

1 **Modelling small groundwater systems: Experiences from the**

2 **Braunton Burrows and Ainsdale coastal dune systems, UK.**

4 **Abstract**

5 Coastal dunes are delicate systems that are under threat from a variety of human and natural
6 influences. Groundwater modelling can provide a better understanding of how these systems
7 operate and can be a useful tool towards the effective management of a coastal dune system,
8 e.g. by identifying strategically important locations for flora and fauna and guiding the
9 planning of management operations through predicting impacts from climatic change, sea level
10 rise and land use management. Most dune systems are small, typically of the size 10 - 100 km²,
11 compared with inland groundwater systems. Applying conventional groundwater modelling
12 approaches to these small systems presents a number of challenges due to the local scale of the
13 system and the fact that the system boundaries (sea, drains, ponds etc.) are close to the main
14 body of the aquifer. In this paper, two case studies will be presented using different modelling
15 approaches to understand the groundwater balance in two dune systems in the UK. The studies
16 demonstrate that, although conventional hydraulic models can describe the general system
17 behaviour, a fuller understanding of the recharge mechanisms and system boundaries is needed
18 to represent adequately system dynamics of small groundwater systems.

19 **Keywords:** Dune system, groundwater flow modelling, hydrogeology, Ainsdale, Braunton
20 Burrows, UK

1. Introduction

1.1 Dune system hydrology

Dunes are an important feature of the British coastline. In England and Wales, they often form shallow rain-fed aquifers draining to the periphery of the dune system; to the fore dunes and the beach and inland to low-lying land (Figure 1).

They typically consist of wind-blown sands (from exposed sea bed in the last glacial period) that accumulated on top of impermeable estuarine or glacial clays, which in turn form the base of the dune system aquifer and provide a distinct hydraulic barrier to the underlying bedrock strata (Robins et al. 2013; Stratford et al. 2013). The British climate provides an average annual excess of rainfall over evaporation during winter months which causes an accumulation of water within the dune systems, creating a so called “groundwater dome”, although the outflow conditions at the edges vary. The extent and height of the dome, and hence the groundwater head distribution within the dune system, is controlled by various factors including recharge, aquifer geometry and the physical properties of the sand aquifer, specifically by dune sand storage coefficient (S) and the distribution of permeability or hydraulic conductivity (K). S and K are often approximated from grain size analysis (Robins 2013) as conventional pump tests methods cannot easily be applied in thin, high conductivity aquifers where the transmissivity (defined as the product of aquifer thickness and K) declines rapidly as the drawdown from pumping increases. Moisture content profiling can be applied to help improve understanding, by providing a recharge value against which formation parameters such as K and S can then be validated (Stratford and Palisse this issue).

Geometry and spatial dimensions of the dune system are also important in controlling groundwater head distributions. The elevation of the aquifer base in relation to main drainage features, for example, controls the saturated thickness of the aquifer (b) and hence its

transmissivity (T). T is defined as the rate of flow through a unit width of aquifer under a unit hydraulic gradient and is also related to the aquifer's hydraulic conductivity ($T=b*K$). Other important factors controlling groundwater head distributions within dunes are the functionality of man-made drainage systems and the effective precipitation (i.e. the amount of water that infiltrates into the dunes following interception of rainfall on the plant canopy, recharge of any soil moisture deficit, evaporation from wet plant surfaces and transpiration by vegetation).

Each dune system has its own unique drainage characteristics (e.g. direct flow to the sea, free drainage inland, agricultural drains, controlled water levels or adjacent river with varying flows). Discharge to the beach beneath the fore dune creates a diffuse brackish zone rather than a saline wedge. This zone is flushed twice daily by the sea tides and, at low tide, a mixture of sea water and dune groundwater can often be seen discharging to the foreshore.

Land use varies between the systems, some are actively grazed whereas others are left unmanaged or have partial tree cover. The sensitivities of the water tables may differ; one site may be susceptible to changes in vegetation, another to coastal erosion and accretion or to the rainfall regime. It is important to understand these sensitivities in order that each coastal dune system can be managed to best advantage.

1.2 Dune system ecology

Coastal dunes are valuable ecological reserves within which a series of hydrological and hydroecological environments exist (Davy et al. 2006; Davy et al. 2010; Lammerts et al. 2001). The dune habitats are strongly influenced by hydrology and groundwater levels within the dune systems especially in the 'slacks', the low-lying areas between dune ridges. The water table in the slacks is near the surface, or intercepts it during periods of high water levels, but has a high

seasonal variation' (Grootjans et al. 1998). Groundwater response to recharge is different in different slack types (Lammerts et al. 2001) and lags between rainfall and groundwater level change in some systems can be 4-7 months (Jones et al. 2006). Groundwater table variations determine the abundance of many slack species, in particular in wet (humid) slacks (Willis et al. 1959a; Willis et al. 1959b). Seasonality is also important, with spring water levels controlling the breeding success of European Priority species. For example, Natterjack toads *Epidalea calamita*, which are on the ICUN red list of threatened species (<http://www.iucnredlist.org/details/54598/0>), need shallow freshwater ponds in sandy environments to breeds successfully. The ponds need to 30-100cm deep between the months of April to June, and ideally should dry out as the summer progresses (Denton et al 1997). Should the water table in these dune systems recede, these slacks will evolve from humid to dry accompanied by a corresponding deterioration in habitat variety and quality (Ranwell 1959). In order to preserve the preferred humid slack environments, dune managers need to have some understanding of likely changes in the elevation of the water table and the factors that control them.

1.3 Groundwater monitoring in coastal dune systems

Dunes have been regularly monitored (in some cases for over 40 years) using dip wells which are usually recorded on a monthly basis (Clarke and Sanitwong Na Ayuttaya 2010) although more frequent water level monitoring (e.g., at 30 minute intervals) is being undertaken at some UK dune systems, e.g., at Formby Point and at Ainsdale. These data provide information on seasonal fluctuations and inter-annual changes in groundwater levels and also the short-term response of groundwater to differing patterns of rainfall and evaporation. No clear climate change signal has yet been detected in these observations, yet climatic change and the impact

of land management is a major concern for nature reserve managers and other environmental organisations (Provoost et al. 2011).

Groundwater monitoring within coastal dune systems is driven by the need to provide appropriate data and understanding for effective dune system management. Spatial and temporal data are needed to develop a conceptual model of the hydrological/ hydrogeological functioning of the dune system. This conceptualisation can in turn be tested by numerical modelling once sufficient data are available for this purpose. The aim of any groundwater monitoring programme is, therefore, to arrive at an understanding of how a dune system operates, the changes that have occurred over a range of timescales and how those changes have impacted the hydrology and ecology of the dunes system. This knowledge informs how changes in environmental drivers or dune management may impact the system in the future.

An important aspect of groundwater data collection and monitoring within coastal dune systems is to understand and quantify the different components of the hydrological water balance (Figure 1). However, there are differences of viewpoint on the value of groundwater monitoring and modelling between the scientific community and the organisations who own and manage the dune systems. Hydrologists are interested in developing process models to assess topics such as long term climatic change effects and the effects of sea level rise whereas a managers usually want to understand the causes of shorter term inter annual variability of aquifer recharge and the impacts of changing land use policy such as grazing or removing tree cover. Nevertheless, an important aspect of groundwater data collection and monitoring is to understand and quantify the different components of the hydrological water balance (Figure 1). This includes understanding the temporal and spatial distribution of groundwater heads (such

as water table and pond levels), flow directions, rainfall recharge inputs as well as aquifer discharge, i.e. inland seepage or groundwater flow towards the sea.

1.4 Groundwater modelling of coastal dune systems

While water level observations provide valuable information, they alone do not explain the processes that drive changes in groundwater levels. A key way of dealing with this problem is the development of dynamic groundwater models, either conceptual or distributed numerical groundwater flow models. Both are data intensive techniques, but a validated groundwater model would enable ‘what if’ scenarios to be tested and the model to be tested on likely impacts of human or natural changes.

A number of different modelling approaches of differing complexities have been applied to understanding groundwater flow and solute transport in dune systems. The simplest is a water balance approach in which inflows and outflows are calculated and compared to storage changes in the aquifer (e.g. Jacobson and Schuett 1984). Analytical solutions, exact solutions of governing equations, have been applied at some sites and examples include a comparison of deterministic models with analytical element approaches which have been undertaken to simulate abstraction for the Amsterdam Water Supply (Olsthoorn, 1999).

Simple regression or other “black box” approaches, in which processes are not explicitly represented, can be applied but must be used within observed limits (e.g. Wheeler et al, 2015).

Otherwise, they may predict water levels that are physically impossible by extrapolating a fitted line between rainfall and water table levels. Another approach might be to develop a point or lumped model (e.g. Mackay et al., 2014) where the whole system is considered to be uniform, i.e. with constant vegetation cover and uniform distributions of grain size and permeability.

This has the advantage of simplicity but a disadvantage is that dune systems are heterogeneous.

A more usual approach is to develop a model that is spatially distributed (e.g. MODFLOW

model of St. Fergus dunes; Malcolm and Soulsby, 2000). The disadvantage is that gaps in data need to be identified and addressed, although the modelling process itself can identify these gaps (e.g. Jackson et al, 2005). Understanding spatially distributed parameters will lend itself to a regional distributed groundwater model.

A specific challenge in dunes system modelling is the representation of slacks (and groundwater-fed ponds) which can form a direct outflow from the groundwater system through evaporation (Winter and Rosenberry 1995) and, hence, can significantly impact the overall water balance. They are by their nature ephemeral, appearing in winter after periods of recharge and disappearing during summer when groundwater heads are low. As such they are similar to groundwater fed, ephemeral lakes and can be modelled using approaches for modelling Eskers (Ala-aho et al. 2015), groundwater-fed lakes (Lubczynski and Gurwin 2005) or Turloughs (Gill et al. 2013). However, the challenge for modellers is dealing with groundwater when it appears above ground level, particularly translating it into a surface water system (pond or lake), groundwater inflow and accounting for evaporation. Potential approaches include using fully-featured models such as Mike-SHE (e.g.(House et al. 2015), MODFLOW lake package (Merritt and Konikow 2000) or combining bespoke pond models with groundwater models using dynamic model linking techniques such as OpenMI (Knappen et al. 2013).

Given the proximity to the sea salinity can be an issue in terms of groundwater flow and abstraction in relation to saline intrusion (Essink 2001). A number of studies have been undertaken using variable density modelling to address this, particularly where groundwater is being abstracted from the dune system. The coastal Belgium dune systems have been extensively researched and a number of models created to help understand the challenges of sustainably extracting groundwater from dune systems. Vandenbohede et al. (2009) report the use of MOCDENS3D to simulate how groundwater abstraction in Westhoek, Belgium affects saline intrusion from the sea into a dune groundwater system.

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2 170 The aim of this paper is to demonstrate how differing approaches to developing groundwater
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5 171 models can lead to a) better understanding and improved conceptual models of the groundwater
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7 172 systems, b) identifying the key drivers that affect water table levels and changes such as
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10 173 recharge and boundary conditions, c) the suitability of existing data to validate and test the
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12 174 conceptual models, including identification of additional data requirements and d) being able
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14 175 to simulate adequately seasonal, inter annual and longer term trends in groundwater levels.
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19 177 Groundwater level observations have been recorded at over 10 dune systems in the UK and
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22 178 Northern Ireland, including Sefton, Braunton, Newbrough, Sandwich, Seascale, Whiteford,
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24 179 Merthyr Mawr, Point of Ayr, Magilligan and Portstewart. We selected two sites for our case
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27 180 studies which have the longest continuously monitored records of groundwater levels in the
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29 181 UK – Braunton Burrows in Devon, South East England (40 years) and at Ainsdale in
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31 182 Merseyside, North West England (44 years). Models for the two groundwater systems were
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34 183 developed independently using different approaches (3D finite difference, distributed model at
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36 184 Braunton Burrows and 1-D recharge distributed spatially at Ainsdale) to demonstrate that
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39 185 modelling provides a better understanding of the systems and assists in identifying what data
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41 186 are crucial to produce functioning groundwater models. In the paper we will assess the ability
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44 187 of groundwater models to represent dune system hydrology validated by historical data in order
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46 188 to evaluate if such modelling is reliable enough to have a role in influencing dune management.
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2. Case studies

2.1 Braunton Burrows

Background

Braunton Burrows is a spit dune system in the south west of Britain (Figure 2a), about 5km long (north south) and 1½ km wide. The area comprises a series of north to south oriented dunes and slacks shaped by the prevailing on-shore winds. The slacks are mainly dry with ephemeral wet weather pools and these are sensitive to the groundwater elevation (Davy et al. 2010). The dunes system rests on an estuarine clay layer which forms the base of a small rain-fed sand aquifer (Burden 1998). The clay is underlain by Pleistocene beach deposits and/or by the Devonian Pilton Mudstone Formation which forms a low-yielding aquifer, with little to no hydraulic contact between the Devonian bedrock and the sand aquifer. Stratford et al (2013) have found that water levels in the dunes have been gradually declining since 1966 by about 0.7m in winter and slightly more in the summer and this has raised concerns of the ‘drying out’ of the dune system (English Nature 1992). A groundwater modelling study was instigated to better understand the controls on the dune groundwater system and to investigate possible reasons for the observed water level decline.

Conceptual model

Water level time series data have been collected at various locations on Braunton Burrows since 1966 (Figure 3, open circles). Over time, some of these dipwells fell in to disrepair, and additional dipwell transects were installed in 1972 (Figure 3, black circles) and 1992 (Figure 3, black triangles) and have been monitored on a monthly basis ever since. This data provided the basis for the conceptual model of the dune groundwater system in Figure 2a (Robins 2007).

The dune system is predominantly rain-fed, with possible inflows from the Saunton Downs in the north. The water table is mounded within the sands with a broad groundwater divide to the east of the dunes system's central axes (N-S), suggesting that the Burrows drain largely towards the coast. A small area of Braunton Burrows drains to the east towards Braunton Marsh where the discharge is intercepted by the West Boundary Drain with flows typically $<0.5 \text{ l s}^{-1}$ during the summer months (Robins 2007). The long term (1961 to 2012) average annual net (rainfall – actual evaporation) is 453 mm (as calculated from MORECS data). This suggests that in most years, rainfall recharge sustains the groundwater system.

Model development

Model development consisted of a series of steps including:

- (1) Grid construction and initial parameterisation
- (2) Sensitivity analysis
- (3) Dynamic balance simulation
- (4) Model calibration.

Grid construction and initial parameterisation

A simple one-layer groundwater flow model was constructed in ZOOMQ3D (Jackson and Spink, 2004) using a uniform grid (cell size 200x200 m) (Figure 2b). Boundary conditions were assigned based on the conceptual understanding provided by Robins (2007). The western and southern model boundaries were located half-way between the low and high (tidal) water mark and constraint by a Dirichlet-type head boundary, representing the mean sea water level. In the north and north-east, no-flow boundaries were assigned representing the contact to the Devonian cliffs and marshland clays, respectively. The south-eastern model boundary coincided with the Western Boundary Drain (WBD) and was represented by series of one-way leakage nodes (Cauchy-type). The model is spatially-distributed, predicting the spatial

distribution of water levels within the dune system as a function of time and a variety of spatial variables (i.e. recharge, aquifer depth, permeability).

Previous studies suggest that there is little spatial variation in aquifer depth, particle size or hydraulic conductivity across the dune system (Burden, 1998; Allen et al., 2014). Hence, a uniform distribution of hydraulic conductivities (10 m d^{-1}) was initially assumed across the entire model domain. The aquifer base was set to 0 m AOD, based on evidence presented by Burden (1998) who identified the presence of an impermeable, silty/clay layer at approximately that depth (mean sea level) at five locations across the site. Recharge was calculated using the recharge model ZOODRM (Mansour and Hughes 2004) with rainfall and Evapotranspiration data from the Bideford weather station (10 km inland) and from MORECS (40 km x 40 km integrated value), respectively. The model was run from 1st January 1970 to the 31st December 2014 using a daily time step. The calculation method used is the modified FAO (Hulme et al., 2001) using soil parameters from soil maps and crop parameters from a combination of Land Cover Map 2000 (Fuller et al., 2002) for their spatial distribution and literature values (Hulme et al., 2001). Temporally varying recharge was calculated, but the same value was applied across the entire model domain, i.e. assuming that there is no spatial variation in recharge across the site.

Sensitivity Analysis

To examine the sensitivity of the model results to the input parameters and model geometry, a series of steady state model simulations were performed. A base run was carried out by running the model using long term average (LTA) recharge inputs until it reached steady state (after about 5 years). Model sensitivity was then tested by modifying a single model parameter and assessing the resulting change by comparing the outputs to those from the original base model

as well as to long term average groundwater levels observed at the 17 active monitoring wells across the dune site (see black circles and triangles in Figure 3). Sensitivities to hydraulic conductivity, aquifer base level, boundary location, leakage node elevation and leakage coefficients were tested as detailed in Table 3.

Boundary conditions were tested and revised as part of the sensitivity study. To address uncertainty around the north-east boundary, a field visit was conducted to map relevant drainage features. The survey revealed the presence of a small stream, entering the model area from the north, as well as a small drainage ditch along the north-eastern boundary. Subsequently, features were included in the model by adding river nodes as well as one-way head dependent leakage nodes along the northeastern boundary (Figure 4a).

From the sensitivity analysis, a best fit model was selected and adjusted within the tested parameter range (Table 1) until the modelled groundwater heads (e.g., Figure 4b) agreed reasonably well with observed water levels. Agreement was tested by comparing modelled (steady state) water levels against observed LTA water levels for three transects across the site (see Figure 3). The model which produced profiles that best matched the envelope of minimum-maximum observed water levels was selected as the best fit model for further simulations (Figure 5).

Dynamic balance simulation

A dynamic balance simulation was performed to obtain the correct initial conditions for the time-variant simulations (Rushton and Wedderburn 1973) and to ensure that the model reproduced the seasonal, time-variant dynamics of the dune system adequately. It consisted of a series of repetitive model runs applying monthly average recharge inputs over a cycle of three years. Successive runs were identical except for initial heads, which were replaced by the

computed heads from the preceding run. Outputs were compared to the previous run in the series as well as to observed LTA monthly water levels. The runs were repeated (each time with a new initial head condition) until the computed heads followed the same cyclical pattern during consecutive runs (i.e. heads from the latest run (blue line in Figure 6) were identical to those of the previous run (red line in Figure 6)). A dynamic balance was reached when the net change in computed heads over a year was zero, despite changes in aquifer storage between the months. The dynamic balance head distribution provided the initial groundwater heads for all subsequent simulations.

Model calibration

Model calibration was carried out using time-variant simulations. Since monthly time steps could not represent the observed system dynamics accurately, a daily time step was used. The ZOODRM model was re-run (as detailed previously) employing daily rainfall data from the CERF model - a regionalized rainfall-runoff model (Griffiths et al. 2008) which includes a national data base of daily rainfall (measured by the UK Meteorological Office) at the 1km scale. Rainfall data from CERF were available for the period from 1983-2006, determining the modelling period for all subsequent runs.

Calculated head distribution from the dynamic balance was used as initial head conditions in all calibration runs. The model was run at a daily time step for the period from 1983 – 2006. Outputs were compared against observed water level data for the 17 observation wells (black circles and triangles in Figure 3), visually by plotting modelled against observed water levels and quantitatively, by calculating the Nash-Sutcliffe efficiency (NSE) and the Root Mean Square Error (RMSE) for each run.

Calibration started with a simple base case of uniform transmissivity distribution (i.e., uniform hydraulic conductivity (K) and aquifer base elevation (z)) and porosity across the entire model

domain. Model complexity was gradually increased during the calibration process to include 4, 6 and 12 zones across which transmissivity was varied by changing K or z. Initially, delineation of zones (4 & 6 zones) was based on the understanding that (1) the bedrock surface beneath the dunes, and hence the base of the aquifer (z), is sloping towards the sea (May 2001) and (2) that the hydraulic conductivities (K) change inland towards Branton Marsh (Burden, 1998). Later, a pilot geophysical survey was initiated using passive seismic (TROMINO®) technology to better constrain aquifer base elevations across the model area. Using these data, a more detailed delineation of transmissivity zones (12 zones) within the dune system was derived.

The use of transmissivity zones was preferred in this study to reduce the number of ‘free’ parameters for calibration (Refsgaard 1997). Instead of varying aquifer base elevation (z) and hydraulic conductivity (K), one parameter, usually z, was fixed for the entire study area while the other one (K) was adjusted during calibration to simulate variations in transmissivity (T). Hence, values of K derived in this study present an adjustment factor for T, not a hydraulic conductivity per se.

Monte Carlo runs were conducted for both, simple (1 zone) and more complex (4, 12 zones) transmissivity distributions to identify the best parameter sets for calibration. Each model setup was run for up to 10,000 iterations, varying transmissivity (K or z) or aquifer storage (S) parameters during each iteration and for each zone randomly within a predefined range (Table 2). A variety of error measures (including NSE) were computed. However, from the computed error measures (which included NSE) it was not possible to identify best parameter values for the different zones (e.g., Figure 7). Hence, a trial-and error method (Refsgaard and Storm 1996) was adopted, manually adjusting either K or z or S within the different zones (while keeping

all other parameters constant) and observing the resulting model fit visually through plots and quantitatively through calculation of the NSE and RMSE.

Model validation, as commonly used in surface water modelling, is not undertaken here as it is not considered useful or even possible within the context of groundwater modelling (Anderson et al. 2015, Konikow and Bredehoeft, 1992). Because of the large numbers of parameters involved, Doherty and Hunt (2010) advise using all available data in the calibration process as omitting any data is likely to result in a poorer calibration.

Results and Discussion

Figures 5-11 and Table 3 summarise key outputs and model performance measures from the different stages of the model development process.

Sensitivity analysis: The final run of the sensitivity simulations, i.e. the selected best fit model, is shown in Figure 5a & b. Figure 5a shows a satisfactory match between the modelled water levels (solid line) and the observed minimum and maximum water levels (broken lines) along the three transects (shown in Figure 3), with better agreement in the northern part of the dune system (Transect 1) compared to the south. Water level contours produced by the model (Figure 5b) were very similar to observed water level contours, e.g., as presented by Burden (1998) and Willis et al. (1959b) and hence, this model was taken to be a satisfactory starting point for further model development.

Dynamic balance: Results from the dynamic balance simulation are shown in Figure 4 for selected observation wells. Initial runs (not shown) displayed a time lag of around one month between the overserved and the modelled seasonal signal, representing the average time needed for effective precipitation at the surface to reach the groundwater table (Moon et al. 2004).

Applying a lag correction of one month to the recharge data resulted in better agreement between modelled and observed system dynamics (Figure 4).

Model calibration: Figure 8 shows output from the Monte Carlo simulations for the uniform (1 zone, see Table 3) transmissivity distribution. In this example, the base of the aquifer was fixed at -2 m AOD, but transmissivity of the zone was varied by randomly varying hydraulic conductivities within the range defined in Table 2. In Figure 8, K values for each run are plotted against the corresponding NSE (green dots representing $NSE \leq 0$ and red dots representing $NSE > 0$) for the 17 observation wells (OBHs) in the study area. The plots show that the K values required to achieve a good model fit vary between the different monitoring wells, suggest that transmissivity (T) varies across the model area. There is a general decrease in K (and hence T) from the western to the eastern boundary, which could indicate a decrease in aquifer saturated thickness (e.g. due to a sloping bedrock surface (May 2001)), a decrease in hydraulic conductivity (Burden,1998) or both. At a number of observation wells, including OBH 6, 12 and 17, NSE remains below zero, i.e. water level fluctuations at these wells could not be simulated satisfactorily by any of the runs. Their location near the edges of the model suggest that the boundary conditions may need to be revised in order to improve the model fit in these areas. A model run was conducted using a K of 10 m d^{-1} . Model parameterisation and performance (NSE and RMSE) are recorded in Table 3 for the different wells. Model fit is predictably poor with an average RMSE of 1.44 (range 0.34 – 3.29) and a $NSE > 0$ at only 2 (12%) of the 17 observation wells. This confirms the conclusion that a single T zone ($z = -2 \text{ m AOD}$, $K = 10 \text{ m d}^{-1}$) cannot describe the dune system hydrology adequately.

An attempt was made to use Monte Carlo for an increasing level of complexity, e.g., including 4 transmissivity zones (Figure 7a) within which K was simultaneously varied within a predefined range (Table 2). The results are shown in Figure 7b for OBH 1, and demonstrate that

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385 this introduced too many degrees of freedom and resulted in non-identifiability. Consequently,
386 calibration was continued by manual parameter assessment through a number of simulation
387 runs.

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389 Defining four and six transmissivity zones (as shown in Table 3) to simulate a gradual increase
390 in transmissivity towards the sea improved overall model performance. Both models were able
391 to reproduce the general water level distribution (i.e. mounding of the water table to the east)
392 Figure 9 as well as the seasonal dynamics of the dune groundwater system Figure 10. Model
393 outputs from the 6-zone model compared reasonably well with observed water levels in the
394 central part of the dune system (e.g., OBHs 1-5, 11, 15) (Figure 10, Table 3), but water levels
395 were overestimated (e.g. OBHs 6, 8, 12, 13) or underestimated elsewhere (e.g., OBHs 9, 10).
396 There is a noticeable discrepancy between modelled and observed water levels in all the
397 observation wells. This discrepancy is greatest during the last three years of the simulation
398 (2003-2006) (e.g., OBH 11, Figure 10). This discrepancy cannot be explained by model
399 performance alone but is more likely to be linked to the driving data (i.e. rainfall) as will be
400 discussed later. Consequently the error measures in Table 3 were calculated for the period 1983
401 – 2003 (i.e., excluding the last three years of simulation) to account for this.

402 Overall model performance (Table 3) was better for the 6-zone model than for the 4-zone
403 model, increasing the number of observation wells with $NSE > 0$ from three (18%) to five
404 (30%) out of a total of 17. The RMSE also improved from an average of 0.94 (range 0.36 –
405 2.36) to 0.64 (range 0.32 – 1.36). Through adjustment of K, model fit could be improved
406 locally but this caused deterioration in model fit elsewhere, hence the overall model fit
407 remained poor. This indicates that the spatial distribution of transmissivity (and probably also
408 recharge) is more complex than represented by these models. In the absence of additional data,

409 it was felt that calibration could not be improved without making unjustifiable assumptions and
 410 that further data, relating to aquifer base topography or K distribution were required.
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 412 A pilot geophysical survey of the bedrock depths was initiated as part of this modelling study.
 413 Based on the data derived from this work, a more detailed delineation of transmissivity zones
 414 was possible. The findings that are of relevance here, include the following points: (1) the
 415 bedrock topography underlying the model area is more complex than initially assumed, (2) the
 416 depths to bedrock generally increases from around -10m AOD in the west to 0.5m in the east
 417 (confirming that the underlying Devonian shelf platform is tilting seawards as suggested by
 418 May (2001)) with a ridge of slightly higher relief in the central part of the dune system, (3)
 419 Depths to bedrock of -34 m to -17 m AOD are observed at the northwestern boundary of the
 420 dune system and at locations in the northeast and southeast of the dune system, respectively.
 421 The extent of these features needs to be investigated further, but they may represent deep
 422 channels or depressions (D.Boon, 2015, personal communication), similar to the Pleistocene
 423 'rock-valleys' near Plymouth (Eddies and Reynolds 1988) or the 'buried channel' in Bideford
 424 Bay, immediately south of the Braunton Burrows site, which was estimated to reach a depth of
 425 about -30 m AOD (McFarlane 1955).
 426 Translating the new understanding into a transmissivity distribution resulted in the definition
 427 of 12 transmissivity zones (Table 3, Figure 11), including a high transmissivity zone in the
 428 north (possibly representing a sediment-filled channel). The bedrock depressions along the
 429 eastern boundary were not considered as separate zones in this distribution as the shape and
 430 extent of these features could not be sufficiently defined from the available data. A new aquifer
 431 base of -5 m AOD was assigned, representing the average bedrock depths observed during the
 432 geophysical survey. Monte Carlo runs were conducted for each zones separately to provide
 433 initial K estimates, which were then adjusted using a trial-and-error calibration method.

The results are summarised in Table 3. It shows a considerable improvement in overall model performance, with 12 from 17 observation wells (70%) displaying a $NSE > 0$ compared to 5 from 17 (30%) for the 6 zone model. Improvement in model fit is also reflected by the lower average RMSE of 0.40 (range 0.25-0.84) compared to the previous 0.64 (0.32 – 1.36).

The water level dynamics are generically well reproduced by the model (Figure 11), except in OBH 6, where water level variations are less dynamic than predicted. Overall water levels are predicted correctly by the model, except at OBH 10 (not shown), where water levels are underestimated by about 50 cm, and OBH 17, where they are overestimated to a similar degree.

There is still a discrepancy between modelled and measured data, which is observable in all hydrographs in Figure 10 and 11. Examining these hydrographs more closely shows that this discrepancy appears to start in the early 2000s. For example, the observed groundwater levels show a significant fall in late 2001 before levelling off, whereas the modelled response is a continued cyclical decrease in groundwater head. There appear to be a number of rainfall events (smaller and one larger) in the observed data which are not reproduced in the modelled response. For example, the observed response shows an event in early-mid 2004 which leads to a rise in groundwater heads in all OBHs across the site but is not seen in the modelled response. This event could result in the groundwater system receiving a large mass of recharge which slows the year on year reduction of groundwater heads within the dune aquifer. If these events were not captured in the gridded rainfall data, used here to drive the model, this could explain why modelled water levels decline whereas the observed data show a level response.

2.2 Ainsdale (Sefton coast)

The Sefton Coast stretches 20 km between Crosby and Southport in Merseyside, UK. The coastline consists of a dune system 2-3 km wide, running parallel with the coast (Figure 12).

Average rainfall in the area is approximately 800 mm y⁻¹ and evapotranspiration is around 500 mmy⁻¹. The dune system comprises approximately 25 km² of open dunes, forest and golf courses and the built up areas of Formby, Ainsdale and Southport. The dunes rise to 20m above sea level and rest on a bed of peaty clay which effectively seals it from deeper Triassic sandstone aquifers. The dune system is home to a number of nature conservation sites and Nature Reserves, the largest of which is Ainsdale Sand Dunes National Nature Reserve, established in the 1960s. The Reserve aims to protect ecosystems which include the seasonally flooded low-lying areas (slacks) between the dune ridges.

Conceptual Model

A set of 12 observation wells were installed at 500 m spacing on the dune system in the early 1970s to monitor groundwater levels on a monthly basis. Contour maps of the levels demonstrated the existence of an elongated mound of groundwater which runs parallel to the coast and from where groundwater drains inland and towards the coast as shown in Figure 12. The highest point of the groundwater mound is 10 m AOD and the typical seasonal variation in groundwater levels is +/- 0.5 m (Figure 13). Highest water table levels occur at the end of the winter season around March when many of the dune slacks are flooded to a depth of 0.1-0.3 m (Clarke and Sanitwong Na Ayuttaya 2010). There appear to be sequences of wet years and dry years in the data but no long term trend can be detected from this 40 year record.

Model development

Clarke (1980) and Clarke and Sanitwong Na Ayuttaya (2010) describe groundwater models based on a water balance between rainfall, evapotranspiration and groundwater flow. This represents a point/lumped model to predict water levels at a selected location within the dune

system as a function of time (but not of space). Key inputs are rainfall and an estimate of actual evapotranspiration. Rainfall data were available from a local meteorological site, which also provided the climatic data to estimate potential evapotranspiration using the Penman Montith equation (Allen et al 1994). Actual evapotranspiration is calculated using a soil root zone storage model and assumed that surface runoff occurs rarely and only when multiple interconnected slack floors are flooded. When the soil water in the root zone is full (i.e. the soil moisture deficit is zero), and any surplus water is assumed to percolate vertically down to the water table. The groundwater balance is computed on a daily time step. Groundwater flow out of the dune system is calculated using the Dupuit formula. The flow is a function of the sand permeability (K) and thickness (b) and the water table gradient towards the sea or inland. In this model the permeability and thickness were assumed to be constant over the study area. At the end of each day, the elevation of the water table at the modelled location is updated based on the balance between the groundwater outflow and the aquifer recharge. On dry days the soil is assumed to dry out first and the water table will descend based on its current height and the dune permeability. On very wet days surplus water percolates to the water table and raises it by a vertical distance of recharge (in mm)/n where n is the effective porosity of the dune sand. When the water table is above ground level, n is set to 1. The model then carries the computed water table level forward to the next day (time step) when the calculation is repeated. This produces a time series of modelled water table levels.

Sensitivity analysis and model validation

The model was initially developed for one site, located in the open dunes in northern part of the area. It was calibrated using parameter optimization based on measured values of sand permeability (K) and dune system thickness (b), the spatial distribution of vegetation/open water areas (which affect evaporation rates), and soil water storage characteristics such as dune

total porosity (n) and the effective porosity (n_e), which changes from 0.28 in clean deeper dune sand to 0.2 in the vegetation close to the surface and 1.0 above the surface. The model was run for a period of 30 years and with successive refinements to values for the dune sand permeability, porosity and aquifer thickness. Typical values for K for blown sand are reported between 8 m d⁻¹ to 15 m d⁻¹ (Freeze and Cherry 1979) and n between 0.35 and 0.4. Model results for the two extremes of K are shown in Figures 15a and 15b. Setting the permeability to the upper value of 15 m d⁻¹ results in too much leaving the model as groundwater flow, and the predicted water table levels are consistently lower than the observed levels (Figure 15a). When K is set to the lower value of 8 m d⁻¹, not enough water leaves the system as groundwater flow and the predicted levels are higher than observed (Figure 15b). Over the 30 year test period, it was found that a value of $K=11$ m d⁻¹ resulted in the average modelled water levels being closest to the observed data (Figure 15c). The amplitude of seasonal variation in modelled water table levels was found to be highly dependent on the effective porosity. The laboratory determined dry dune sand porosity was 0.39 but model outputs suggest the amplitude between winter and summer was too small. As the natural dune system retains some water in capillary spaces between the sand grains, the effective porosity (n_e) of the sand should be <0.39. A sensitivity analysis showed that when the water table was >0.5m below ground level the best fit value of effective porosity (n_e) was 0.28. This was adjusted as the water table rose closer to the surface and in the top 50cm n_e was set to 0.2 and above the ground level, n_e =1.0 (i.e. 100% air space).

Two measures of goodness of fit were used to evaluate model performance – the root mean square error between observed and modelled levels (RMSE) and the Nash-Sutcliffe efficiency coefficient (NSE). Values of these measures are shown in Figure 15 when the model is applied to a typical observation well in the dune system. The best model fit (RMSE=0.12m, NSE=0.84) was found to occur when permeability (K) was set to 11 m d⁻¹, effective porosity (n_e) to 0.28

for the dune sand deeper than 50cm, rising to 1.0 at the surface (i.e. open air) and the dune sand thickness (b) equal to 60 m (Figure 15d).

Following testing and calibration, the model was able to reproduce the vertical changes in water table levels within +/- 10cm over a 30 year period. The model was applied to two other wells, one in the open dune fields close to the sea and another under the pine forest further inland. In both cases, the model parameters required adjustment and re-calibration as the vegetation cover differed. In the case of the dune fields closer to the sea, there is a larger area of slacks and fewer dune ridges. This affected the soil water balance and in winter time, the flooded slacks joined up and were able to generate some overland flow in addition to the groundwater flow. Under the pine trees, the effects of rainfall interception had to be included in the model, based on the algorithms suggested by Calder (2005). In both cases, the adjusted models were able to replicate observed water table levels. However, the general applicability of the water balance approach to different parts of the dune system required fine tuning to the specific sets of conditions at each location.

3. Discussion

In the previous sections, we have described two independent approaches for modelling dune groundwater systems, (1) a three-dimensional, numerical groundwater flow model (ZOOMQ3D) with spatially distributed parameters for dune system properties and (2) a one-dimensional single-point / lumped parameter model, to simulate groundwater flow in small sand dunes systems at Branton Burrows and Ainsdale, respectively.

Developing the groundwater flow of the Branton Burrows dune system has shown that a higher degree of model complexity/heterogeneity has been required than was initially

anticipated based on the conceptual model. Whilst the system itself is of relatively modest size
 (8 km²) and has been subject to a variety of surveys and studies (e.g. Mcfarlene 1955; Kidson
 & Carr 1960; Kidson et al 1989; Burden 1998; May 2001; Stratford et al. 2013; Allen et al.
 2014), quite a high degree of uncertainty was discovered during model development relating
 to the definition of the model boundary conditions (e.g., drainage conditions in the northeast
 of the model domain) and the transmissivity distribution within the model domain.
 Simplifying assumptions had to be made during the early stages of model development, but
 these were gradually adjusted using sensitivity analysis. The importance of such an analysis in
 defining the correct model boundary conditions has been demonstrated by Hunt et al., (1998).
 Targeted field investigations were an important part of the model development process,
 specifically the geophysical survey, which provided an improved characterization of the
 bedrock topography and led to a more detailed delineation of transmissivity zones within the
 model domain. Constructing models with increasingly more complex spatial distributions of
 transmissivity within the model domain, led to considerable improvements in the fit between
 predicted and observed heads.
 Calibration of transmissivity (T) (= one parameter) rather than hydraulic conductivity (K) and
 depths to aquifer base (z) (= two parameters) was chosen here to reduce the degrees of freedom
 or “free parameters” in model calibration, as proposed by Refsgaard (1997), and to reduce the
 problem of equifinality or non-uniqueness in numerical modelling (Beven 2006), which says
 that there are many different conceptualizations of a numerical groundwater flow model that
 fit the observed data equally well. This problem has been demonstrated by the Monte Carlo
 analysis (Figure 7), where many different combinations of T resulted in the same or similar
 NSE values (despite the reduction in free parameters). This non-uniqueness is also the reason

for why numerical groundwater models cannot be truly validated (Konikow and Bredehoeft, 1992) and why their use must be constraint by their inherent uncertainty (Wondzell et al., 2009).

In the Braunton Burrows model, model uncertainty need to be reduced and the problem of equifinality must be further investigated. While the topography of the aquifer base (i.e. z) is relatively well-constrained by the data from the geophysical survey, there remains large uncertainty relating to the distribution of hydraulic conductivity (K) within the dune system. The inability of the model to reproduce the observed water level response in some parts of the model may indicate that the distribution of hydraulic conductivities across the model domain is not as uniform as Burden (1998) and Allen et al. (2014) suggest. Recent drilling in the central part of the dune system has revealed the presence of coarse sands and gravels at depths within the dunes (D. White, 2015, personal communication), hence challenging the general assumption that sand-blown dune systems consist of uniform, well-sorted granular sediments throughout. Furthermore, the lack of water level data in the north of the dune system must be addressed and an improved understanding of how rainfall events in 2004 influence recharge is required.

Groundwater modelling is often considered to be a linear process, consisting of a series of successive steps as, for example, outlined in Hobma et al. (1995). The present study illustrates that it should be a more iterative process and that modelling should be carried out in conjunction with field studies, i.e. not as a postscript, but as ongoing interaction. This interaction is required throughout the investigation process. The importance of feedback between numerical modelling, conceptual modelling and data collection is increasingly recognised in the

modelling of dune systems (e.g. Spring (2005)) as well other groundwater systems (Voss 2011).

The simple, conceptual modelling undertaken for the Ainsdale Dune system demonstrated that such a model could be calibrated with reasonable generic hydraulic parameters ($K = 11 \text{ m d}^{-1}$; $n_e = 0.28$). There are a number of observation boreholes on the Ainsdale site and the model transferability was tested by applying it to two more boreholes. However, adjustments were required as at one location the dune slack generation was more pronounced, and the other was covered by pine trees. For the latter, the recharge module of the model needed adjustment to take into account interception. The changes required by the model illustrate the variability within a small site. The subtle variation of land use and surface response required changes to the model structure thus reinforcing the need for interaction and subsequent flexibility within the modelling methodology.

The modelling process is often represented by a flow chart to illustrate the interaction between different activities. Figure 16 shows an extension to those typically presented in the literature (e.g. Anderson et al. 2015) and illustrates the approach adopted in this study. It shows that modelling is not just a passive activity, but one that involves developing a conceptual understanding of the system, encapsulating this into a numerical model and then testing the model results against observed data (e.g., during model calibration). This process enables the observed data to be actively interrogated and not just examined passively. The result is that the model can show the user whether their conceptual model, when translated into a groundwater model, reproduces the observed response.

In first runs of models, a poor fit is usually found between the water table levels observed in the field and the model-generated data. This often forces the modeller to return to the

conceptual model or to question the data used to parameterise or run the model (e.g. the representativeness of the available dune property data or the scale at which rainfall or evapotranspiration data are employed). This interactivity is key to heuristic learning, i.e. learning by someone doing something themselves, and helps guide the user through developing their understanding of the system and identifying important controls. Voss (2011) points out that rather than use automatic calibration the interaction between the user and the model should be “learning something from a model-based analysis”.

4. Conclusions and recommendations

- Data collection in dune systems was initially instigated in the UK in the 1970’s to monitor system behaviour, but managers of these systems realised that large variations in water table levels could not be explained as a simple response to rainfall or changes in land use practices. Groundwater models provide effective tools to explore what controls such water level variation and to investigate the hydrology of dune systems.
- Two modelling approaches were presented in this study which differ in complexity, but which both have produced models that successfully describe the water table variations in the simulated dunes systems.
- A high degree of model complexity and between-site adaptations in model structure were required to be able to reproduce the dune systems’ behaviour. This illustrates that these systems are hydrologically complex despite their small size and clear boundaries. Factors such as bedrock topography, land use and local climatic conditions are important controls on their hydrological response and hence, need to be described adequately by the model. The general assumption that sand-blown dune

systems have a uniform and well-sorted sediment composition, and hence a uniform K distribution, needs to be investigated for each dune site individually and treated cautiously until proven by representative field surveys.

- Because of their small size, models representing such small aquifer systems are more sensitive to uncertainties in input data (i.e., basic driving data such as rainfall and evaporation), model geometry (positioning of model boundaries) and model parameterisation as well as to changes (i.e. land use) that occur during the simulation time period. Thus it is critically important to collect time series data (e.g., rainfall, evapotranspiration, water levels) at relevant temporal and spatial scales and also to explore the dune system for variations in thickness, land cover, grain size distribution and permeability.
- The case studies have demonstrated that modelling can support the development of systems understanding through repeated interrogation of the model outputs, observed data and conceptual understanding. This process usually raises question relating to conceptual understanding and data availability. It is therefore important that modelling is carried out in parallel to field investigations and monitoring, ideally during earlier stages of the research project, so that it can inform researchers and managers of important data needs or identify locations where additional monitoring or data collection would result in improved system understanding and reduction in uncertainty.
- Modelling should be an iterative process which guides the user towards a better understanding of the modelled system. Deficiencies in the model in reproducing the observed response, both spatially and temporarily, point the modeller to where further data and/or process understanding is needed.

- Given that the role of modelling is to raise questions as well as to answer them, this study has demonstrated that this applies even in small systems that are thought to be well understood.

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5. References

- Ala-aho P, Rossi PM, Isokangas E, Kløve B (2015) Fully integrated surface–subsurface flow modelling of groundwater–lake interaction in an esker aquifer: Model verification with stable isotopes and airborne thermal imaging J Hydrol 522:391-406
- Allen, D, Darling, WG, Williams, PJ, Stratford, CJ, Robins, NS (2014). Understanding the hydrochemical evolution of a coastal dune system in SW England using a multiple tracer technique. Applied Geochem 45: 94-104.
- Allen RK, Smith M, Perrier A, Pereira LS (1994) An update for the calculation of Reference Evapotranspiration. ICID Bull 43:35-92
- Anderson, M.P., Woessner, W.W. & Hunt, R.J. 2015. Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Elsevier Academic Press.
- Beven, K. 2006. A manifesto for the equifinality thesis. J Hydrol, 320, 18-36.
- Burden, R.J. 1998. A hydrological investigation of three Devon sand dune systems: Branton Burrows, Northam Burrows and Dawlish Warren. PhD, University of Plymouth.
- Calder, I.R. 2005. Blue revolution: integrated land and water resources management. 2nd edition ed. Earthscan.
- Clarke, D. 1980. The groundwater balance of a coastal sand dune system. PhD thesis, University of Liverpool.

- Clarke D, Sanitwong Na Ayuttaya S (2010) Predicted effects of climate change, vegetation and tree cover on dune slack habitats at Ainsdale on the Sefton Coast, UK. *J Coastal Conserv* 14:115-125 doi:10.1007/s11852-009-0066-7
- Davy A, Grootjans A, Hiscock K, Petersen J (2006) Development of eco-hydrological guidelines for dune habitats - Phase 1. English Nature Reports Number 696
- Davy A, Hiscock K, Jones M, Low R, Robins N, Stratford C (2010) Ecohydrological guidelines for wet dune habitats – Phase 2. Environment Agency Report
- Denton JS, Hitchings SP, Beebee TJC, Gent A (1997) A Recovery Program for the Natterjack Toad (*Bufo calamita*) in Britain. *Conserv Biol* 11:1329-1338 doi:10.1046/j.1523-1739.1997.96318.x
- Doherty, J.E. & Hunt, R.J. 2010. Approaches to highly parameterized inversion—A guide to using PEST for groundwater-model calibration. United States Geological Survey Report Scientific Investigations Report 2010–5169.
- Eddies, R.D. & Reynolds, L.M. 1988. Seismic characteristics of buried rock-valleys in Plymouth Sound and the River Tamar. *Proceedings of the Ussher Society*, 7.
- English Nature. 1992. Braunton Burrows SSSI management brief. South West Region.
- Freeze, R.A. & Cherry, J.A. 1979. *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, NJ.
- Fuller, R. M., Smith, G. M., Sanderson, J. M., Hill, R. A., & Thomson, A. G. 2002. The UK Land Cover Map 2000: construction of a parcel-based vector map from satellite images. *The Cartographic Journal*, 39(1), 15-25.
- Gill LW, Naughton O, Johnston PMO (2013) Modeling a network of turloughs in lowland karst. *Water Resour Res* 49:3487-3503
- Griffiths, J., Keller, V., Morris, D. & Young, A.R. 2008. Continuous Estimation of River Flows (CERF). Environment Agency Report SC030240

- Grootjans, A.P., Ernst, W.H.O. & Stuyfzand, P.J. 1998. European dune slacks: Strong interactions of biology, pedogenesis and hydrology. *Trends in Ecology & Evolution*, 13, 96-100, doi: 10.1016/S0169-5347(97)01231-7.
- Hobma, T.W., Bottelier, R.C. & Janssen, L.L.F. 1995. Groundwater modelling of a coastal dune using remote sensing and GIS. *EARSel Adv Remote S*, 4, 115-127.
- House, A.R., Thompson, J.R., Sorensen, J.P.R., Roberts, C. & Acreman, M.C. 2015. Modelling groundwater/surface water interaction in a managed riparian chalk valley wetland. *Hydrol Proc*, doi: 10.1002/hyp.10625.
- Hulme P, Rushton K, Fletcher ST, 2001. Estimating recharge in UK catchments. *IAHS PUBLICATION*. Jul:33-42.
- Hunt, R.J., Anderson, M.P., Kelson, V.A., 1998. Improving a complex finite-difference ground water flow model through the use of an analytic element screening model. *Ground water* 36, 1011–1017.
- Jackson CR & Spink AEF. 2004. User's manual for the groundwater flow model ZOOMQ3D. British Geological Survey Internal Report IR/04/140.
- Jackson CR, Hughes AG, Dochartaigh BÓ, Robins NS, Peach DW (2005) Numerical testing of conceptual models of groundwater flow: a case study using the Dumfries Basin aquifer. *Scot J Geol*, 41(1), 51-60
- Jacobson, G. & Schuett, A.W. 1984. Groundwater seepage and the water balance of a closed, freshwater, coastal dune lake: Lake Windermere, Jervis Bay. *Marine and Freshwater Research*, 35, 645-654.
- Jones MLM, Reynolds B, Brittain SA, Norris DA, Rhind PM, Jones RE (2006) Complex hydrological controls on wet dune slacks: the importance of local variability. *Sci Total Environ* 372:266-277.

- Kidson, C. and Carr, A.P. (1960) Dune reclamation at Braunton Burrows, Devon. Chartered Surveyor, 93, 298–303.
- Kidson, C., Collin, R.L. and Chisholm, N.W.T. (1989) Surveying a major dune system – Braunton Burrows, north west Devon. Geographical Journal, 155, 94–105
- Knapen R, Janssen S, Roosenschoon O, Verweij P, De Winter W, Uiterwijk M, Wien JE (2013) Evaluating OpenMI as a model integration platform across disciplines. Environ Modell Softw 39:274-282.
- Konikow, L.F., Bredehoeft, J.D., 1992. Ground water models cannot be validated. Advances in Water Resources 15, 75–83.
- Lammerts EJ, Maas C, Grootjans AP (2001) Groundwater variables and vegetation in dune slacks. Ecol Eng 17:33-47
- Lubczynski MW, Gurwin J (2005) Integration of various data sources for transient groundwater modeling with spatio-temporally variable fluxes—Sardon study case, Spain. J Hydrol 306:71-96
- Mackay JD, Jackson CR, Wang, L (2014) A lumped conceptual model to simulate groundwater level time-series. Environ Modell Softw, 61, 229-245
- Mansour, M.M. & Hughes, A.G. 2004. User's manual for the distributed recharge model ZOODRM. British Geological Survey Report IR/04/150.
- May VJ (2001) Sandy Beaches and dunes - Braunton Burrows. Geol Conserv Rev 28:2731-2740
- McFarlane, P.B. 1955. Survey of two drowned river valleys in Devon. Geological Magazine, 92, 419-429.
- Merritt, M.L. & Konikow, L.F. 2000. Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model. US Geological Survey.

- 778 Moon, S.K., Woo, N.C. & Lee, K.S. 2004. Statistical analysis of hydrographs and water-table
779 fluctuation to estimate groundwater recharge. *Journal of Hydrology*, 29, 198-209.
- 780 Provoost, S., Jones, M.L. & Edmondson, S. 2011. Changes in landscape and vegetation of
781 coastal dunes in northwest Europe: a review. *J Coastal Conserv*, 15, 207-226, doi:
782 10.1007/s11852-009-0068-5.
- 783 Ranwell, D. 1959. Newborough Warren, Anglesey: I. The Dune System and Dune Slack
784 Habitat. *J Ecol*, 47, 571-601, doi: 10.2307/2257291.
- 785 Refsgaard, J.C. 1997. Parameterisation, calibration and validation of distributed hydrological
786 models. *J Hydrol*, 198, 69-97, doi: [http://dx.doi.org/10.1016/S0022-1694\(96\)03329-](http://dx.doi.org/10.1016/S0022-1694(96)03329-X)
787 X.
- 788 Refsgaard, J.C. & Storm, B. 1996. Construction, Calibration And Validation of Hydrological
789 Models. In: Abbott, M.B. & Refsgaard, J.C. (eds.) *Distributed Hydrological*
790 *Modelling*. Springer Netherlands, Dordrecht, 41-54.
- 791 Robins, N.S. 2007. Conceptual flow model and changes with time at Braunton Burrows
792 coastal dunes. British Geological Survey.
- 793 Robins NS (2013) A review of small island hydrogeology: progress (and setbacks) during the
794 recent past. *Q J Eng Geol Hydroge* 46:157-165 doi:10.1144/qjegh2012-063
- 795 Rushton, K.R. & Wedderburn, L.A. 1973. Starting conditions for aquifer simulations. *Ground*
796 *Water*, 11, 37-42.
- 797 Spring, K. 2005. Groundwater flow model for a large sand mass with heterogeneous media,
798 Bribie Island, Southeast Queensland. MSc thesis, Queensland University of
799 Technology.
- 800 Stratford, C. & Palisse, M. this issue. Moisture profile dynamics and the quantification of
801 rainfall recharge. *J Coastal Conserv*.

- Stratford CJ, Robins NS, Clarke D, Jones L, Weaver G (2013) An ecohydrological review of dune slacks on the west coast of England and Wales. *Ecohydrology* 6:162-171
doi:10.1002/eco.1355
- Voss, C.I. 2011. Editor's message: Groundwater modeling fantasies —part 1, adrift in the details. *Hydrogeol J*, 19, 1281-1284, doi: 10.1007/s10040-011-0789-z.
- Wheeler DC, Nolan BT, Flory AR, DellaValle CT, Ward MH (2015) Modeling groundwater nitrate exposure for an agricultural health study cohort in Iowa. *Sci Total Environ*, 536, 481-488
- Willis A, Folkes BF, Hope-Simpson J, Yemen E (1959a) Braunton Burrows: The dune system and its vegetation. *Parts 1 J Ecol* 47:1-24
- Willis AJ, Folkes BF, Hope-Simpson JF, Yemm EW (1959b) Braunton Burrows: The dune system and its vegetation - Part 2 *J Ecol* 47:249-288 doi:10.2307/2257366
- Winter, T.C. & Rosenberry, D.O. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east- central North Dakota, 1979-1990. *Wetlands*, 15, 193-211.
- Wondzell, S M, LaNier, J & Haggerty, R. 2009. Evaluation of alternative groundwater flow models for simulating hyporheic exchange in a small mountain stream. *J Hydrol*, 364, 142-151.

List of Figures

- Figure 1: Generic cross section through a dune system showing main groundwater and surface water features (Stratford et al. 2013).
- Figure 2: Conceptualisation of (a) groundwater flow in the Braunton Burrows aquifer and (b) model boundaries of the numerical model (displayed as 1km grid)

Figure 3: Location of current (full circle, triangle) and past (open circle) water level monitoring wells at Braunton Burrows

Figure 4: Sensitivity analysis: (a) refined model grid (200m x200m) and boundary conditions (small red circles = no flow, small green circles = constant head, small blue circles = river, big green circles = one way leakage), (b) simulated groundwater head distribution (uniform parameter distribution)

Figure 5: Identification of best fit model through comparison of modelled LTA water levels along transect 1, 2 and 3 (shown in Figure 3) against minimum and maximum observed water levels along the transects

Figure 6: Final dynamic balance run for selected observation well (red = previous model run, blue= latest model run) and observed LTA water levels (green)

Figure 7: Monte Carlo simulations: (a) Transmissivity zone delineation used for MC runs, (b) Impact of varying hydraulic conductivity (K) in zones 1-4 on model fit (Nash Sutcliffe Efficiency) in OBH 1. Red circles indicate NSE values > 0 (i.e acceptable model fit).

Figure 8: Monte Carlo simulations: (a) Location of observations well and delineation of transmissivity zone, (b) Plots of hydraulic conductivity (K) against Nash-Sutcliffe efficiency (NSE) for all observations wells (arranged along transects 1-3)

Figure 9: Water level contours generated by (a) the 4-zone and (b) the 6-zone model

Figure 10: Model output from the 6-zone model: (a) Location of observations well and delineation of transmissivity zones, (b) Plots of observed (black circles) versus modelled (green line) water levels for all observations wells (arranged along transects 1-3)

Figure 11: Model output from 12-zone model: (a) Location of observations well and delineation of transmissivity zones, (b) Plots of observed (black circles) versus modelled (green line) water levels for all observations wells (arranged along transects 1-3)

Figure 12: Ainsdale Nature Reserve on the Sefton coastline. Arrows indicate directions of groundwater movement from the high point of the groundwater mound.

Figure 13: Monthly observations of water table levels at Ainsdale 1972-2013. Red line = ground level. Shaded bands are based on Ranwell (1953) classifications of slack type – wet/transitional/dry

Figure 14: Conceptual model of the components of the water balance in the dune system. The water table (red line) slopes towards the sea and intersects low lying areas to create humid or flooded slacks.

Figure 15: Model validation for water table levels at Ainsdale. Sand dune properties, K (hydraulic conductivity) and n (effective porosity), were successively adjusted until the best fit was obtained between the model and the observations. Note that the aquifer thickness ('b') was kept constant at an assumed thickness of 60m based on BGS local borehole logs.

Figure 16: Representation of the groundwater modelling process

List of Tables

Table 1: Parameter ranges and model geometries tested as part of the sensitivity analysis

Table 2: Parameter ranges for the Monte Carlo simulations

Table 3: Summary of key model runs: zone delineation, parameterisation and model performance measures (NSE, RMSE)

Figure 4

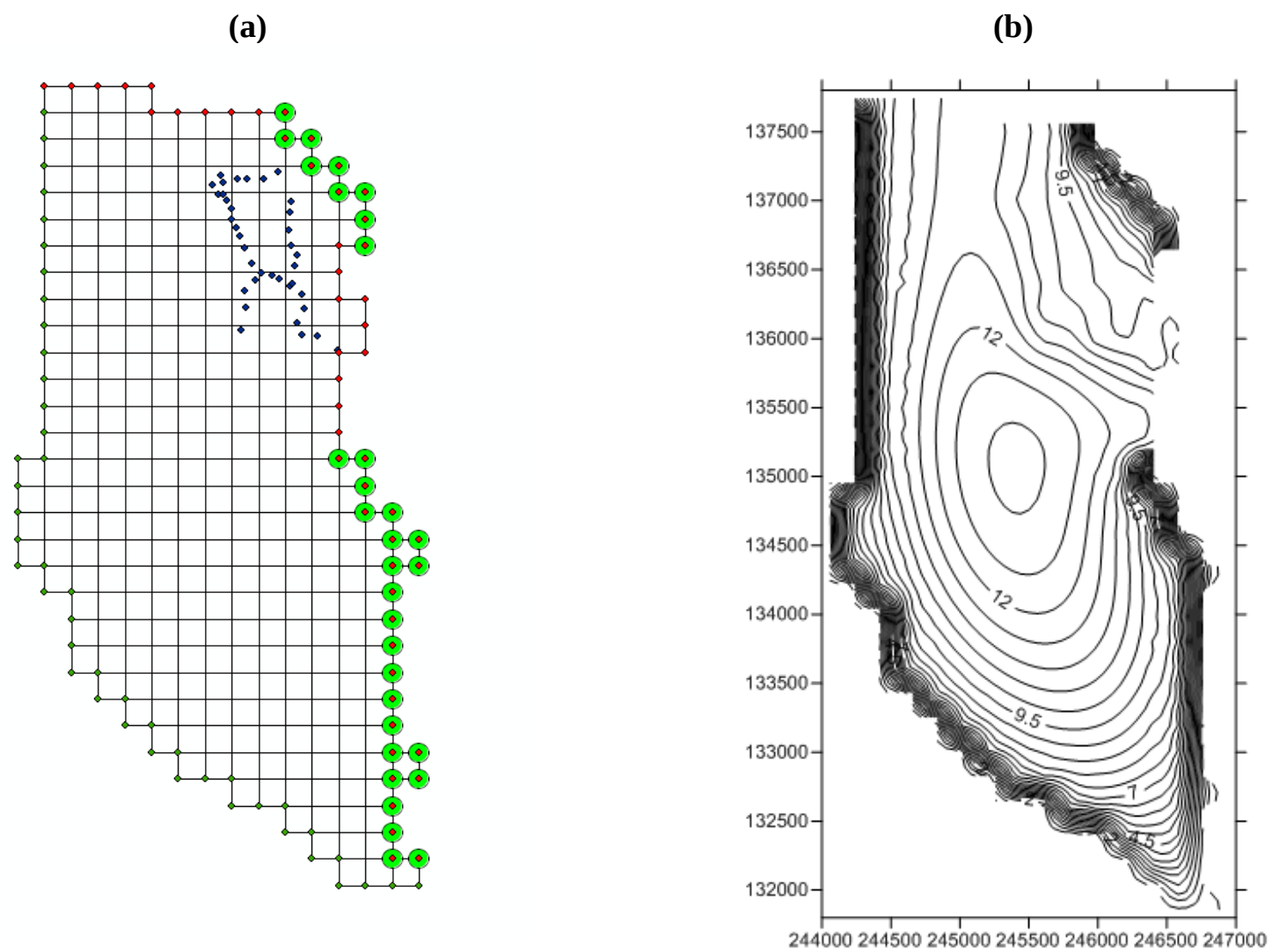


Figure 6

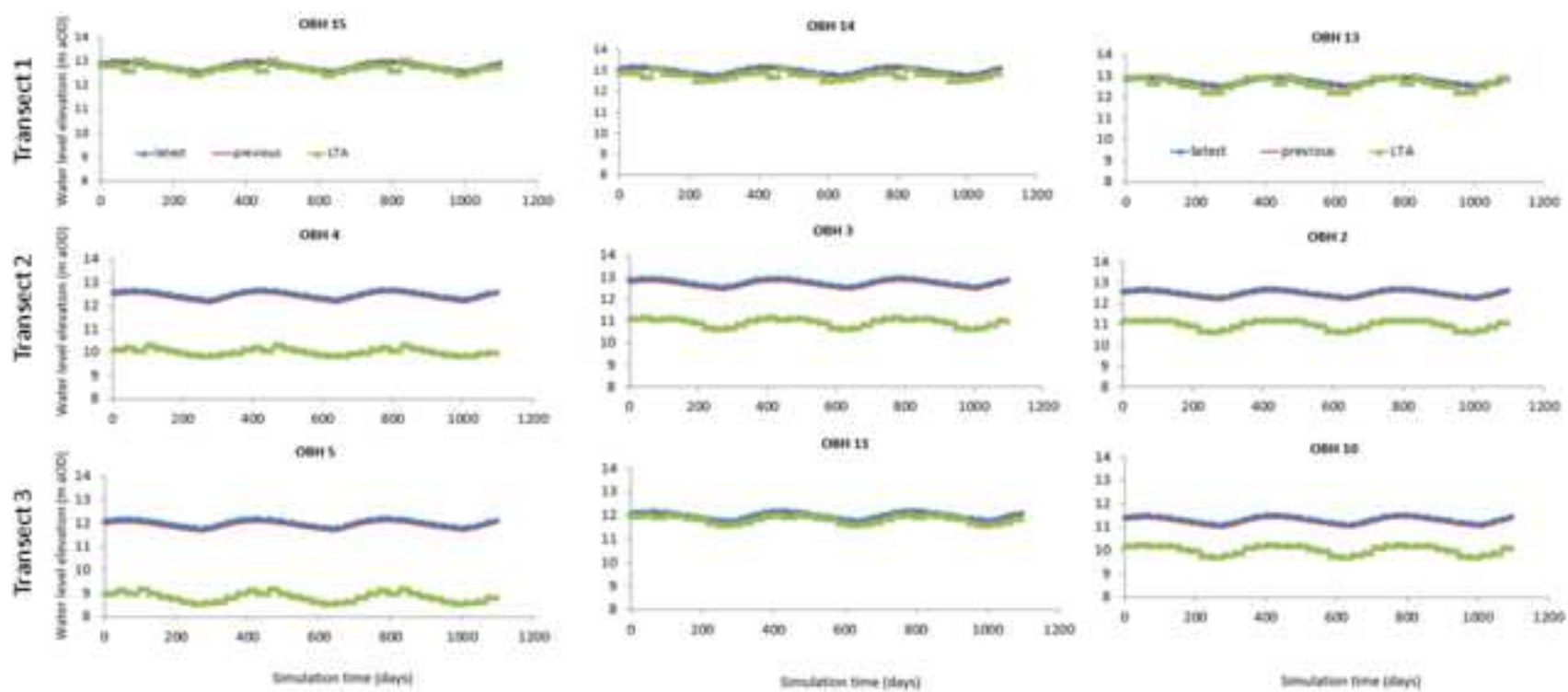


Figure 7

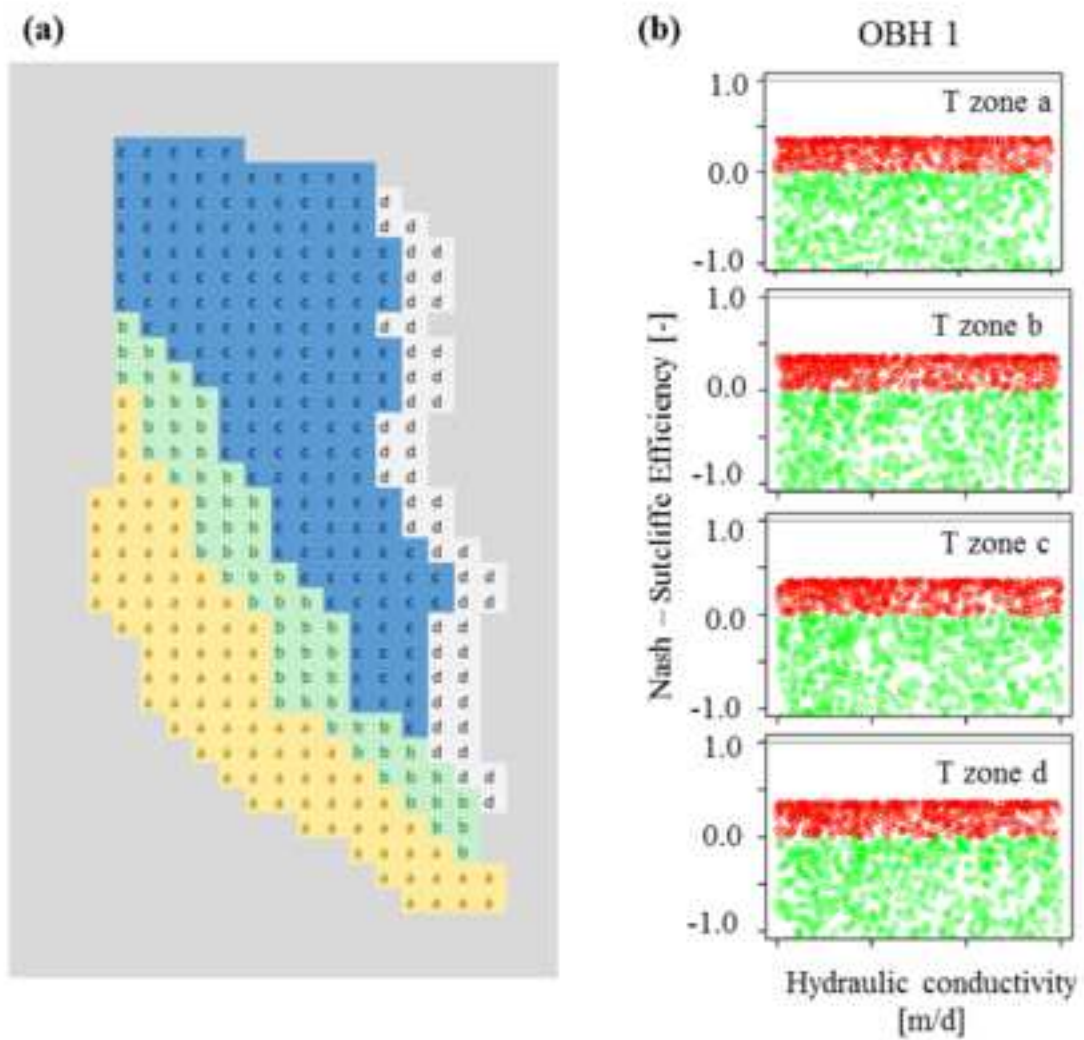


Figure 8

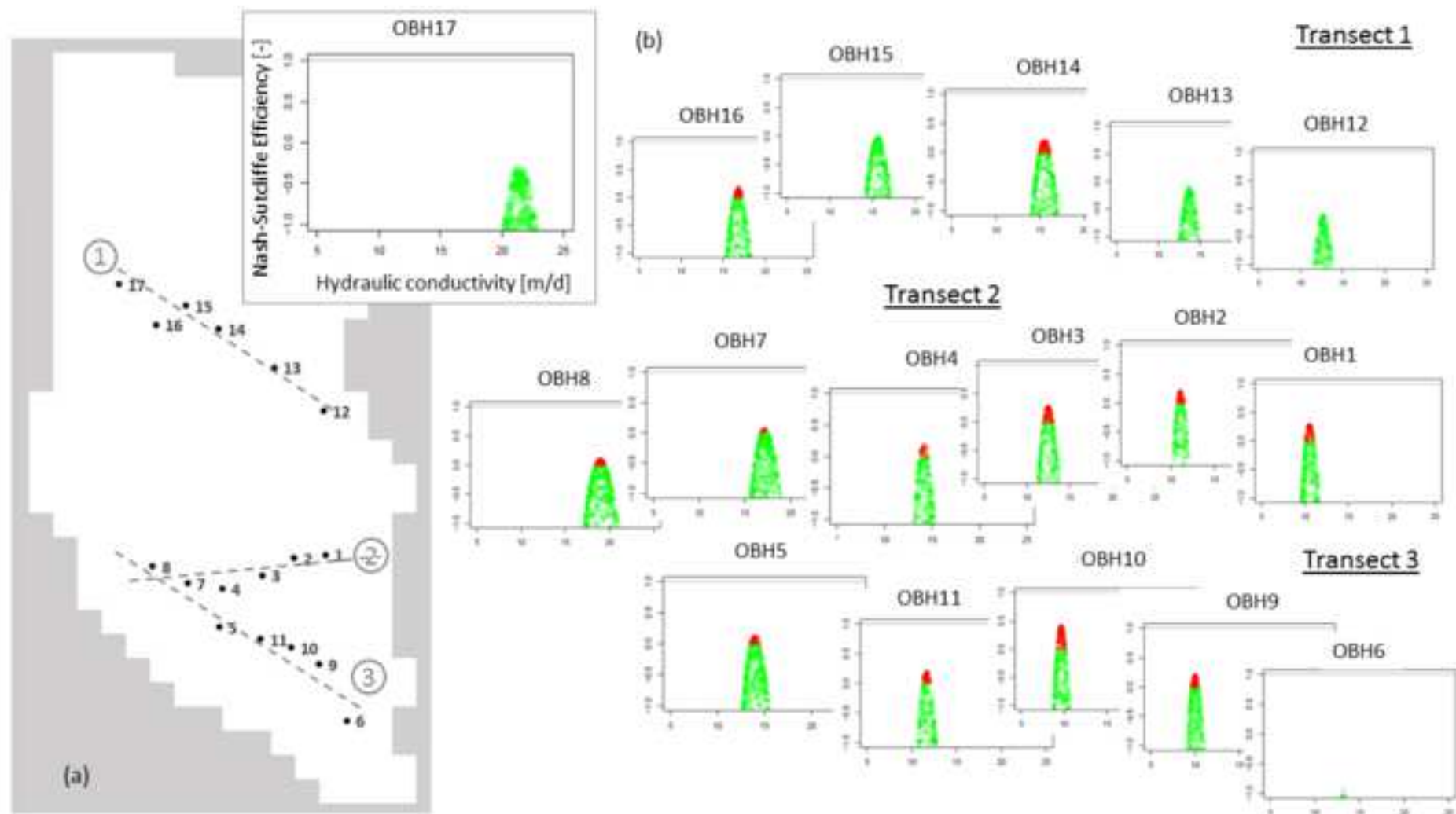


Figure 10

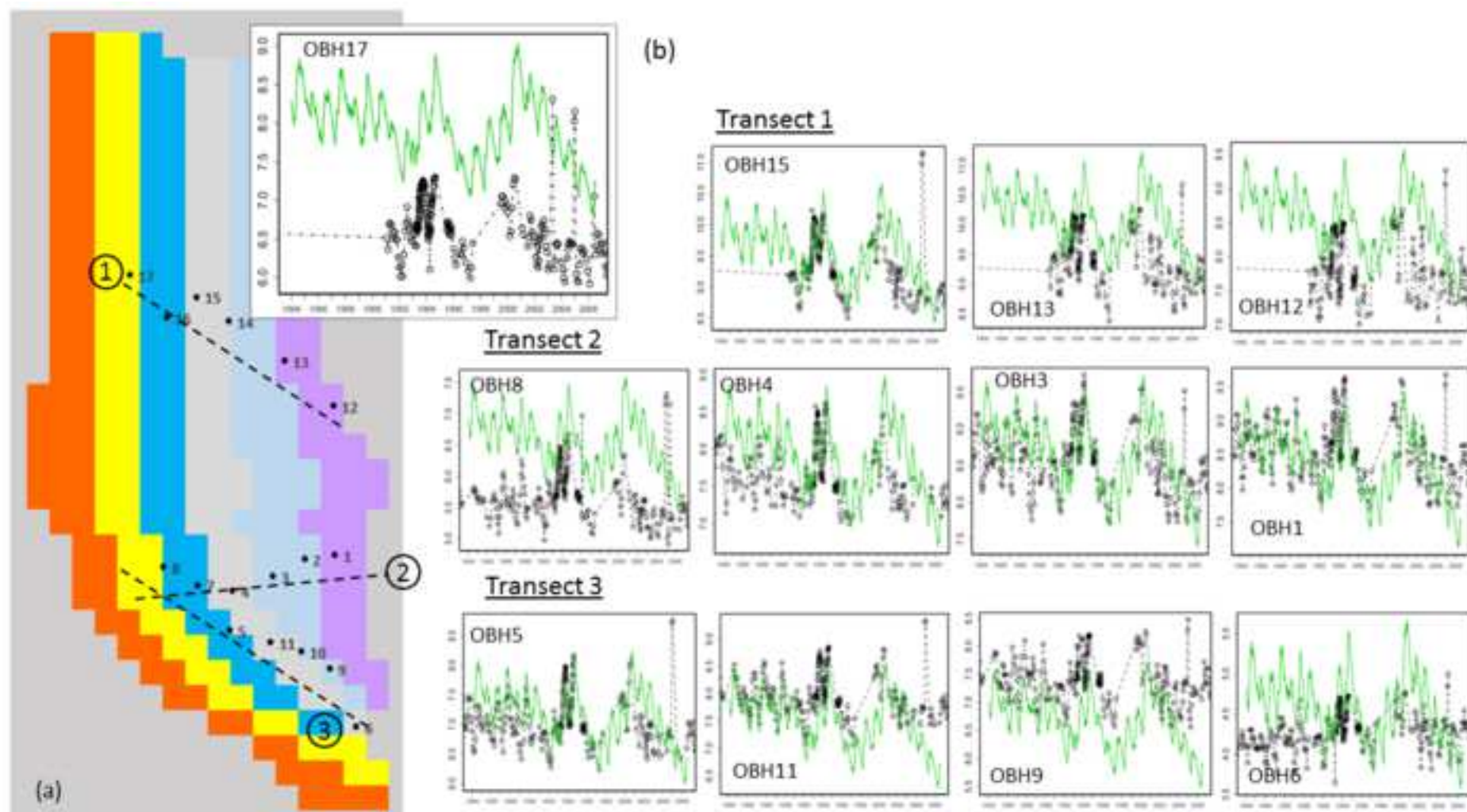


Figure 11

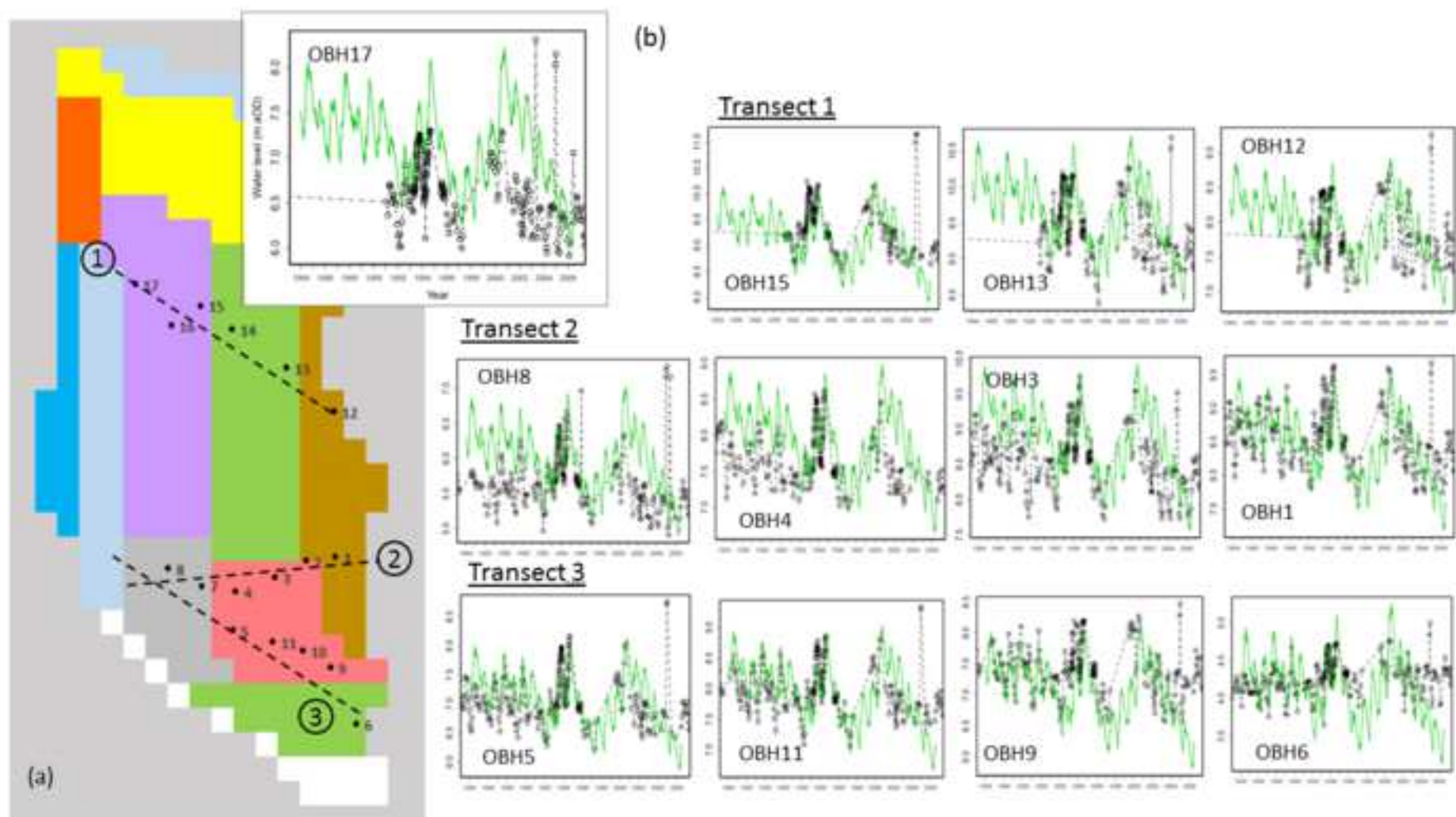


Figure 12

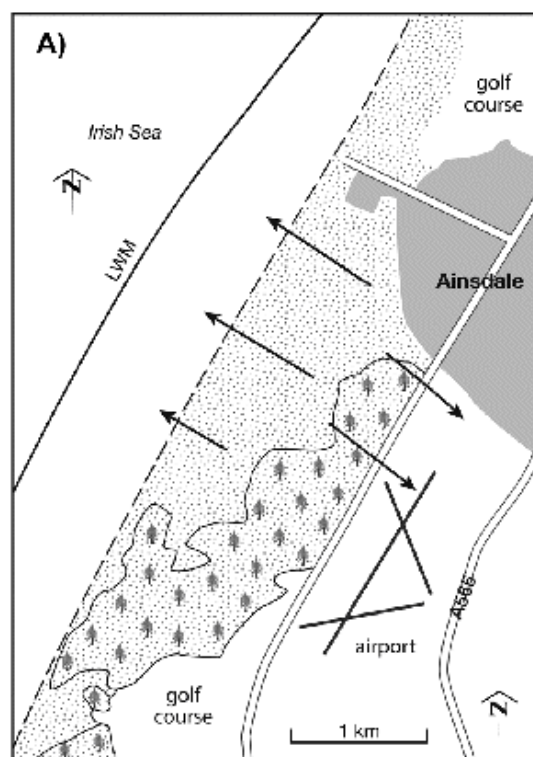


Figure 13

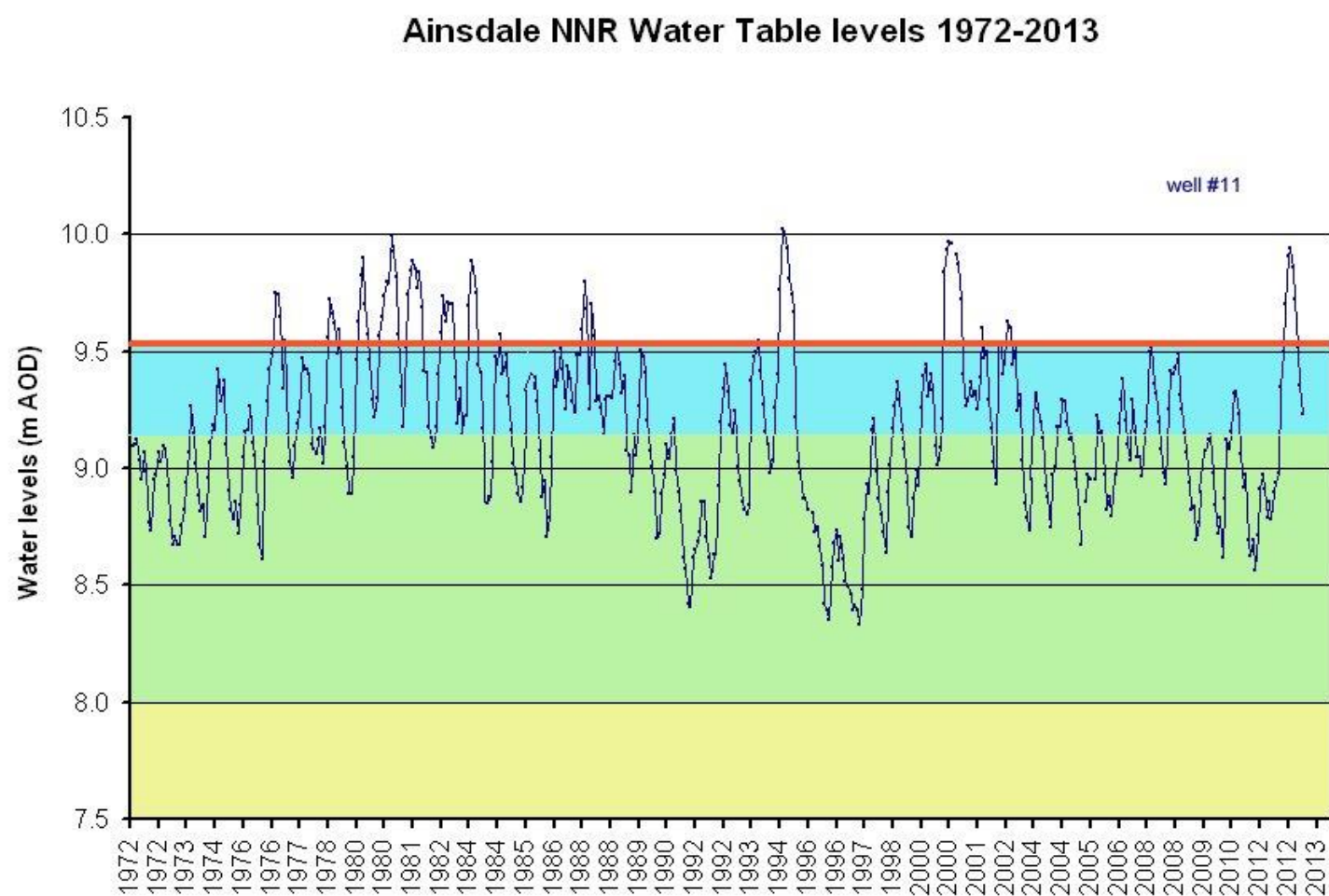


Figure 14

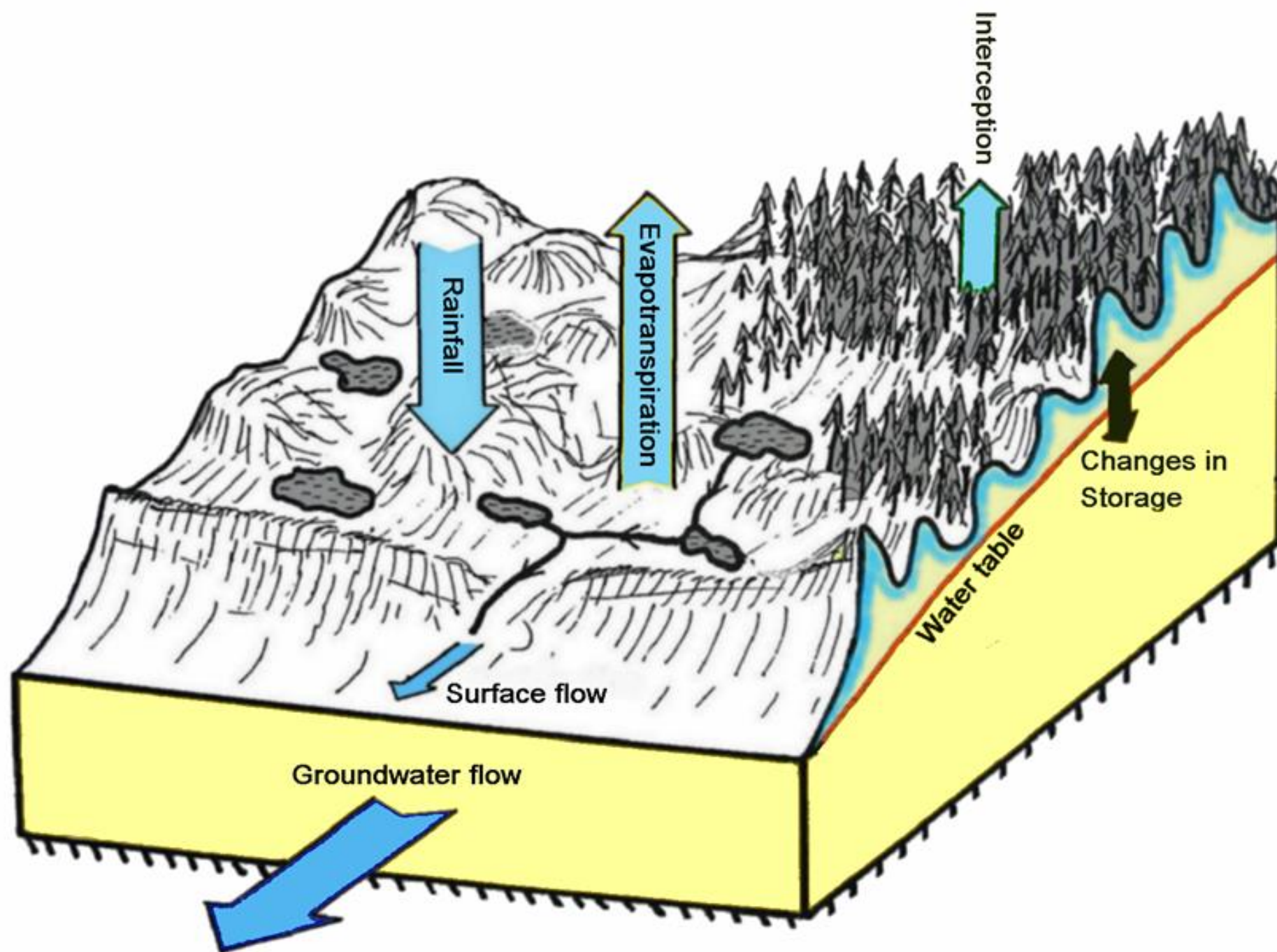


Figure 15

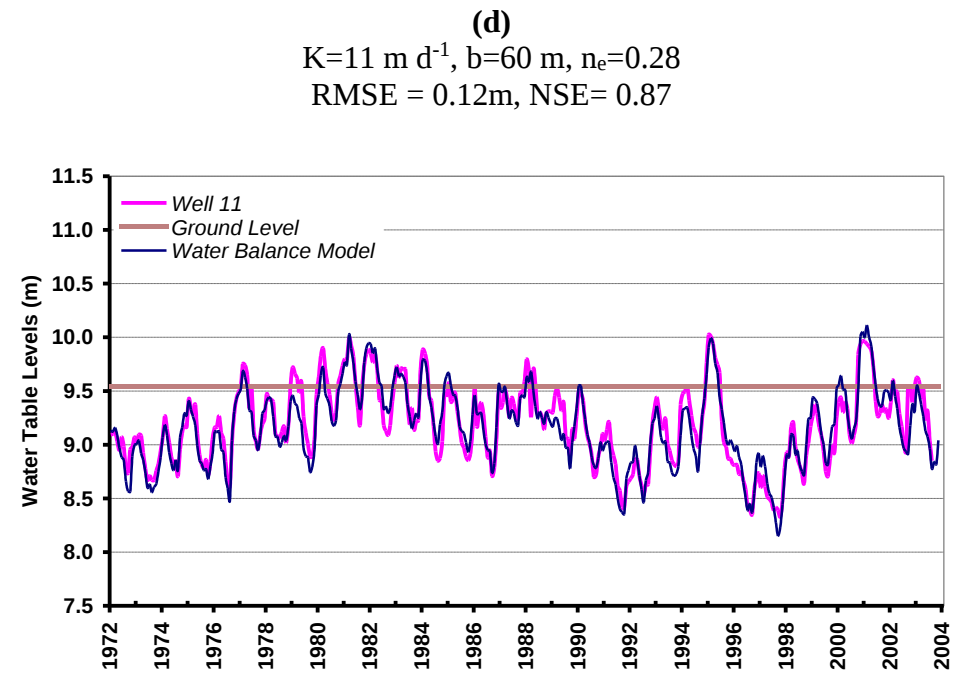
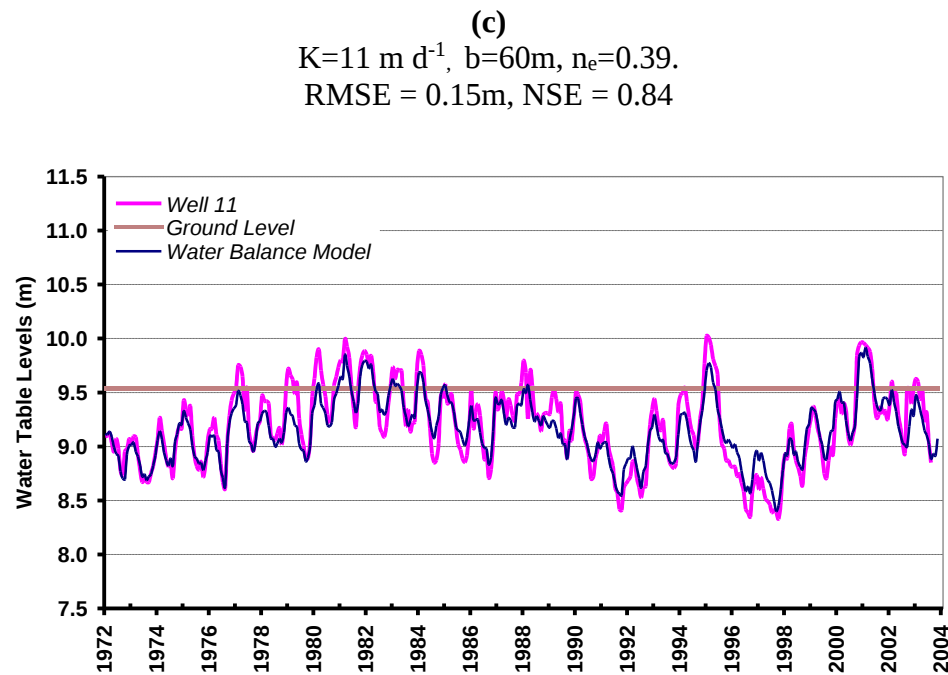
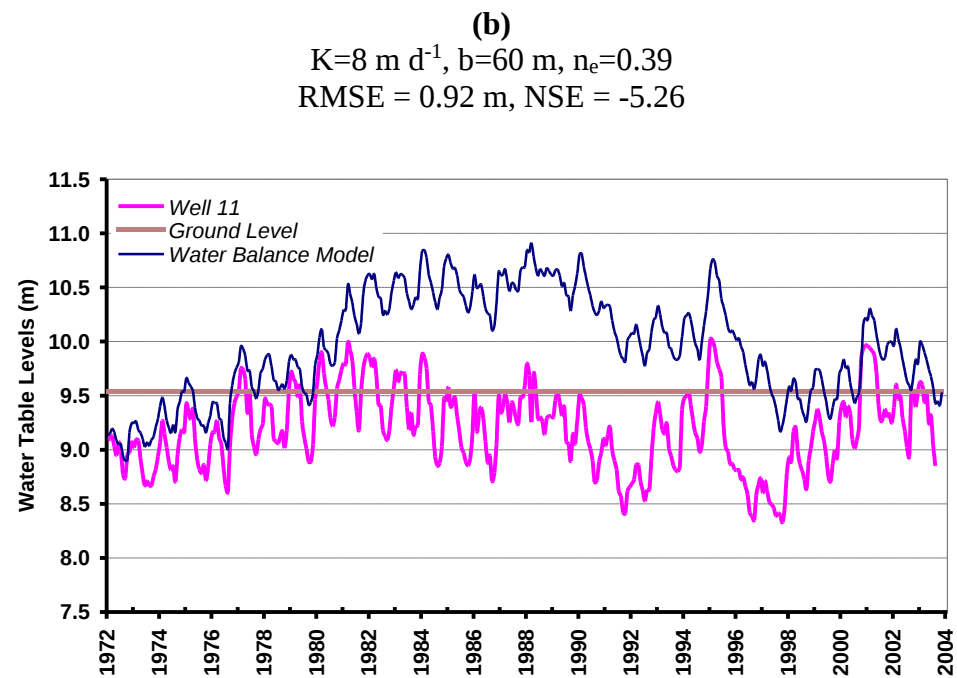
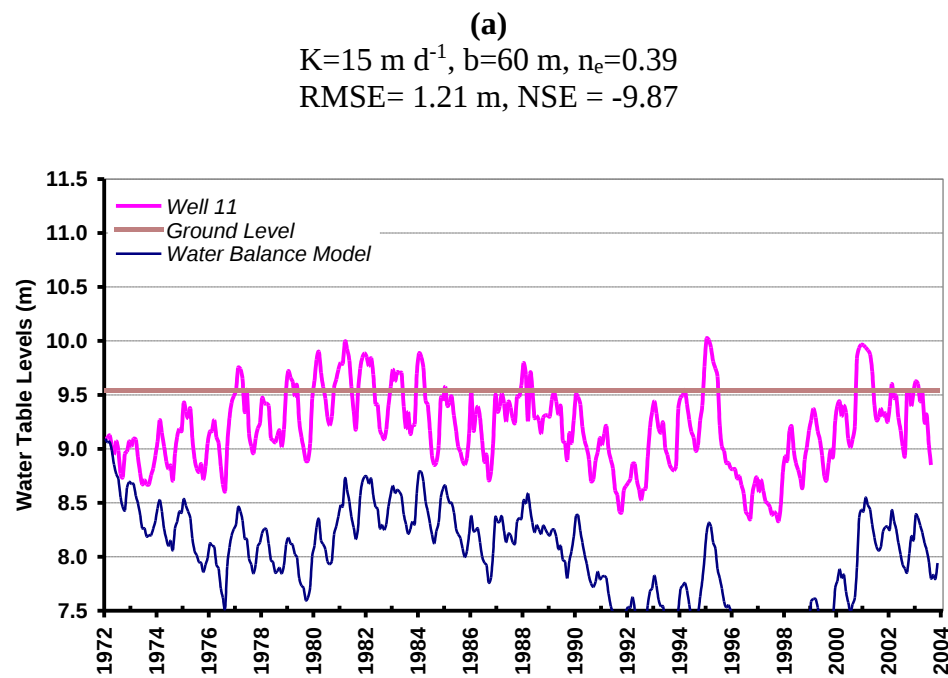


Figure 16

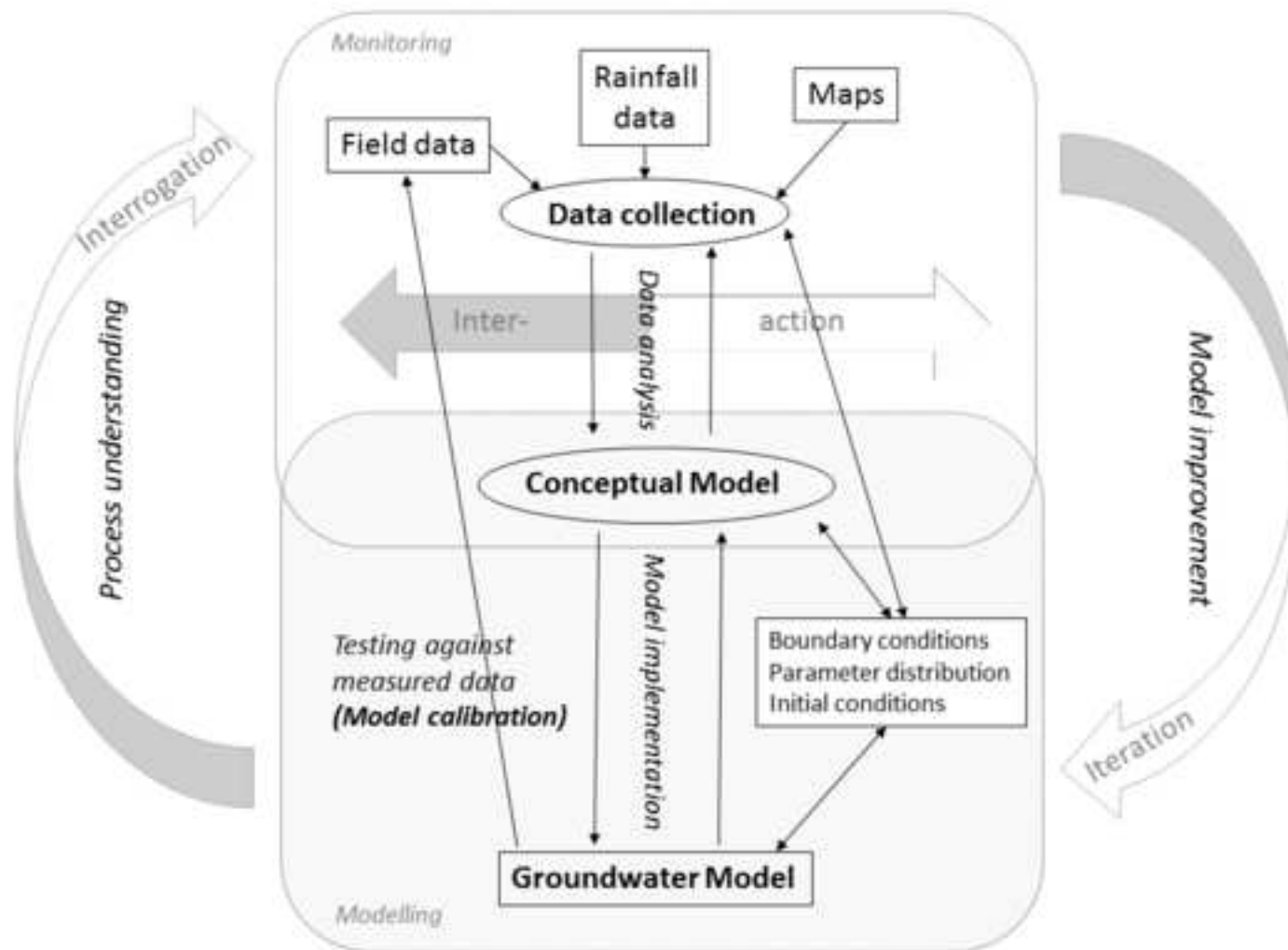


Figure 1

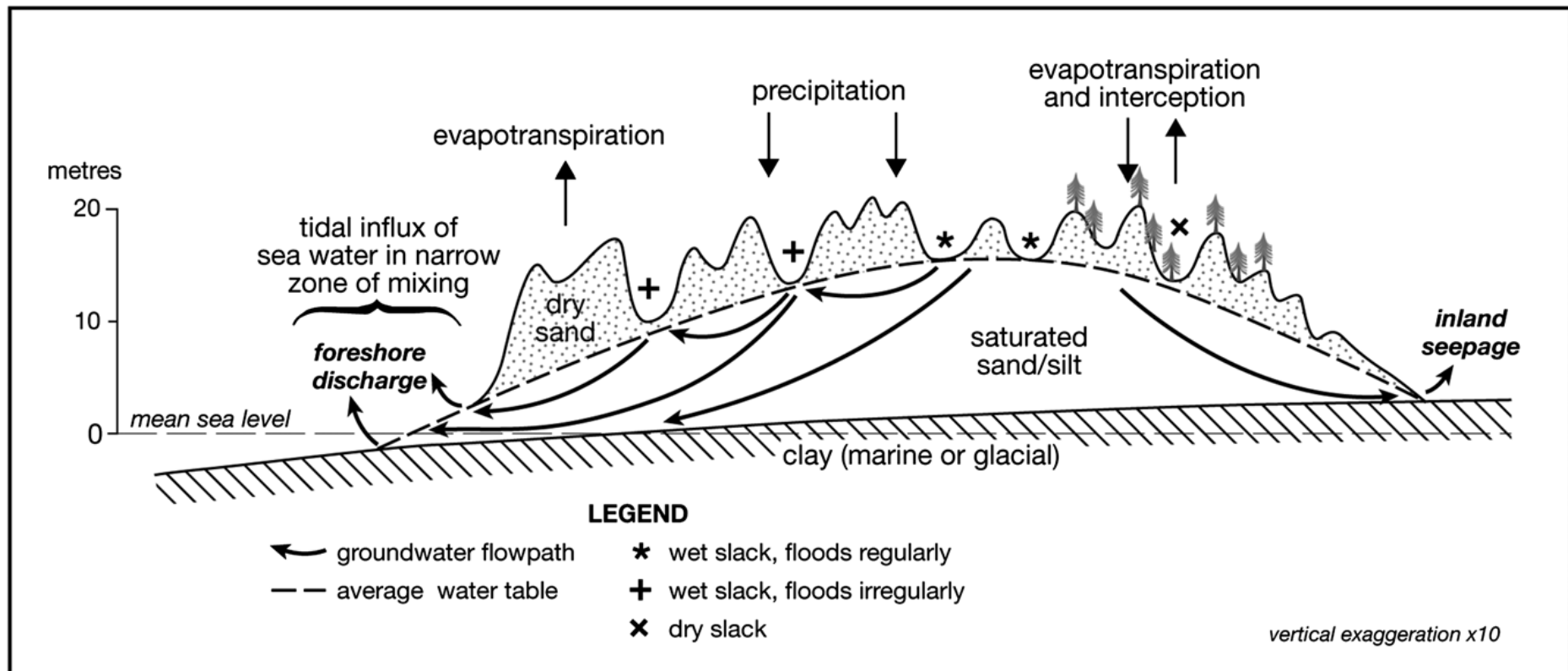
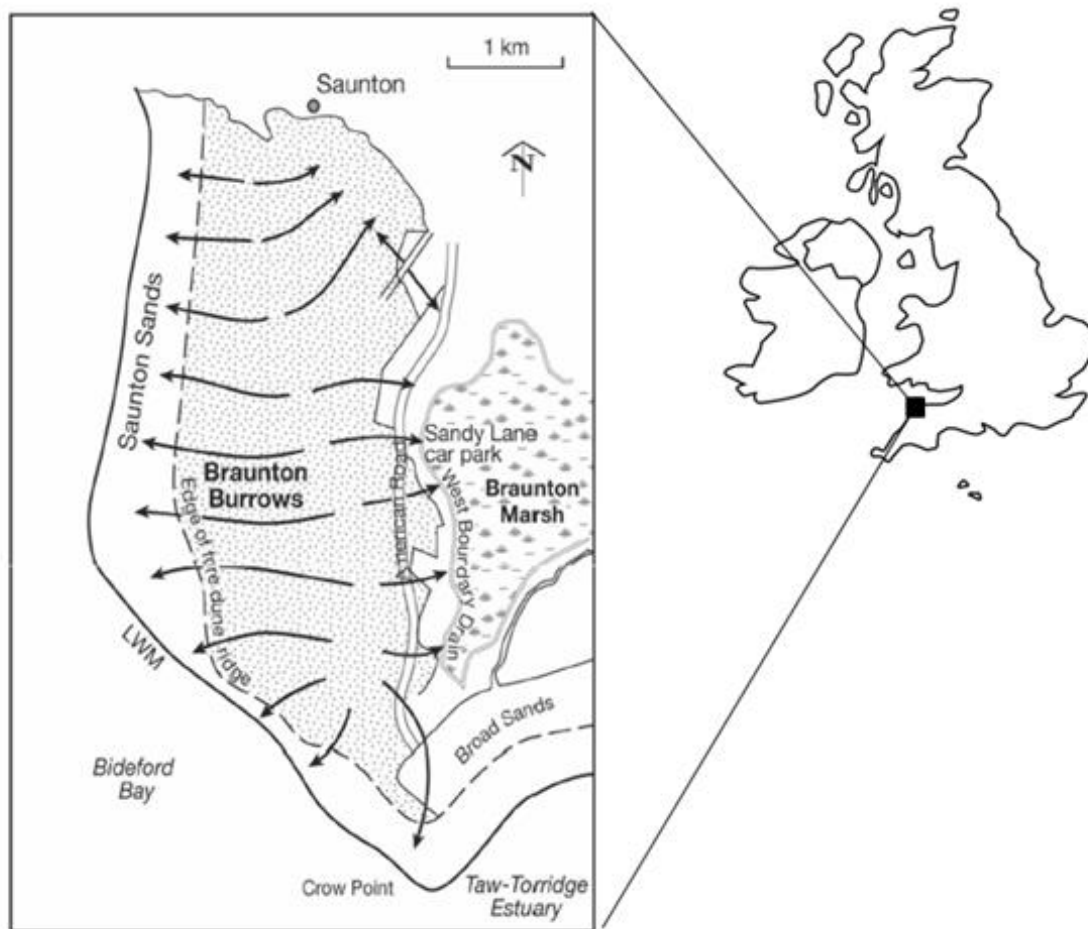


Figure 2

(a)



(b)

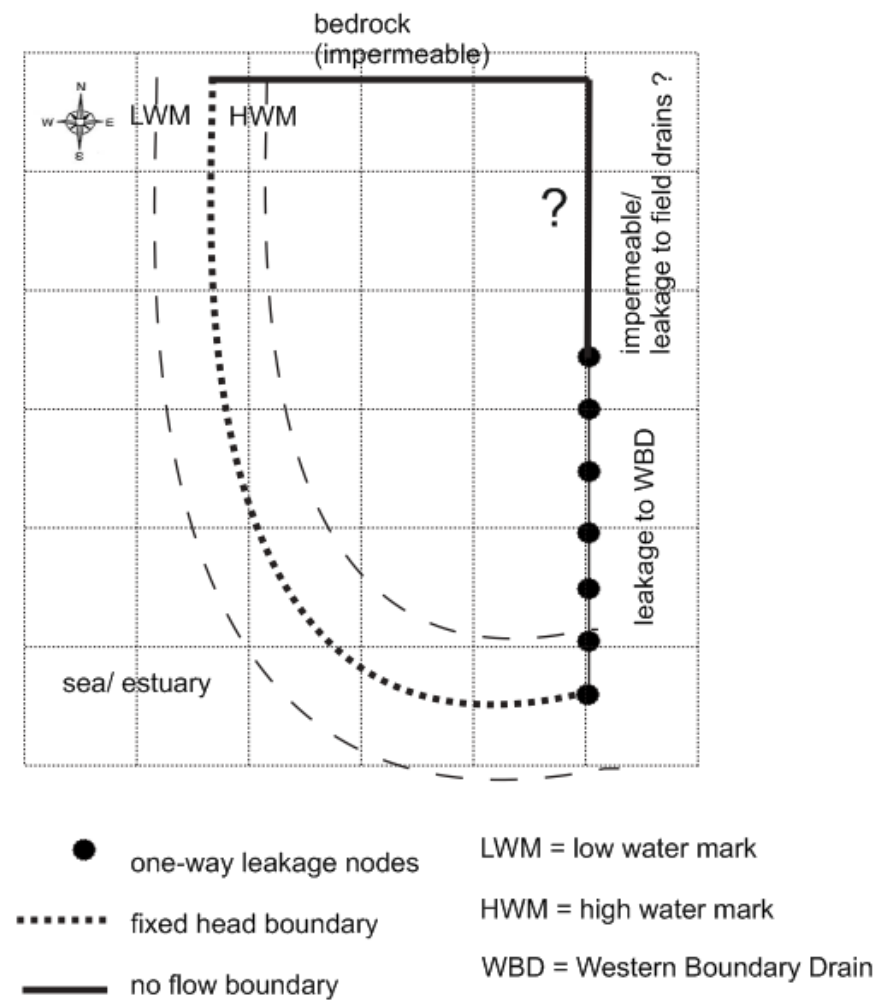


Figure 3

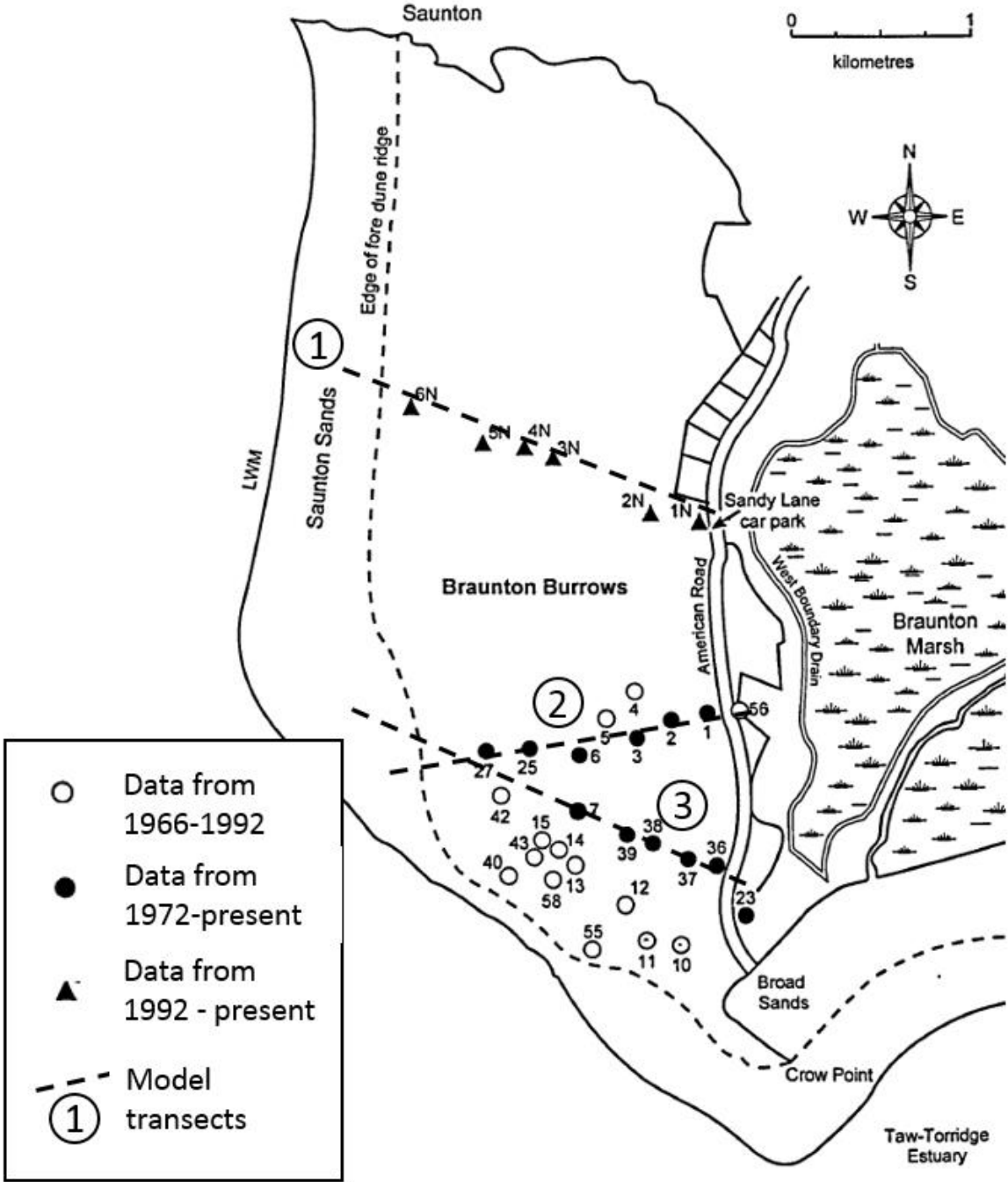


Figure 5

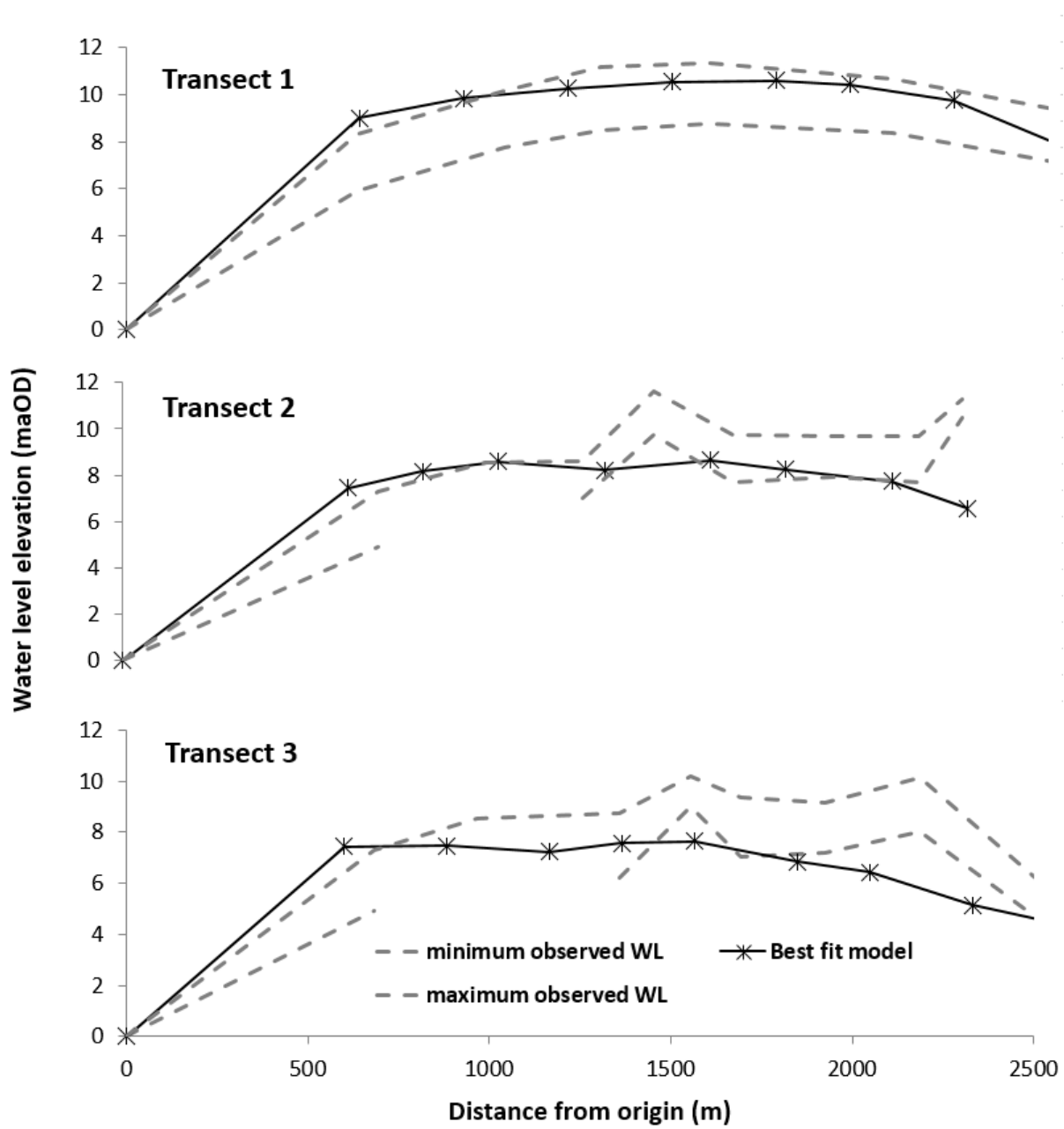


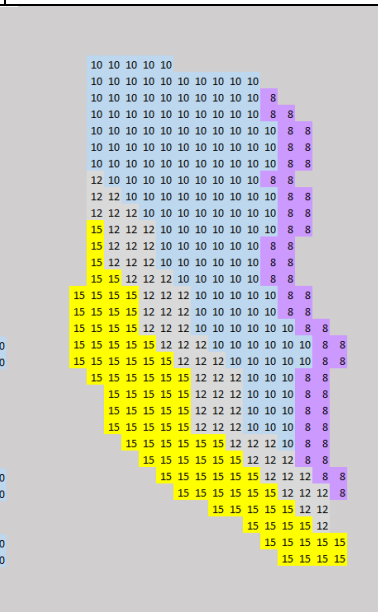
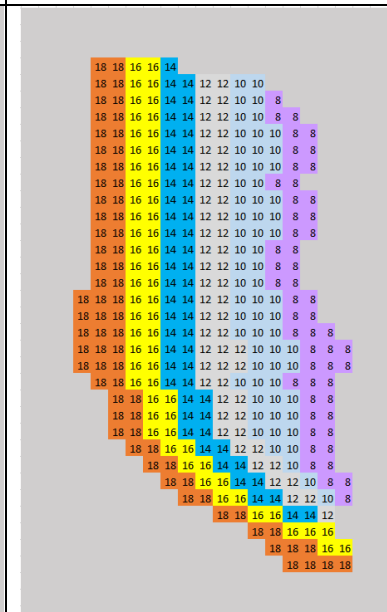
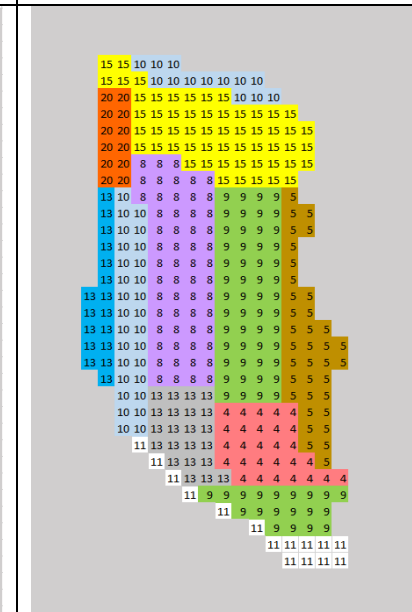
Table 1

Test parameter	Changes to model
Transmissivity	decreasing/increasing hydraulic conductivity (K) by 25% and 50%
	decreasing/increasing aquifer base elevation (z) by 0.5 m and 1.0m
Specific yield	decreasing/increasing specific yield by 30% and 60%
Boundary location	Move eastern boundary eastwards (2 nodes)
	Move western boundary westwards (2 nodes)
Leakage node elevation	decrease/ increase leakage node elevation by 0.5m
Leakage node conductance	decrease/ increase leakage node conductance by 1 order of magnitude
Model boundary conditions	Add/remove leakage nodes along NE boundary
	Add/remove river nodes to NE part of model

Table 2

<u>Parameter</u>	<u>Unit</u>	<u>Range</u>
Hydraulic conductivity (K)	m d ⁻¹	5 – 25
Aquifer base elevation (z)	m a OD	-2 – 2
Aquifer storage (S)	–	0.1– 0.5

Table 3

Zones	1		4		6		12		
K distribution									
	S		0.3		0.3		0.3		
	z		-2.0		-2.0		-5.0		
		NSE[-]	RMSE[m]	NSE[-]	RMSE[m]	NSE[-]	RMSE[m]	NSE[-]	RMSE[m]
	OBH1	0.31	0.37	0.31	0.37	0.09	0.42	0.26	0.38
	OBH2	-0.79	0.54	0.19	0.36	-0.39	0.47	0.27	0.34
	OBH3	-5.68	1.12	0.13	0.40	0.39	0.34	0.17	0.40
	OBH4	-14.98	1.68	-1.19	0.62	0.06	0.41	0.04	0.41
	OBH5	-10.34	1.55	0.06	0.45	0.53	0.32	0.55	0.31
	OBH6	-20.07	0.98	-3.85	0.47	-2.46	0.40	-0.35	0.25
	OBH7	-40.78	2.54	-7.63	1.15	-3.00	0.78	0.19	0.35
	OBH8	-48.82	2.74	-11.17	1.35	-4.24	0.89	-0.04	0.40
	OBH9	0.37	0.34	-2.33	0.78	-3.10	0.86	-0.51	0.52
	OBH10	-0.12	0.45	-7.62	1.24	-9.43	1.36	-2.95	0.84
	OBH11	-2.33	0.76	-0.03	0.42	-0.92	0.58	0.41	0.32
	OBH12	-3.87	0.98	-4.68	1.05	-1.96	0.76	0.33	0.36
	OBH13	-7.02	1.21	-5.30	1.08	-1.63	0.69	0.27	0.37
	OBH14	-18.42	1.78	-8.91	1.27	-0.46	0.49	0.33	0.33
	OBH15	-18.45	1.79	-8.16	1.23	0.34	0.33	0.14	0.38
	OBH16	-34.59	2.30	-12.85	1.43	-0.53	0.48	0.44	0.29
	OBH17	-87.62	3.29	-45.56	2.39	-12.80	1.30	-1.50	0.55