed elevation of the Stour over its middle reaches has eroded below its Chalk tributaries because of the relatively high energy flood flows associated with its flashy Jurassic upper catchment. This helps to explain why tributaries like the Tarrant lose water as they approach the lower drainage elevation of the main river channel.

The observed groundwater level response to winter recharge is very rapid in both boreholes, even though the unsaturated depth at the end of the summer recession may be over 25 m beneath the interfluve. In the valley, groundwater discharges into the winterbourne so the amplitude of groundwater fluctuations is limited in comparison with the interfluve. Away from the valley, levels rise by 10 to 15 m to increase the gradients driving flow towards the Stour, and also towards the Tarrant. If there are storm rainfall events resulting in intensive recharge when groundwater levels are already high, extremely rapid rises and falls in level are observed which are also apparent with lower amplitudes next to the winterbourne.

ES Fig. 6 includes schematic annotations developed as part of the conceptual model to help explain the contrasts between Chalk valley and interfluve. Fissure transmissivity in the Chalk is mostly associated with bedding plains (typically sub-horizontal, particularly above lower permeability tabular flint or marly horizons), or with perpendicular jointing. The blue dashed lines on ES Fig. 6 represent these fissures, the thickness of which indicates their degree of development. Immediately beneath the shallow soils across the interfluves, these schematically suggest a large number of pressure relieved small cracks and weathered fractures with the dominant direction of unsaturated zone flow being downward – through the Chalk matrix, and along fissure surfaces over a wide area. Processes of unsaturated flow and recharge to the water table have



ES Fig. 6. Observed groundwater level hydrographs on a schematic section across the Tarrant winterbourne illustrating contrasts in fissure development and hydraulic conductivity variation with depth (VKD) between valleys and interfluves.

been described previously by Mathias *et al.* (2005), with most significant volumes draining relatively slowly through the bulk of the rock matrix and small fractures. However, ES Fig. 6 suggests that larger fissures may also be found in the unsaturated zone which may carry significant flows relatively rapidly in response to intensive recharge events. Bedding plain fissures (particularly associated with hardgrounds) could collect water from a wider area and focus it down dip into a relatively fewer number of larger vertical joints. As dissolution continues and the recharge flows down through the unsaturated zone, it becomes more saturated with respect to calcium carbonate and therefore less chemically aggressive. Once at the water table, the saturated aquifer hydraulic gradient becomes important in determining the direction and rate of flow, whereas geological structure is likely to dominate under gravity in the unsaturated zone.

As a dual porosity fracture/matrix aquifer, the flow response of the Chalk appears to depend on the intensity of the stresses put on it. Hence a sharp storm may result in the activation of an otherwise abandoned, low storage fissure system above and around the water table which rapidly conveys water through the unsaturated zone and away to river and winterbourne discharges. Ireson *et al.* (2009) describe 'same day' Chalk groundwater level responses to high intensity rainfall at an experimental site where the unsaturated depth is *c.*70 m. Rapid baseflow responses are commonly gauged throughout the Wessex Basin river network if rainfall exceeds 10 mm/day, even during summer months when regional soil moisture deficits have been established. Short term nitrate spikes observed in the raw water abstracted from public supply wells may provide further evidence of rapid transport from the soil in such events (Rukin & de Vial, 2010).

During prolonged, slower recession periods, low flows are supported by gravity drainage from the matrix and smaller fissures which is associated with a higher specific yield. The Chalk water table will always 'drain away' from this unsaturated fissure system until the rate of drainage is exceeded by the rate of recharge. With increasing geological time and exposure to rainfall recharge, ongoing Chalk dissolution could be expected to result in a gradual lowering of minimum interfluve groundwater levels until, as around the Tarrant, they are the same as in the adjacent valleys.

These dry valleys and river corridors are exposed to much more concentrated fluxes of throughflow than the interfluves because they are the 'collector drains' of the groundwater system. Unsaturated depths are also much less so recharge water is more chemically aggressive. As a result, bedding plain and jointed fissuring are developed to greater depth beneath minimum groundwater levels (ES Fig. 6) and transmissivities can become very high. Virtually all large Chalk groundwater abstractions in the Wessex Basin area are therefore located in valleys.

ES Fig. 6 also includes two schematic profiles of horizontal hydraulic conductivity with depth drawn to contrast typical valley and interfluve locations.

In the valley systems, permeabilities are developed down to significant depths – perhaps 50 m or more beneath the water table. Some horizons have particularly enhanced flow capacities, but these will only carry significant flows from under interfluve areas if water can easily get into them up-gradient. Hydraulic conductivities may be extremely high in the near surface but the seasonal fluctuations in groundwater levels are small so that there is little variation in transmissivity between the winter and the summer – it remains high all the time.

In interfluve areas, however, ES Fig. 6 suggests that fissure development is much shallower beneath the minimum water table. The hydraulic conductivity profile has been extended up through the unsaturated zone to the ground surface *as if it was saturated.* This is no longer the case, but the profile drawn assumes that fissuring is present above the present day water table because of the preceding long history of recharge and flow. When groundwater levels are low, transmissivities are also very low, unless 'underdrained' by an active flowing hardground. But transmissivities increase rapidly as recharge reactivates flow in fissures above the minimum water table.

Springs and flow accretion supported by the Upper Greensand or associated with marls, faults and clay formations

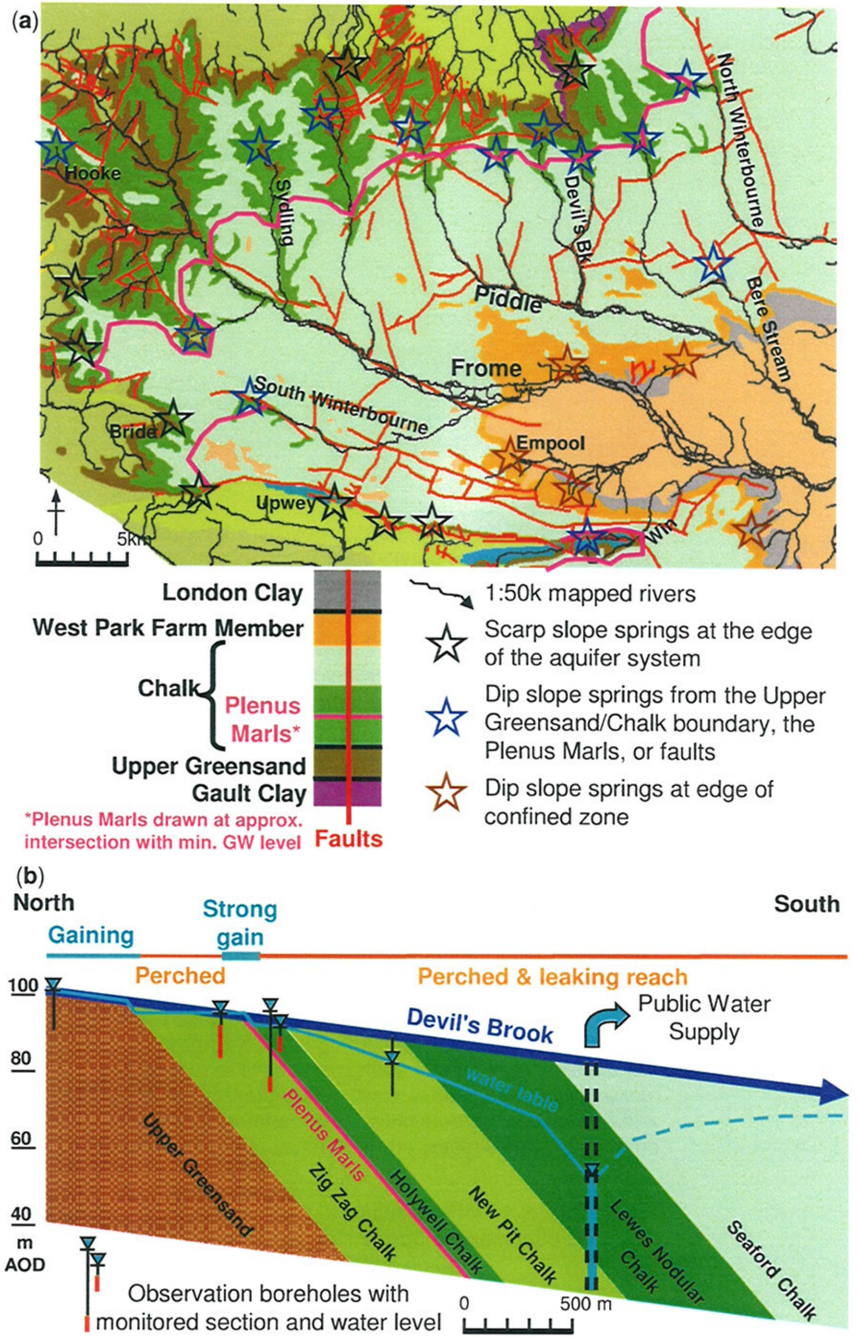
Around the northern and western margins of the Wessex Basin, extensive areas of the relatively high specific yield and lower transmissivity Upper Greensand sustain springs and support baseflow into river headwaters. Faults and the valley outcrop of hardgrounds and lower permeability marl horizons can also act as barriers to groundwater flow which bring the water table to the surface and promote spring discharge. And both the underlying Gault Clay and confining London Clay are effective aquicludes with springs emerging where they outcrop. Scarp springs flow from the base of the Upper Greensand over the Gault Clay, and dip slope groundwater outflows from locally karstic springs along the West Park Farm Member margins of the Palaeogene because flow into the confined zone is very limited (the London Clay aquiclude prevents discharge to the sea).

ES Fig. 7(a) shows the western catchments of the Frome and Piddle and illustrates how these factors help to explain the mapped distribution of springs and rivers. The source of the River Bride which flows away from the Wessex Basin to the west is a scarp slope spring from the Upper Greensand. Spring flow from the lowest formations of the Chalk and from the Upper Greensand provides perennial baseflow into the River Hooke which is reliable enough to support a headwater surface abstraction. A very large karstic spring emerges from Jurassic Limestones which are faulted against the main Chalk aquifer at Upwey on the southern boundary of the Basin. Upper Greensand inliers are also mapped at the headwaters of the Sydling, South Winterbourne and Win, although some spring flow may be associated with the Plenus Marls outcrop or with faulting, as at the source of the North Winterbourne, the Bere Stream and the Piddle.

The cross section in ES Fig. 7(b) (after Colley 2005) is drawn along the Devil's Brook (labelled on ES Fig. 7(a)). Groundwater levels measured around the Plenus Marls suggest that this acts as an important dipping barrier here as well, promoting discharge to the Brook and limiting the upstream propagation of drawdown associated with abstraction from a public supply borehole. Downstream of the Plenus Marls the Brook is naturally perched above the groundwater system although groundwater levels are artificially drawn down by abstraction where it flows past the borehole. Some of the abstracted water is returned to the stream to augment flows through the nearby village for amenity purposes.

Some of the rivers on ES Fig. 7(a) follow fault lines and these may also promote the development of preferential groundwater flow paths along them. Faulting along the North Winterbourne, for example, may be associated with the observed loss of flow where the path of the bourne turns eastward to the Stour. These fault lines extend south towards the Bere Stream where discharges from springs and artesian watercress farms can only be accounted for as cross-catchment transfers from the north.

Groundwater from the Chalk and West Park Farm Member also discharges at a number of prominent watercress and fish farms at the edge of the confining London Clay (e.g. near Empool, ES Fig. 7(a)). Recharge through the West Park Farm Member is undersaturated with respect to calcite and may further enhance local secondary permeability development. There are few areas now where runoff from the Palaeogene flows onto the Chalk, so the large active swallow holes and sinks which occur around the karstic margins of the London Basin are not a feature of the Wessex Basin. However, several large solution collapse features close to the Chalk – Palaeogene contact are evidence of significant secondary fissure development in the past.



ES Fig. 7. (**a**) Mapped relationships of scarp and dip slope springs and river lines with the outcrop of the Upper Greensand, the intersection of the low permeability Plenus Marls with the dry period water table, the confining London Clay, and with faulting across the Frome and Piddle catchments, and (**b**) Section down the Devil's Brook with observed groundwater levels, losing and gaining reaches, and inferred groundwater table: Plenus Marls promote discharge to the Brook and act as a barrier to drawdown associated with public supply abstraction.

Numerical model overview

The numerical Wessex Basin model is constructed on a regular 250 m grid and combines a daily representation of rainfall, runoff, evapotranspiration and recharge simulated using the 4R code (Heathcote *et al.* 2004) with a groundwater model built in a version of the MODFLOW code adapted by the Environment Agency to include the representation of variable hydraulic conductivity with depth (i.e. MODFLOW-VKD, Environment Agency 1999).

The runoff and recharge model extends over the total catchments of all the Wessex Basin rivers including the Jurassic upper-catchments of the Nadder and Stour. The influence of surface water abstractions and discharges is included within 4R runoff accounting which routes accumulated flows into the rivers simulated by the groundwater model. The largest surface water abstraction in the model is at Knapp Mill which pumps from the lowest reaches of the groundwater baseflow dominated River Avon. Modelled surface water discharges include the return of treated mains effluent, and outfalls associated with groundwater to river support schemes (intended to maintain low flows for environmental and amenity purposes), and with pumped discharges from water cress beds and fish farms. For predictive scenario runs, the switching on and off of abstractions and discharges for river support schemes is automated within the simulation according to predefined triggers based on modelled flows and pumping rates (Lewis & Power 2006).

The groundwater model has three layers to represent the contrasting storage and flow properties of the Reading Beds (layer 1), the Chalk (layer 2) and the Upper Greensand (layer 3). It runs with 3 stress periods per month of variable length (10 days, 10 days, plus the remainder of the month) and incorporates the influence of groundwater abstractions - the largest being for public supply, water cress and fish farm support.

The combined simulation starts with a five year 'warm-up' period from 1965 before the calibration period running from 1970 to 2008.

Processes simulated in 4R are dominated by recharge on the Chalk, including a rainfall intensity related bypass of soil moisture deficits. Although the arrival of recharge at the water table is subject to lags which are spatially distributed according to a fixed grid of unsaturated depth, the 4R and MODFLOW models are not coupled. So the lags do not change according to the modelled heads, although a rapid 'same day fracture flow' route can be optionally activated if recharge exceeds a daily intensity threshold.

On the flood plains of the larger rivers the water table is close to the surface so a greater proportion of the excess of rainfall over potential evaporation is routed as runoff into surface flows. A combination of runoff and shallow groundwater interflow provides a credible representation of the total flow response from the Jurassic and Palaeogene parts of the model area. This is combined in MODFLOW with modelled groundwater baseflow from the Upper Greensand, Chalk and Reading Beds.

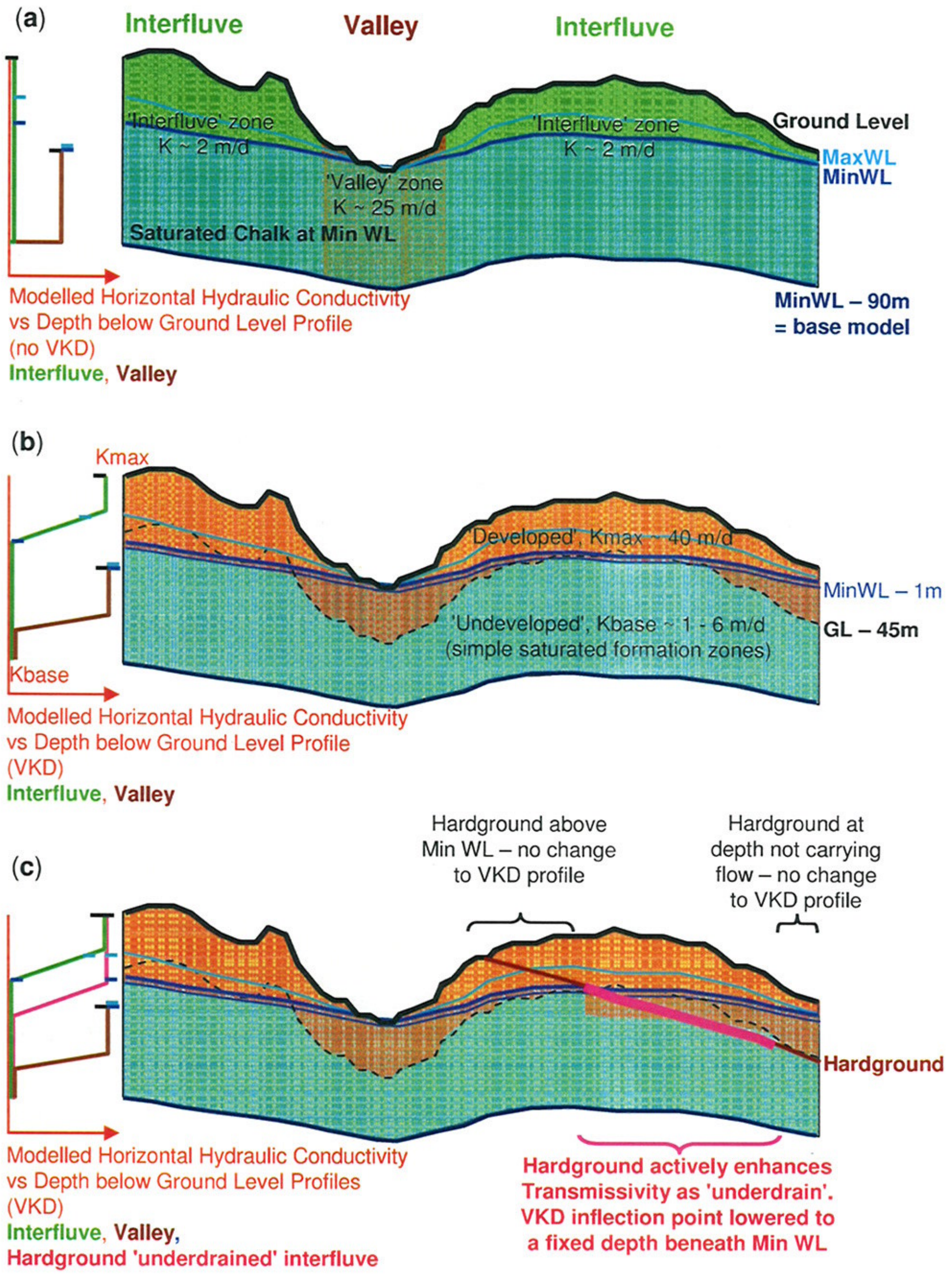
The MODFLOW Stream Package (Prudic 1989) is used as the top boundary condition to simulate groundwater – surface interaction and accumulate routed river flows. Chalk winterbourne behaviour suggests there is little resistance to baseflow discharge from the aquifer, so modelled stream conductances are generally high. But leakage back to the aquifer typically appears to be limited by bed sediments, particularly during low flow periods. In the model, this means that the stream bed bottom elevation is often brought close below the stage elevation until rates of modelled leakage match observed losses. Establishing accurate and smoothly interpolated stream stage profiles, controlled by ground surveys wherever possible, is a very important stage in the model build because winterbourne behaviour is often related in part to these drainage boundary elevations.

Investigating alternative numerical implementations of the conceptual model of Chalk transmissivity development

Use of a single MODFLOW layer representing the Chalk has advantages in avoiding cell drying and re-wetting instabilities, but requires marked simplification of the three dimensional complexities evident in the 'real' multiple fissure, hardground, marl and matrix flow structures and 'two speed' storage described in ES Figs. 5, 6 and 7. During the early stages of modelling with the MODFLOW-VKD code, alternative ways of simplifying the conceptual understanding of transmissivity development were investigated. These are illustrated in ES Figs. 8 and 9. In all cases the base of both the modelled Upper Greensand and Chalk layers were limited by the BGS structural model down to a maximum depth of 90 m below the contoured minimum water table (ES Fig. 8(a)), or below the base of the London Clay in confined parts of the Wessex Basin. There is considered to be little active groundwater flow beneath this depth.

Initial model runs assumed that hydraulic conductivity was constant with depth, with spatial distribution based on manually defined zones drawn to differentiate between valleys and interfluves (ES Fig. 8(a)). Zones were also defined to distinguish the formations saturated around the water table (ES Fig. 9(a)), and to introduce higher transmissivity zones associated with the plunging axes of synclines (ES Fig. 9(c)) in an attempt to represent the preferential development of flow horizons within them.

This approach has a number of disadvantages. Definition of the manual zones, whilst essential during subsequent more localised model refinements, can be overly influenced by the modeller's pre-conceptions. It does not make best use of readily available information on the topography and distribution of unsaturated depth, and the conceptual understanding of how these can influence the transmissivity distribution. ES Fig. 9(d) is the steppy transmissivity profile down a north – south section line within the model based on these manually drawn hydraulic conductivity zones and assuming the minimum water level and model base shown above in ES Fig. 9(b). There is no transition in transmissivities from valley to interfluve, and there are only small seasonal variations in interfluve transmissivity as water levels change. Overall, as a method of regional default parameter control, this numerical implementation did not capture many of the key characteristics of the conceptual model. The resulting flow simulation was also not promising, so alternatives were sought.



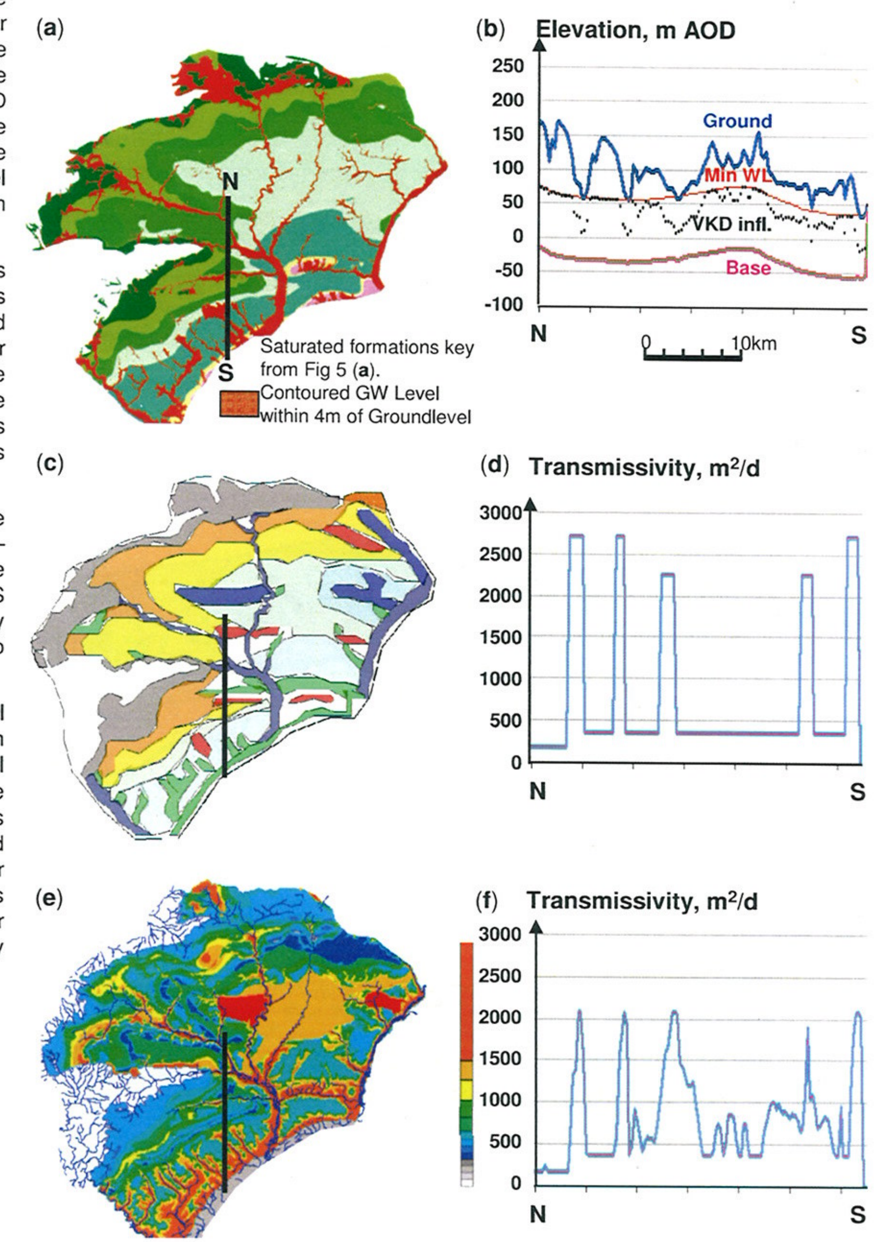
ES Fig. 8. Alternative approaches to the distribution of hydraulic conductivity profiles with depth in the numerical representation of valley – interfluve contrasts, as trialled early in the development of the Wessex Basin model: (**a**) manually zoned transmissivity with no VKD; (**b**) using the Agency's VKD profile, aiming for the same transmissivity at average groundwater levels as for the manually defined zones, but with a fixed Kbase, and an inflection point elevation set at the minimum of {minimum GW level minus 1m, minimum ground level minus 45m}; and (**c**) modification of the VKD profile to represent the additional fixed transmissivity associated with fissure development in a hardground horizon – where this lies within the active flow zone close to the water table.

ES Fig. 8(b) shows how the MODFLOW-VKD functionality was used to capture more of the conceptual characterisation of transmissivity development. The ES Fig. 9(a) minimum water level saturated formation map was retained to define variations in the 'undeveloped' base hydraulic conductivity of the Chalk (Kbase), if differences are considered significant. But the majority of the transmissivity calculated in the Chalk layer is developed above the VKD 'inflection point', the elevation of which is distributed continuously across the model using the topographic and minimum groundwater level surfaces mapped during conceptualisation. The inflection point is set at the lowest elevation of (topography – 45 m) and (minimum water level – 1 m). Above the inflection point the hydraulic conductivity increases up to a maximum developed Kmax.

The effect of this implementation is that the depth of more developed saturated Chalk is greatest in river and dry valleys where the water table is close to the surface (e.g. areas shown in brown on ES Fig. 9(a)). ES Fig. 8(b) includes the VKD profiles for both valley and interfluve areas which have been annotated to show the minimum and maximum groundwater levels. In the valleys, there is a deep, well developed profile and water level fluctuations are minimal - so there will be little variation in the high resulting transmissivities throughout the year. On the interfluves, the seasonal water level amplitude is much greater and is associated with marked increases in hydraulic conductivity such that winter transmissivities are much greater than during dry periods.

The first run carried out according to this approach was parameterised to provide transmissivities at average water levels which were close to the formation and interfluve – valley values used in the 'no-VKD' run summarised in ES Fig. 8(a), in an attempt to compare roughly equivalent models. The flows and groundwater levels simulated using the ES Fig. 8(b) combination of zoning and continuously varying VKD profiles were relatively encouraging in many parts of the model, and provided appropriately high transmissivities to support most of the large groundwater abstractions. So this approach was carried forward.

A further refinement to the regional approach was important to represent the additional transmissivity which may be associated with developed hardground 'underdrainage' at depth beneath some interfluve areas (ES Fig. 8(c)). The elevations of the most prominent potential flow horizons – the Melbourn Rock, Chalk Rock, and Whitway Rock – were inferred from the BGS structural model and compared with the minimum water table. Where the hardground is above the minimum water level it is assumed to have no influence on the modelled transmissivity. Where it occurs at greater than a fixed depth beneath the minimum water table (estimated with reference to examples like the Bourne in ES Fig. 5(b) to be 35 m), it is also assumed to be inactive. Over the areas where the hardgrounds lies closer to the water table, they are assumed to add a fixed amount of additional transmissivity to the profile by lowering the inflection point to a fixed depth beneath the water table (25 m).



ES Fig. 9. (**a**) Minimum groundwater level geology map of part of the Wessex Basin model, also showing areas where the contoured water level is within 4 m of the ground surface. (**b**) Schematic short north-south cross section through the modelled Chalk showing the elevation of the ground level, groundwater level and base of the model. (**c**) An illustration of manual transmissivity zoning (like Fig. 8(a)), and (**d**) a north-south profile of the resulting transmissivity. (**e**) A map of transmissivity developed for an early model run from the known elevations of the ground surface, minimum groundwater level and hardground horizons according to the approach shown in Fig. 8(c), and (**f**) the more continuously varying transmissivity profile which results..

This approach uses the VKD profile functionality available in the code but is still a marked simplification of the 'real system'. In reality the extra transmissivity lies within the fissuring associated with the hardground, as illustrated schematically in ES Fig. 6 and this may become an effective drain over larger areas as groundwater levels rise. Nevertheless the result is that the hardgrounds generate broad areas of enhanced transmissivity where they occur within the shallow Salisbury Plain syncline, as shown around the Bourne in ES Fig. 9(e). In these areas the effect of the VKD profile in amplifying seasonal variations in transmissivity is reduced – the 'underdrainage' mechanism makes VKD less important. Further south, where the hardgrounds dip away from the water table more steeply and regularly, they result in relatively narrow areas of transmissivity enhancement parallel to strike.

The transmissivity distribution developed through early runs using this approach is shown in ES Fig. 9(e), and the more continuously varying profile for the same north-south profile is shown in ES Fig. 9(f). This numerical implementation seemed to capture many of the important features of the conceptual model and also produced the most promising simulation of flows. Its more continuously varying range of transmissivities is probably a better approximation of the variation in the real system than the use of simpler manually defined zones of fixed properties.

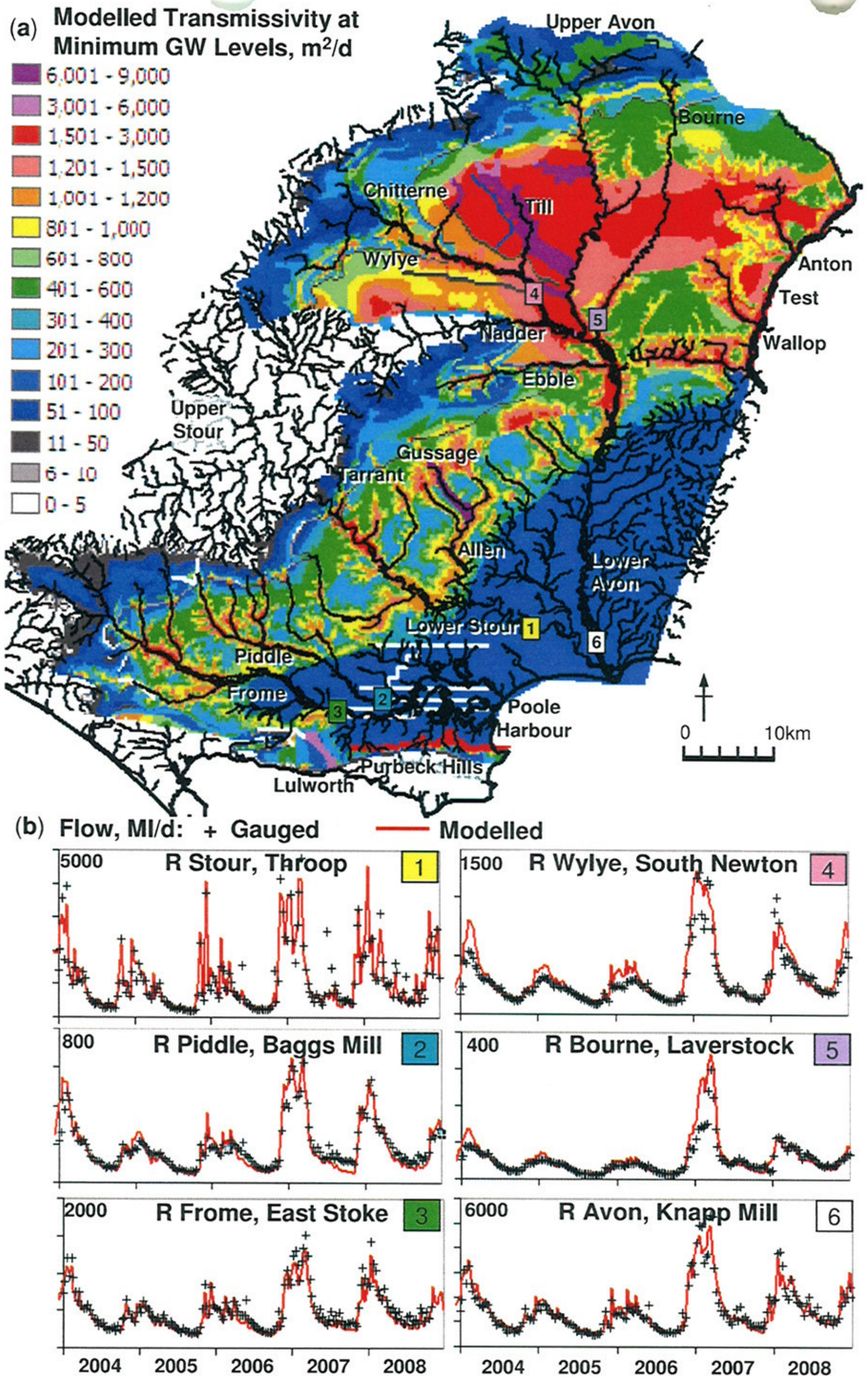
The numerical modelling continued to refine the controls influencing this parameterisation. A number of local overrides were built in where necessary, but the approach summarised in ES Fig. 8(c) appears to be reasonably sound, within the constraints of the MODFLOW-VKD code used.

Model transmissivity distribution and flow simulation

ES Fig. 10(a) shows the modelled transmissivity distribution based on low groundwater levels simulated by the Wessex Basin run finally agreed as 'fit for purpose' following refinement against observed groundwater levels and river flows. It has been calculated to combine the dry period transmissivity associated with all three model layers according to their saturated depth.

The distribution reflects the influences of lithostratigraphy, structure, hardground 'underdrainage' and barrier zones representing the Plenus Marls and the down-gradient outcrop of the Chalk Rock, as previously introduced. Some of the faults identified on recent BGS maps have been represented in the model using the Horizontal Flow Barrier (HFB) package (ES Fig. 10(a)) where they appear to be essential to simulate observed spring heads, or to improve the simulation of confined groundwater levels. The need for refinement of regional concepts and parameters is also locally apparent.

Around the western and northern margins of the Wessex Basin the modelled transmissivity of the Upper Greensand is relatively low compared with the Chalk. Its saturated depth above the Gault Clay is typically shallow (5 to 30m) which is multiplied by hydraulic conductivity in the range 2.5 to 5 m/d to give transmissivities of *c.*20 to 150 m^2/d. Combined with specific yield in the range 5 to 10%, these headwaters are a source of relatively reliable baseflow to many of the streams and rivers.



ES Fig. 10. (**a**) Wessex Basin transmissivity distribution at the end of model refinement, simulated for November 2003 (low groundwater level). Faults modelled using the Horizontal Flow Barrier (HFB) package are shown as white lines. (**b**) Comparison of modelled and gauged flows for the largest rivers.

The flow barrier associated with the Plenus Marls is represented as a one cell wide zone of lower transmissivity at its interpreted intersection with minimum water levels (i.e. as highlighted in ES Fig. 7(a)). As a vertical line of cells, this is clearly a simplification of the real dipping combination of lower and higher permeability horizons shown in ES Fig. 7(b). This zone is important in matching the observed distribution of springheads, often in intersection with faults implemented using the HFB package, and particularly in the tributary catchments of the Piddle and Frome.

ES Fig. 10(a) shows that contrasts between valley and interfluve transmissivities (using the VKD profile approach summarised in ES Fig. 8(c)) are most apparent up the main river corridors, and in the mid-catchments of Rivers Allen, Piddle and Frome. Beneath Salisbury Plain (the Chitterne, Till and Bourne catchments), the development of enhanced flow horizons within the shallow open synclinal structure is apparent in the larger areas of more regionally uniform high transmissivity.

On both the north and south side of the River Wylye anticline structure, the outcrop of the Chalk Rock is represented as a line of low permeability cells in a similar manner to the Plenus Marls, even though flow within this horizon is responsible for the wide area of high transmissivity to the north. Within the constraints of a single MODFLOW layer, this representation was the only effective way of modelling enhanced flow within the horizon to spring heads in the Chitterne and Till which discharge from it at outcrop. To the south, the barrier zone is necessary to shift the modelled groundwater divide northward to the Chalk Rock outcrop, promoting preferential southward drainage of the Chalk in the Great Ridge area, down geological dip towards the tributaries of the Nadder.

Within the confined Chalk and West Park Farm Member aquifers to the south and east of the Basin, modelled transmissivities are low (140 m^2/d). To the north of Poole Harbour, investigations into the viability of an aquifer storage and recovery scheme provided additional information on confined aquifer flows and storage properties. Following test abstraction, rates of recovery were slow. An associated groundwater modelling study (CH2M HILL 2000) suggested that faults in this area act as barriers to flow. These were incorporated into the Wessex Basin model as well because without them, the simulated groundwater levels in the confined zone were too responsive to unconfined recharge, and rates of simulated recovery were too rapid.

In a number of areas manually zoned local overrides have been essential to improve the simulation of flows and heads. These include the introduction of particularly high transmissivities down the Gussage Valley. This is the only tributary of the River Allen where artificial lining of the river bed has been carried out in association with stream support discharges to maintain some flow during the summer. This suggests much higher transmissivities (up to 7100 m^2/d) than are developed according to the regional parameterisation rules.

Similarly high transmissivity zones are required beneath the Till catchment to represent cross-catchment flows in the Chalk Rock and around the top of the Lewes Chalk Formation into the River Avon. Data from detailed pumping test investigations and monitoring of a public supply source in the Chitterne valley have also been used to improve parameterisation in this area, and to justify the introduction of a low transmissivity line of cells between the Chitterne and the Till in order to match observed drawdown patterns. Abstraction at Chitterne is associated with a rapid drawdown response up to 6 km away towards the south east. But this stops where there is a step in rest water levels, indicating the existence of a barrier - perhaps fault related. In formations where much of the transmissivity may be associated with the development of karstic fissuring, such local discontinuity features are inevitable and should serve as a warning to treat impact predictions at local scales of a few model cells with great caution.

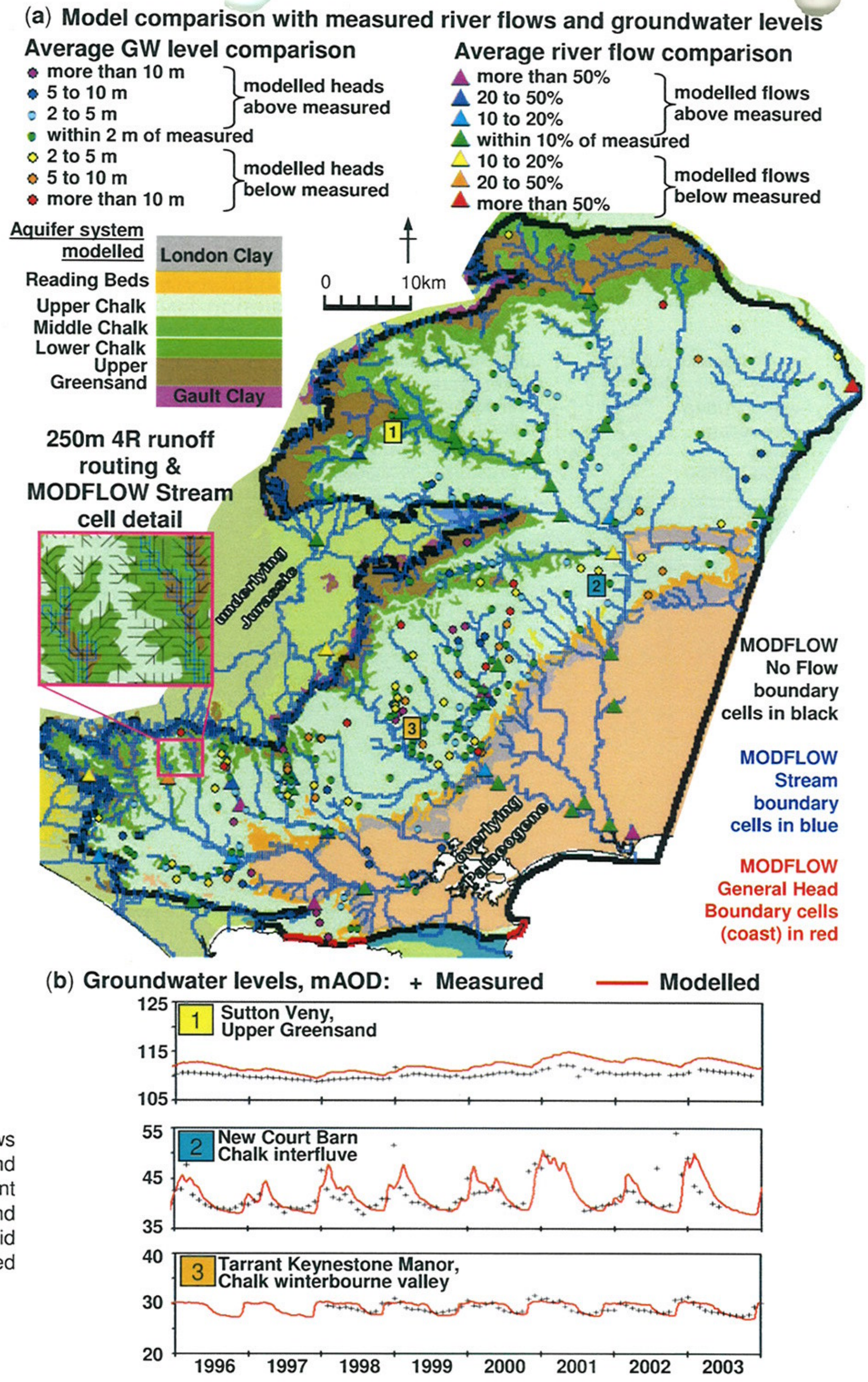
With continued pumping at Chitterne, drawdown develops more gradually, suggesting a slower vertical drainage from the water table. This 'two speed' response – rapid 'semi-confined' fissure drawdown, followed by slower 'unconfined' dewatering – is not easily captured by the single Chalk MODFLOW layer.

Along the southern margin of the Wessex Basin all the main aquifers are folded to vertical within the narrow (*c.* 500 m wide) outcrop of the Purbeck Hills. The numerical model grid spacing of 250 m is too coarse to retain the aquifer layering in this area – the combined Upper Greensand – Chalk – West Park Farm Member groundwater system is all represented within layer 2. Investigations and groundwater level monitoring around Lulworth suggest a locally complex and faulted flow system with spring outflows to the sea only occurring in bays and coves where coastal erosion has broken through the vertical barrier formed by the Plenus Marls and lower Chalk formations.

ES Fig. 10(b) includes flows simulated at 6 of the 42 gauging stations which were routinely reviewed during the refinement process alongside the groundwater records from some 284 observation boreholes. A comprehensive review of the calibration is included in the main report but these 6 flow hydrographs illustrate that modelled flows compare reasonably well with the gauged record in the lower reaches of all of the main rivers. The fit is acceptable at most gauging stations although, as is typical for many groundwater models, predictions become less reliable as the upstream catchment area becomes smaller.

A broader summary of the model calibration is provided by comparing modelled and measured average flows and heads at all the locations used during the refinement process (ES Fig. 11(a) – which also shows modelled boundary conditions). The groundwater level calibration is much more variable – many hydrographs are reasonably matched (e.g. those shown in ES Fig. 11(b)), but others are not.

In some cases this is because no attempt has been made to improve the fit – either because there is uncertainty as to how representative the observed borehole record is of the regional groundwater flow system modelled, or because the area has not yet been the focus of local refinement which typically accompanies investigation of a particular question or scenario test.



ES Fig. 11. (**a**) Wessex Basin model boundaries and comparisons of average river flows and groundwater levels against measured records for the flow gauging stations and observation borehole sites used during model refinement. Black boundary shows the extent of active MODFLOW cells with red General Head Boundaries along coastal outflows and blue Stream Package cells inland. Inset shows detail of 4R runoff routing across 250m grid and through MODFLOW stream cells. (**b**) Comparison of modelled and measured groundwater levels at three contrasting locations.

Model use, update and ongoing refinement

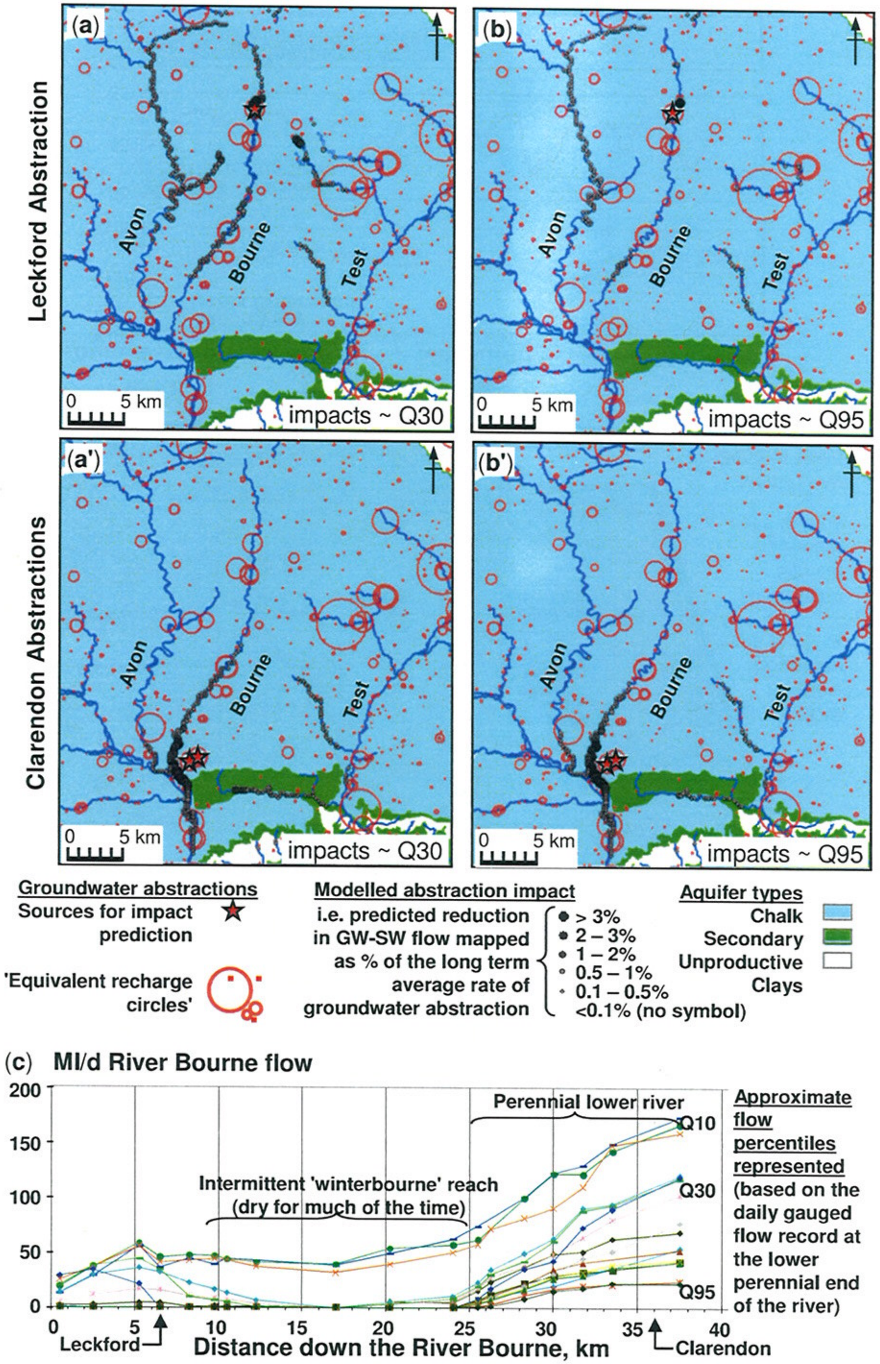
The Wessex Basin model has already been used for over 100 predictive scenario runs in support of Habitats Directive investigations for the River Avon, and water resource management decisions associated with abstractions elsewhere. Examples of flow impact predictions for Leckford and Clarendon - two groundwater sources next to the intermittent and perennial reaches of the Bourne - are illustrated in ES Fig.12, and summarised below.

Leckford is located next to the upper to middle reaches of the Bourne whereas Clarendon lies close to its perennial confluence with the Avon. Two stream cell maps of groundwater to river flow reductions are presented for each of these sources in ES Fig. 12. Separate model runs were carried out for each source and in all cases they have been mapped as percentages of the licensed abstraction rate being investigated so the can be compared against a common key. The groundwater model stress periods sampled to calculate the impacts were selected to represent different percentile exceedance conditions according to flows simulated at the Laverstock gauging station.

Thus ES Figs. 12(a) and 12(a') represent the impacts associated with Leckford and Clarendon respectively for stress periods when flows at Laverstock were *c.* Q30 (actually Q29.5 to Q30.5), whereas ES Figs. 12(b) and 12(b') are impacts averaged from stress periods around the low-flow Q95 statistic.

Leckford impacts (ES Figs. 12(a/b)) vary significantly according to the flow condition - both in their spatial distribution, and in the total impact summed across the river network - in a manner which reflects the natural variations in groundwater – river flow relationships described previously. At Q95 there can be no impact on the middle reaches of the river because they do not flow naturally. Overall impacts amount to much less than the average rate of abstraction and these are mostly apparent along the River Avon, together with a short reach next to the source itself and a few stream cells along the lower river. A greater percentage of the abstracted water is accounted for at Q30 with more impacts upstream and downstream along the Bourne, plus along longer reaches of the Avon, and on some of the tributaries to the Test in the east. When considering the equivalent maps for higher flow stress periods (e.g. around Q10 – not shown here), the total impacts are considerably higher than the average abstraction rate for reasons reflecting the natural catchment behaviour associated with the hardground 'underdrainage'.

Impacts mapped for Clarendon (ES Figs. 12(a'/b') are, however, much less seasonally variable. Groundwater levels are locally constrained by flow to the perennial river reaches of the Bourne and the Avon and these are where the impacts of abstraction are apparent both at Q95 and at Q30, together with minor impacts on a tributary to the Test further east. A very similar pattern is maintained across the whole flow range from Q1 to Q99.



ES Fig. 12. The location of the Leckford and Clarendon boreholes close to the River Bourne with illustrations of the spatial variation of their associated abstraction impacts under contrasting flow conditions, as predicted by the Wessex Basin groundwater model. Groundwater to surface water flow impacts for both Leckford and Clarendon(') sources for stress periods when modelled flows at the downstream reference gauge are (**a**)/(**a'**) around Q30 (moderately high flows); and (**b**)/(**b'**) around Q95 (low flows); (**c**) Ml/d measured flow in the River Bourne from repeated longitudinal spot flow gauging surveys across a range of flow conditions

Model predictions of this kind have been carried out for many sources, both individually, and 'in-combination', on behalf of the Environment Agency and also the water company (Wessex Water). The model continues to be updated annually as an important investigation platform for options appraisal which is used alongside evidence from field tests.

Wherever new questions are asked of the model, further local refinement will usually be beneficial if time and resources allow – where possible, incorporating understanding from field investigations.

Both the conceptual understanding and numerical datasets are also feeding into more integrated studies of diffuse pollution problems, particularly concerning predictions of future nitrate trends, as summarised in Rukin & de Vial (2010).

Future conceptual and numerical modelling challenges

Now that the Wessex Model has been, and uploaded to the Environment Agency's National Groundwater Modelling System, the first priority should be to ensure that it is made easy to update, improve and use. It provides a platform to support water resource decision making in the context of climate change predictions, and to help investigate other issues such as diffuse pollution and (possibly) groundwater flooding.

However, in addition to maximising the benefits from the model as it has been developed to date, there are a number of areas where ongoing research and development would be helpful.

Understanding of Chalk stratigraphy and associated implications for hydraulic properties will continue to develop into the future. This should include an improved appreciation of lateral variations in the thickness, lithology and developed hydrogeological characteristics of the various formations. These are probably less uniform than is currently assumed.

Recharge and unsaturated zone flow processes through fissures and the matrix remain an important area of investigation, including the possibilities for a more coupled simulation of the daily shallow surface processes with the longer stress period saturated groundwater model. The 'two speed' characteristics of Chalk groundwater level and flow responses to 'short sharp' storms compared with the slower water table drainage during summer recessions is not yet completely represented in the model. This has a bearing on both diffuse pollution studies (e.g. nitrate 'spikes'), the resilience of low flows, and the observed rapid recovery of flow after drought periods. Rapid groundwater flooding is also occurring more frequently, as intense rainfall events become more common during both winter and summer. This points to the importance of soil moisture bypass mechanisms and the short term activation of unsaturated zone pathways above the zone of normal water table fluctuation.

Improved numerical modelling techniques should also be sought to better capture the conceptual understanding of preferential bed-parallel Chalk hydraulic conductivity development, further enhanced at some hardground horizons. The MODFLOW-VKD code is helpful in providing a simple and stable simulation of the broad seasonal variations in interfluve and valley transmissivity development. But an alternative approach to defining the vertical profile of hydraulic conductivity more flexibly could improve the representation of the flow structures described in ES Figs. 5, 6 and 7. This might allow a more three dimensionally realistic interaction between groundwater levels and discrete flow horizons or marly barriers, or with more general bed-parallel anisotropy, without the need for multiple layers with all the typical wet/dry instability problems which could result. Extension of similar ideas into the recharge models might also improve the representation of lateral recharge displacement down dip within the unsaturated zone.

Conclusions

The construction and refinement of Wessex Basin model of the Chalk groundwater system has been described. This has built on the improved definition of lithostratigraphy and structure provided by recently revised BGS mapping. There are many similarities with the conceptual models of runoff, recharge, groundwater flow and discharge developed for other Chalk models in Southern and Thames Region of the Environment Agency.

The Chalk in Wessex is hilly and lacks the low permeability glacial Till cover which blankets some of its outcrop in East Anglia and further north. Long exposure to recharge and groundwater flow has developed secondary fissure transmissivity which, because of the existence of lower permeability marls or hardgrounds which promote flow on top of them, often leads to bed-parallel anisotropy. In the unsaturated zone, this may result in lateral, down-dip displacement of recharge. In the saturated system, preferential flow paths will be developed toward the lowest discharge boundary of least resistance. Shallow synclines may often encourage the development of 'underdrainage' within hardground horizons which can drain large areas, sometimes pulling groundwater across surface water divides.

Intermittent winterbourne streams are a common feature everywhere. In the winter, these wet up, reducing drainage path lengths and increasing the speed of the aquifer's flow response to recharge. Abandoned fissures within the unsaturated zone also become active so that winter transmissivities on the interfluves increase rapidly as heads rise. Winter – summer flow response contrasts are often highly non-linear and this is a 'two speed', 'dual porosity', fissure – matrix aquifer. There is little saturated storage of water carried from one year to the next but river flows may be more resilient to drought because of steady drainage from the unsaturated zone matrix, or because the groundwater catchment is much larger than topographic divides would suggest. But groundwater level and flow recovery is surprisingly rapid when recharge returns.

The outcrop of marl and hardground horizons is often associated with springs, flow accretion, or flow loss. Faulting may also be locally important as a barrier to flow, or possibly to promote flow along the fault. Around the Wessex Basin the Upper Greensand is a very important headwater aquifer, providing a relatively reliable source of summer flow.

The numerical model demonstrates that it is possible to achieve a reasonable simulation of the regional flow system using MODFLOW with a single layer representing the Chalk. It is important to 'get the simple things right' such as the elevations of the river and spring discharge boundaries, and the use of the MODFLOW Stream Package (Prudic 1989) is essential because of the winterbourne characteristics of many watercourses. The MODFLOW-VKD code has been be used in association with ground and groundwater level data, and saturated formation maps to provide an appropriate regional transmissivity distribution as a starting point for model refinement. Further local adjustments and manual overrides were then necessary to improve calibration. More flexibility in representing profiles of hydraulic conductivity with depth within a layer might capture the conceptual characterisation of the Chalk more completely in future.

If used with care and understanding, the model provides an excellent platform to support water resources decisions alongside information from field investigations. The associated understanding and numerical datasets are also being used in source protection zone and diffuse pollution studies.

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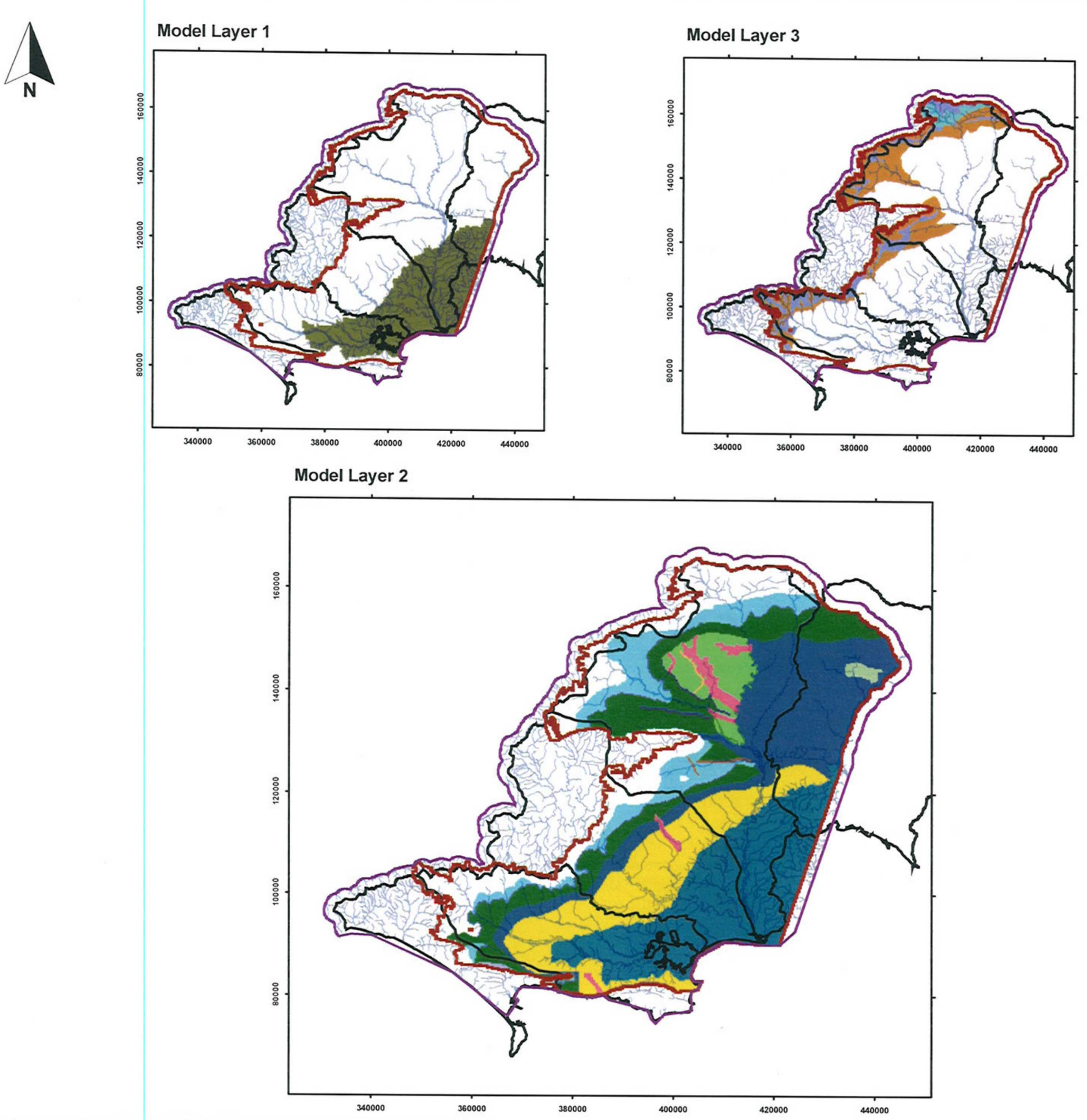

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Wessex Basin
Groundwater Modelling Study

Figure 3.11
Final Transmissivity Zonation
(Run 70)

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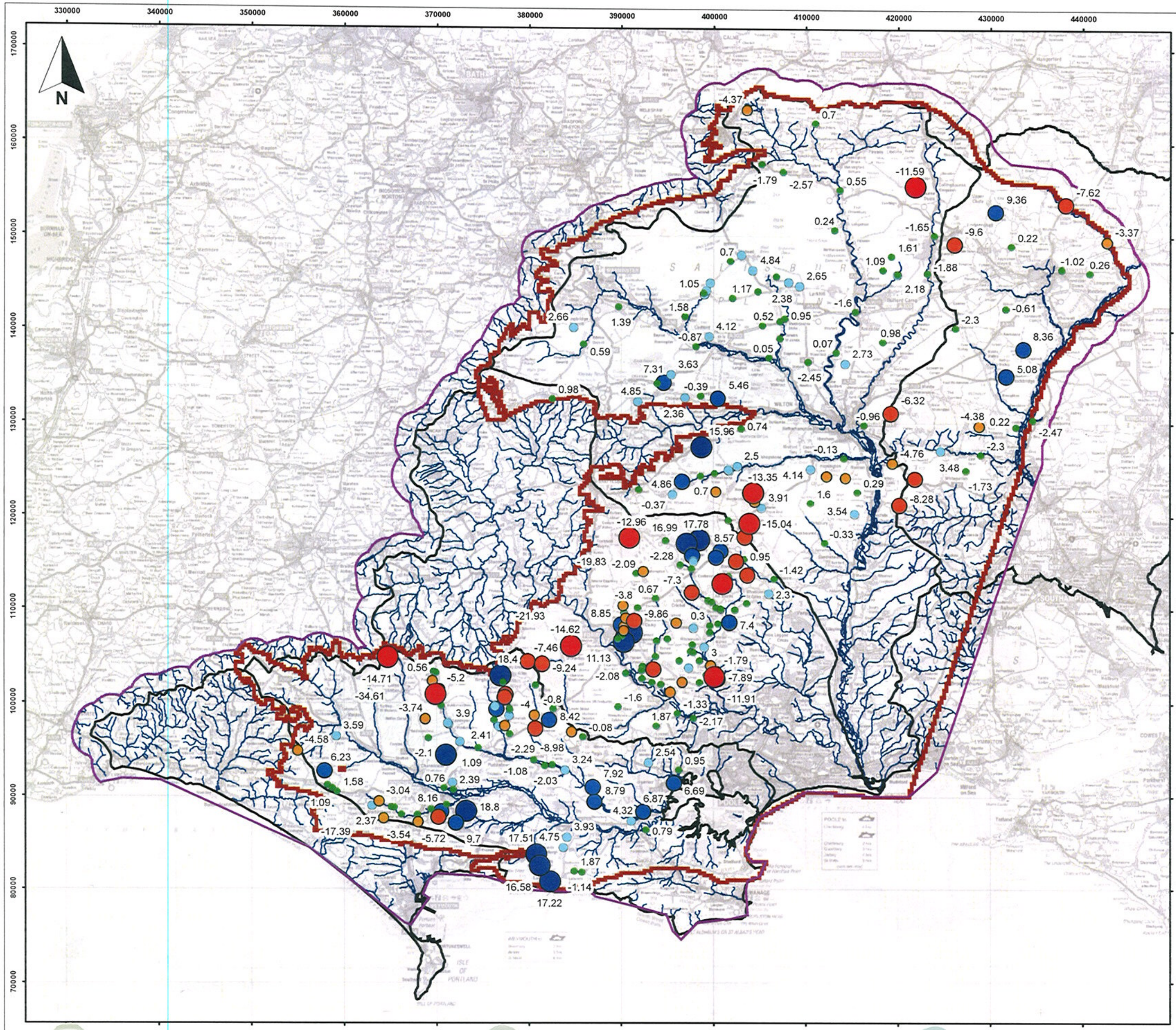

Key:

Average Modelled minus Average Observed Water Level, m

- ● 11 - 30
- ● 6 - 10
- ● 3 - 5
- ● -2 - 2
- ● -5 - -3
- ● -9 - -6
- ● -16 - -10

- ▭ Recharge & Runoff model boundary
- ▭ Groundwater model boundary
- ▭ CAMS areas
- 〰 Rivers

0 1.5 3 6 9 12 15 Kilometers

Scale: 1:400,000 @ A3

H:\Projects\Hm-250\20821\Drawings\Phase 4 rr195\mxds \20821a147 Figure 4.27.mxd

Wessex Basin
Groundwater Modelling Study

Figure 4.27
Difference between Average Modelled Heads and Average Observed Heads at EA Observation Borehole locations

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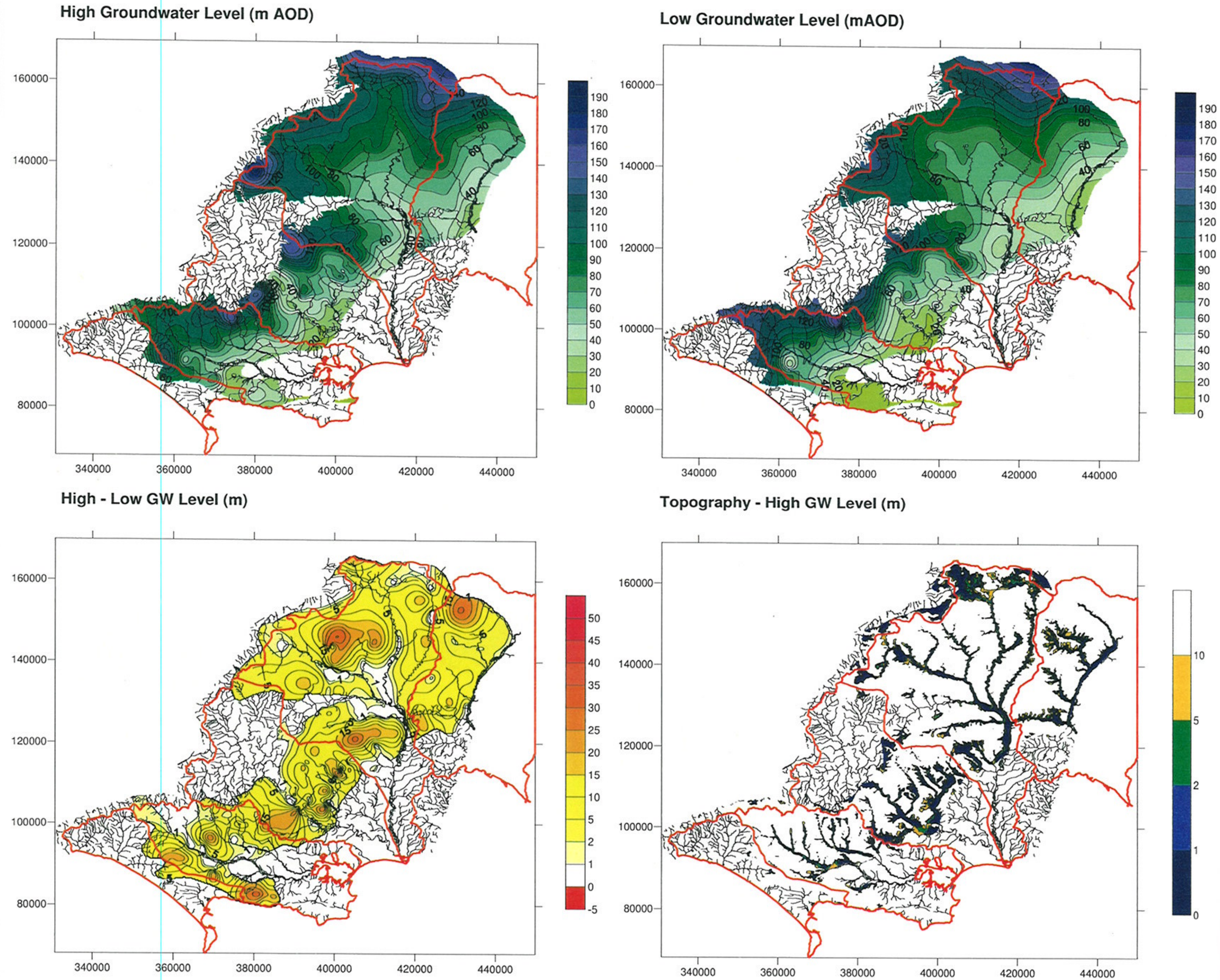

Frome, Piddle & Dorset Stour
Groundwater Modelling Study

Figure 4.15
Contoured High and Low Groundwater Levels, Range and Unsaturated Depth

May 2008
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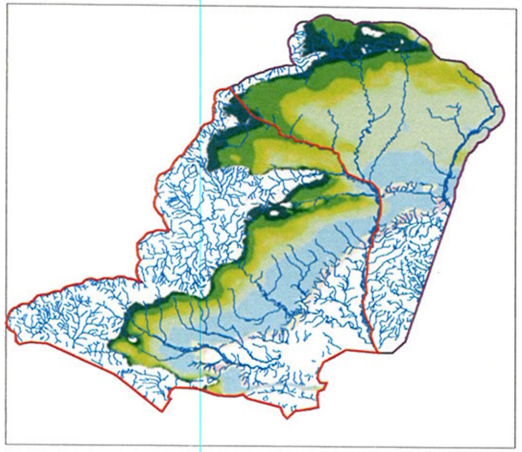
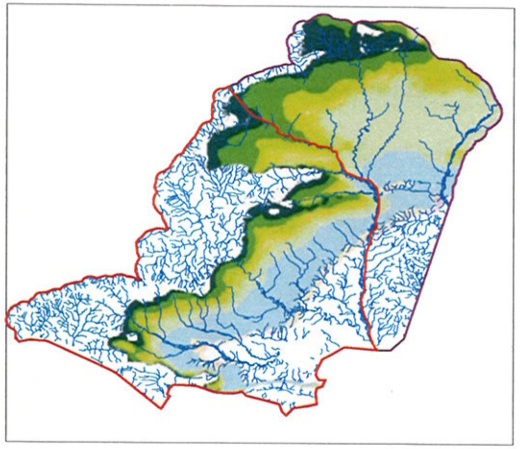
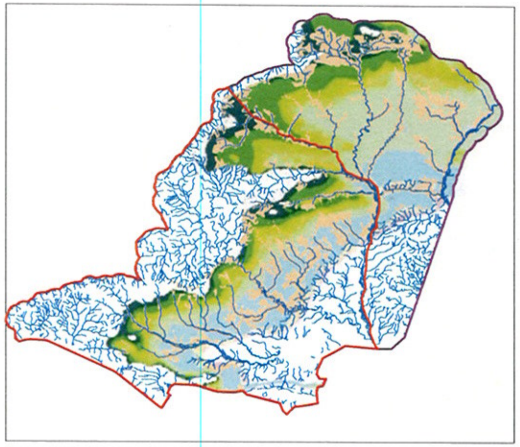
High Groundwater Level



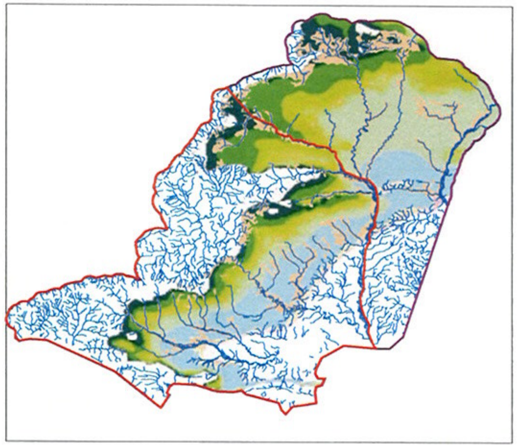
Low Groundwater Level



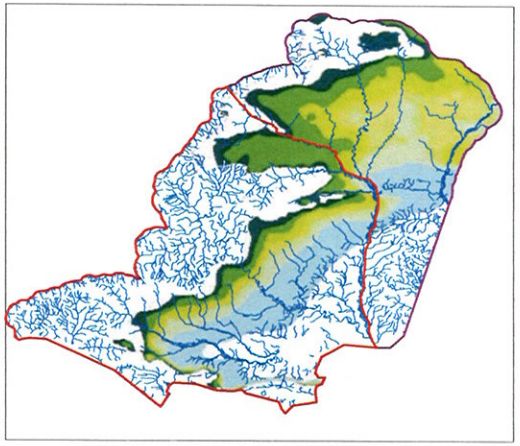
High Groundwater Level including water table within 4 m of surface



Low Groundwater Level including water table within 4 m of surface

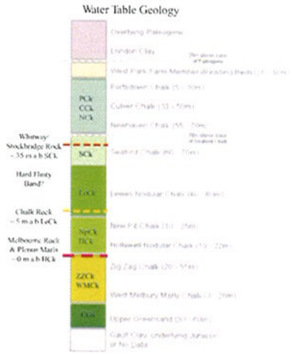


Low Groundwater Level minus 60 m



Key

- 〰 Rivers
- ▭ Runoff & Recharge area boundary
- ▭ Groundwater model boundary
- ▨ Water table within 4 m of surface



Frome, Piddle & Dorset Stour
Groundwater Modelling Project

Figure 4.16
Variation of Saturated Geological Formations with Depth

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