UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

School of Civil Engineering and the Environment

Impacts of Climate Change on Groundwater levels in Coastal Aquifers

by

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ABSTRACT

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IMPACTS OF CLIMATE CHANGE ON GROUNDWATER LEVELS IN COASTAL AQUIFERS

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Groundwater in coastal aquifers is affected by many environmental factors including rainfall, evapotranspiration, sea level, coastal erosion, aquifer recharge and land use. The key factors that affect groundwater levels in two target sites have been evaluated up to the year 2100: (1) a coastal sand dune system in North West England and (2) confined aquifers at Samut Prakan near Bangkok in Thailand. A water balance model was constructed and tested against observed well levels. The model comprised a daily simulation of rainfall, soil moisture deficit and recharge based on a potential evapotranspiration sub model using the Penman-Montieth equation and crop/soil descriptors. Groundwater flow is simulated with the Darcy's law assumption for unconfined flow. Residual water is assumed to contribute to groundwater storage and this storage is converted into modelled water table levels based on dune porosity functions. The model was calibrated by parameter estimation against observed data for 1972-2007 in North West England but limited data availability restricted the calibration in Thailand.

In the North West England study, UKCIP02 "Medium-High" climate change scenarios were used in the model on a daily basis between 2008-2100. The modelled groundwater levels were found to be highly dependent not only on the amount of rainfall but when it falls and the size of each rain storm event. A Monte Carlo modelling approach enabled the model to be run with 1,000 sequences per simulation of rainfall patterns along with variations in estimates of sea-level rise, climate change (changes in precipitation and temperature), land use change, and erosion scenarios. This approach was able to deal with uncertainties in these factors effectively and it is strongly linked with the climate inputs such as rainfall and evapotranspiration which are expected to change in the future. The most important parameters that affected the modelled groundwater levels at both sites were found to be rainfall, followed by change in temperature, actual evapotranspiration, tree coverage and coastal erosion (which will become more significant as erosion progresses). The models were less sensitive to uncertainties in system properties such as permeability. Sea-level rise and crop variety had the smallest impact on coastal groundwater recharge. The impact of sea-level rise was relatively unimportant over the short time period studied (100 years). The relative importance of these factors will probably change further into the future.

Findings from the North West England study are that on average, hotter drier summers will cause a reduction in total evapotranspiration due to soil moisture deficit and that wetter winters will cause an increased range of amplitude of water table levels. The overall trend is that groundwater levels may fall by about 1m in the next 100 years, causing the fragile ecosystems in the dune floors to dry out completely. The model also showed that for areas planted with pine trees, increased interception losses may cause the water table to fall by up to 1.5m, with prolonged periods of low water table levels. This will have the effect of drying out the inland slack floors and reducing the biodiversity of these areas.

In Thailand, the expected change in shallow groundwater levels is that the water table will fall as less recharge arrives from rainfall and decreased river flows in the dry season. Runoff could decrease more than 50 per cent in certain areas of the lower basin. This will lead to water shortage in the central plain, especially during the dry season.

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COMMON NOTATIONS

ρ_f	Reference density of fresh water = 1000 kg/m^3	M/L^3
ρ_s	Reference density of saline groundwater = 1025 kg/m^3	M/L^3
β	Transpiration fraction	1
α	Relative density difference = 0.025	1
Δ	Slope vapour pressure curve	M/T
γ	Interception parameter = 6.1-7.6 mm	L
δ	Interception parameter = 0.099 mm^{-1}	1/L
w	Fraction of the day the canopy is wet	1
A	Cross-sectional area to flow	L^2
AET	Actual evapotranspiration	M/T
C_1, C_2	Constant number determined by setting boundary conditions	1
dx	Length of the sand column	L
e_s	Saturation vapour pressure	M/LT^2
e_a	Actual vapour pressure	M/LT^2
e_s-e_a	Saturation vapour pressure deficit	M/LT^2
E_d	Daily evaporation	M/T
E_T	Daily Penman evaporation estimate	M/T
ET	Evapotranspiration	M/T
ET_o	Reference evapotranspiration	M/T
ETc	Crop potential evapotranspiration	M/T
$\overline{E}$	Mean evaporation rate from a saturated canopy during rainfall	M/T
f	Natural groundwater recharge	M/T
G	Soil heat flux density	M/L^{2}T
GW	Groundwater flow in/out of the system,	M/T
h_1	Hydraulic head at the position $x=1$	L
h_2	Hydraulic head at the position $x=L$	L
h	Piezometric head of with respect to mean sea level	L
H	Depth of the fresh-salt interface below mean sea level	L
H_{max}	Deepest depth of the fresh-salt interface in the middle of the lens	L
I	Daily interception loss	L

k	Horizontal hydraulic conductivity	L/T
K	Saturated hydraulic conductivity	L/T
Kc	Crop coefficient factor	1
L	Length of the sand column	L
m	Number of rain days	1
n	Number of rain days which each storms are large enough to saturate the canopy and each separated by a sufficient period for the canopy to dry	1
PET	Potential evapotranspiration	M/T
p	Free throughfall coefficient	1
p_t	Proportion of rain which is diverted to the trunks as stemflow	1
P_G	Gross rainfall incident on the canopy	M/T
P'_G	Amount of rain necessary to saturate the canopy	M/T
q	Groundwater flow per unit coast length	L^2/T
Q	Rate of flow through the sand per unit width of the aquifer	L^3/T
R	Rainfall or precipitation	M/T
R_n	Net radiation at the crop surface	M/L^2T
$\overline{R}$	Mean rainfall rate	M/T
RAW	Readily available water	M/T
RE	Net recharge from the surrounding soil	M/T
RO	Runoff	M/T
S	Canopy capacity	M/T
S_t	Trunk water store	M/T
ΔS	Change in groundwater storage (water table level)	M/T
SM	Change in stored water within the soil	M/T
SMD	Soil moisture deficit	M/T
t	Duration of rainfall	T
TAW	Total available water in the active root zone	M/T
u^2	Wind speed at 2 m height	M/T
x	Horizontal position (distance from the axis of symmetry)	L

CHAPTER 1

Introduction

Understanding how climate change and sea-level rise may affect groundwater systems in coastal aquifers is important to the water resources and ecosystems of many countries. In this thesis, a series of models will be used to identify which factors will be the most important factors affecting coastal aquifers under likely expectations of climate change and sea-level rise over the next 100 years. In the following section, the background and motivation of the thesis are presented including the importance of groundwater, the role of groundwater in the hydrologic cycle, aquifers and coastal aquifers, climate change, and sea-level rise. It then follows with the aim and objectives of the thesis. Lastly, the outline of the thesis is described.

1.1 Background and Motivation

Coastal groundwater problems

The coastal areas of the world are characterised by high population; hence, overexploitation of groundwater has become a common issue (Narayan et al., 2007). Many coastal regions in the world have recently experienced extensive salinisation in aquifers resulting in severe deterioration in groundwater quality, and also quantity (Essink, 2001); for example, Cecina and Ravenna in Italy (Grassi et al., 2007; Giambastiani et al., 2007), Queensland in Australia (Narayan et al., 2007), Bangkok in Thailand (Phien-wej et al., 2006), and Greece (Lambrakis and Kallergis, 2001; Voudouris, 2006). Groundwater over-pumping and sea-level rise cause permanent groundwater reserve loss due to sea water intrusion. Relative sea-level rise could exacerbate saline intrusion and inundation in areas where seawater intrusion has already occurred due to groundwater withdrawal; for example, coastal areas along the Mediterranean Sea (Melloul and Collin, 2006), and Estonia (Kont et al., 2003). In addition to changes in mean sea level, extreme events such as the tsunami which occurred in the Indian Ocean at the end of 2004, could impact on permanent groundwater loss. Furthermore, groundwater overexploitation leads to land subsidence in many places; for example, Bangkok (Phien-wej et al., 2006; IGES 2007), and Taiwan (Chen et al., 2007).

The climate system is a complex interactive system related to many components consisting of the atmosphere, oceans, snow and ice, land surface, and all living things (IPCC, 2007). Therefore, changes in climate whether due to natural variability or as a result of human activity can cause a huge impact on the environment and all living things on the earth. The direct impacts of climate change on freshwater systems and water resources management are mainly due to increases in temperature, and precipitation variability, with sea level being an additional factor in coastal areas. Nevertheless, one aspect that has not been investigated in depth is the impact of climate change on groundwater systems, and in particular, the effects on the relationships between surface waters and aquifers that are hydraulically connected (Kundzewicz et al., 2007; Alley, 2001). Some of the many possible factors that affect coastal groundwater are shown in Figure 1.1 and many of these are driven by climatic change.

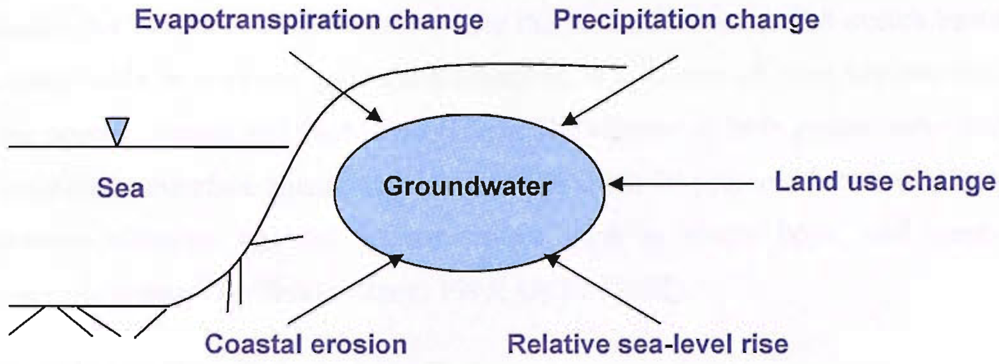


Figure 1.1: Factors which may affect groundwater level in a coastal aquifer

The importance of groundwater

Freshwater is very important for all living things on the earth but it is limited by sources. Throughout history, water has been considered to be the lifeblood of human existence and the heart of civilization. For basic irrigation needs as well as modern industrial development; water is an essential factor. Vajpeyi (1998) reports that almost 70 percent of the earth surface is covered by the vast oceans, lakes, and rivers. Hence, it seems that there is plenty of water for all living things. However, more than 97 percent of the water on the earth is salt water, which is unsuitable for either for consumption or cultivation. Although fresh water is nearly all of the remaining 3 percent, it is inaccessible as a result of being effectively secured in the ice-caps of Greenland and Antarctica and glaciers. (Table 1.1) (Vajpeyi, 1998).

Table 1.1: Distribution of water on the Earth's surface (Shiklomanov, 1993; UNEP, 2002)

Major Stocks of Water	*Volume(10^3 km^3)*	*% Total water*	*%Freshwater*
Salt water			
Oceans	1,338,000	96.54	
Saline/brackish water	12,870	0.93	
Salt water lakes	85	0.006	
Inland waters			
Glaciers	24,064	1.74	68.5
Permafrost ice	300	0.022	0.86
Fresh groundwater	10,530	0.76	30.06
Freshwater lakes	91	0.007	0.26
Marshes/wetlands	11.5	0.001	0.03
Rivers	2.12	0.002	0.006
Soil moisture	16.5	0.001	0.05
Atmospheric water	12.9	0.001	0.04
Living organisms	1.12	0.0001	0.003
Total water	1,386,000	100	
Total freshwater	35,029		100

Groundwater, which is usually reserved for the subsurface water that occurs beneath the water table in soils and geologic formations, is a subject of great importance for all the people on earth and their environment. The volume of fresh groundwater builds an extensive subsurface aquatic domain forming about 30 percent of the world's total freshwater reserves; whereas, surface waters, such as rivers, lakes, and marshes, comprise less than 1% (Shiklomanov, 1993; UNEP, 2002).

Groundwater in the Hydrologic cycle

The hydrologic cycle is the circulation of water between atmosphere, land, and ocean, which has neither beginning nor end; its many processes also occur continuously. Freeze and Cherry (1979) concluded that there are two major parts in the cycle: inflow and outflow. The important inflow of the cycle appears in the form of rainfall or snow melt as precipitation; in addition, condensed water vapour, which is transported and lifted in the atmosphere until it condenses, also associates with precipitation on the land and ocean; however, it may be intercepted by vegetation and then become overland flow over the surface, infiltrate into the ground, flow through the soil as subsurface flow, and discharge into streams as surface runoff to be outflow of the system. In outflow, the important process is carried out by evapotranspiration which is a combination of evaporation from open water, for example, oceans, lakes, rivers, and soil surfaces and transpiration from soil by plants; this returns much of the intercepted water and surface runoff to the atmosphere as shown in Figure 1.2.

Freeze and Cherry (1979) concluded that groundwater's role is accounted since precipitation is active via infiltration from the surface through the top of the vadose zone consisting of all earth materials above the water table: soil and rock. Infiltrated water that percolates through the vadose zone may then enter the groundwater system or zone of saturation where saturation flow occurs, called recharging. Simultaneously, the groundwater will slowly flow, compared with surface water, toward the ocean as seen in Figure 1.1; partial water flow may be consumed by plants, animals, and humans during the flow. Additionally, some water may emerge as springs or seeps into streams to form surface runoff (Chow, 1988).

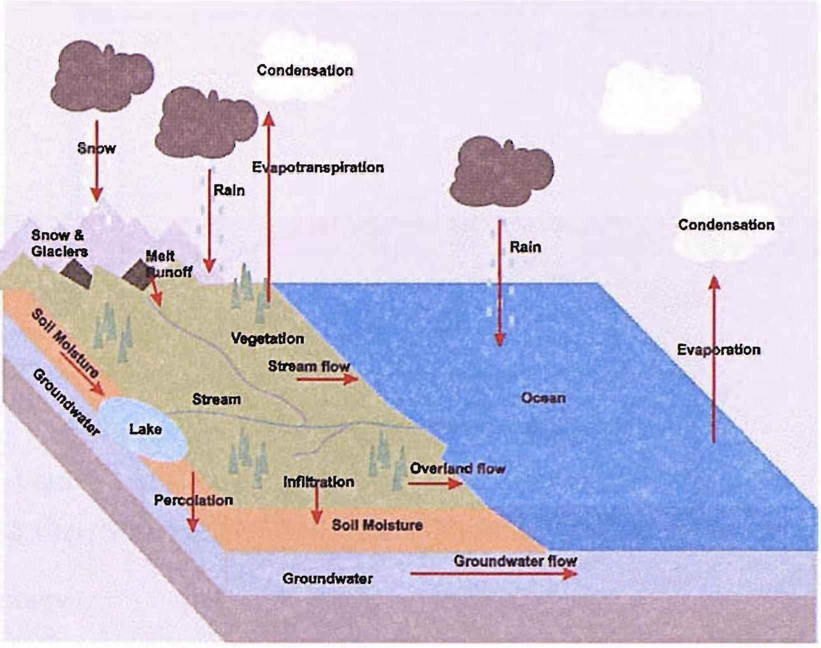


Figure 1.2: Groundwater in the Hydrological Cycle
(Modified after Pidwirny, 2002)

The Importance of Coastal aquifers

Coastal aquifers are underground layers from land toward ocean which are capable to supply groundwater at a rate that can be extracted by a well. A coastal aquifer may consist of various types of material; for example, gravel, sand, fractured sand stone, granite and porous metamorphic rocks, which results in groundwater permeability of aquifers (Todd, 1980).

Coastal aquifers, especially in low-lying deltaic areas, are important sources of water supply due to the high concentration of human settlements and economic activities located there. A trend of increasing human utilisation of the coastal zone during the 20th century seems certain to continue through the 21st century (Nicholls et al., 2007). The near-coastal population within 100 km of a shoreline and <100 m above sea level was estimated as 1.2 billion people (approximate by 23% of the world population) for 1990, with average population densities nearly 3 times higher than the global average density (Small and Nicholls, 2003). As a result of the increasing concentration of human settlements in coastal zone, demands for domestic, agricultural and industrial water uses are increasing (Cohen et al., 1997). Figure 1.3 shows global populations versus distance from the coast.

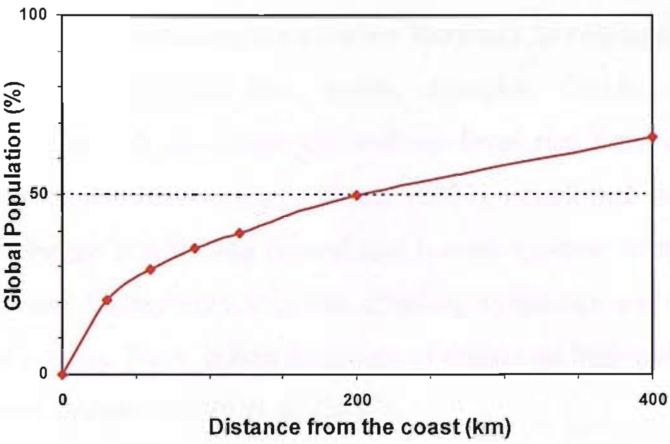


Figure 1.3: Global populations versus distance from the coast
(Modified after: Small and Nicholls, 2003; Nicholls, 2002; Gommes et al., 1998)

Climate change

Climate change studies have been made since the early 1900s. As a result of climate change, small changes in climatic parameters, particularly temperature, can cause enormous consequences on the global environment. Donald (1981) stated that the average global temperature at present is only about 4°C warmer than the period of maximum glaciation. This change over decades effectively causes melting of land-based ice in the Arctic and other ice areas around the poles which will raise sea levels and shift the earth's major climatic zones polewards, and this may bring drought to regions that used to have a reliable rainy season, which is essential for agriculture; and unpredicted flooding into lands that rarely have a history of flooding.

The Intergovernmental Panel on Climate Change (IPCC, 2007) concluded that human activities contribute to climate change by causing changes in the Earth's atmosphere concentration of greenhouse gases, aerosols (small particles), and cloudiness. The burning of fossil fuels, which release carbon dioxide to the atmosphere, is the largest contribution. As part of Earth's energy balance, incoming solar radiation and outgoing infrared radiation are blocked by greenhouse gases and aerosols. Warming and cooling of the climate system can be altered by changing the properties of these gases and particles in the atmosphere. The estimated radiative forcing from changes in natural processes, such as solar irradiance changes and volcanic eruptions, since the start of the industrial era (about 1750) are very small compared to the change in radiative forcing resulted from human activities. Therefore, the radiative forcing from human activities is much more important for current and future climate change than the one from natural processes (IPCC, 2007).

Regional climate changes including temperature increases, precipitation changes, and changes in extreme events like heat waves, droughts, floods, and hurricanes, decreases in the amount of snow and ice, and sea-level rise have already affected physical and biological systems. Parry et al. (2007) concluded that for physical systems, climate change is affecting natural and human systems in regions of snow, ice and frozen ground; furthermore, it is also affecting hydrology and water resources, coastal zones and oceans. There is now evidence of effects on both natural marine and terrestrial biological systems (Parry et al., 2007).

International organizations have issued many reports, and suggestions as a result of climate change; for example, Meehl et al. (2007) stated that all models assessed in IPCC (2007) project increases in global mean surface air temperature continuing over the 21st century for all the non-mitigation scenarios considered. Daily minimum temperatures are projected to increase faster than daily maximum temperatures almost everywhere. In the middle and high latitudes, the growing season is projected to increase. Moreover, average mean water vapour, evaporation, and precipitation are projected to increase globally. Precipitation in areas of tropical precipitation maxima such as the monsoon regimes is projected to increase for a future warmer climate. IPCC (2001) suggested that rainfall totals will not change significantly in north-west Europe but higher temperatures will cause increased evaporative demands and seasonal variation will increase considerably in 2001.

In the UK, climate change scenarios were described by the United Kingdom Climate Impacts Program (UKCIP, 2002) in a series of dimension grid squares covering the UK. Each scenario describes a 30year time horizon for 2020s, 2050s, and 2080s and also various CO_2 emissions scenarios from low to high. UKCIP suggested that climate change under a high emission scenario in 2080 would impact slightly on average rainfall, but higher mean annual temperatures will raise evapotranspiration rates by 9-22%. Furthermore, there will be a modest overall decrease in groundwater recharge. The Regional Climate Change Impact and Response Study (RegIS) at East Anglia and North West England (Holman et al., 2002) concluded that in the North West of the UK under the low scenario of climate change in the 2050s, winter rainfall will be greater than today. However, river flows will generally be less in summer, when evaporation rates are higher. Under the high emission scenario in the 2050s, there will be a modest decrease in both groundwater recharge and average of river flows in the North West.

Rise in sea level

IPCC (2007) presented that there is a strong evidence to support that global sea level gradually increased since the late 19th century. It is estimated that global average sea level rose at a rate of about 1.7mm yr^{-1} for the 20th century; furthermore, global sea level is rising at an even greater rate in this century (IPCC, 2007). Relative sea-level rise is traditionally defined as the combination of eustatic sea-level change and subsidence, irrespective of the potential for sediment deposition, and is therefore a component within the definition of effective sea-level rise. Relative Sea level over the last 300 years is shown in Figure 1.4.

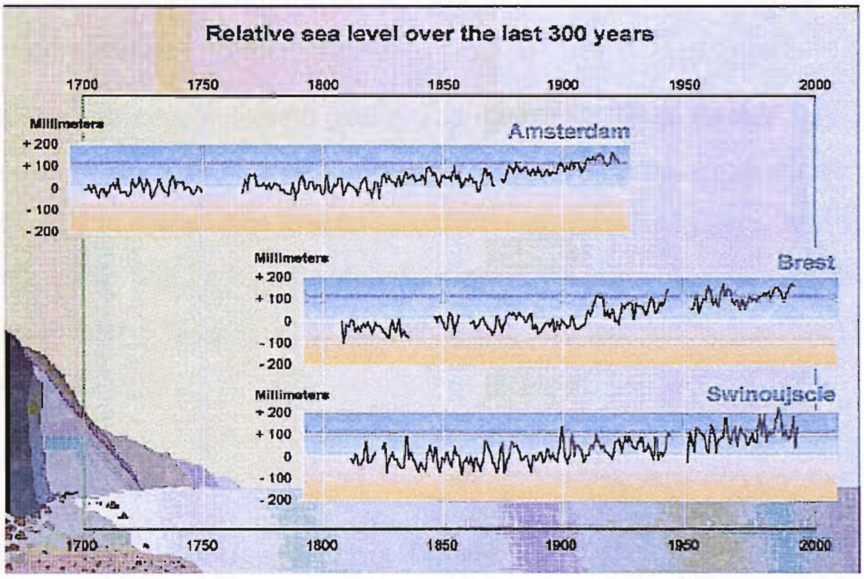


Figure 1.4: Relative Sea level over the last 300 years
(Source: IPCC 2001 also at *http://www.grida.no/climate/ipcc_tar/slides/04.17.htm*)

As a consequence of temperature increases, sea levels will rise due to several processes including thermal expansion of ocean water, the loss of land-based ice due to melting of mountain glaciers and small ice caps and ablation (melting and subsequent runoff) of the polar ice sheets of Greenland and Antarctica. It might even be possible that a great part of the West Antarctic ice sheet disintegrates, and thus sea level might rise several meters (FAO 1997).

The global sea level is currently rising at about 3 mm yr^{-1} based on satellite measurements (IPCC, 2007). Nicholls et al. (2007) reviewed that the best estimate of the global mean sea-level rise scenarios based on thermal expansion and ice melt shows an acceleration of up to 2.4 times compared to the 20^{th} century. These projections, which are smaller than the previous estimate by Church et al. (2001), reflect improved understanding, particularly of estimates of ocean heat uptake (Nicholls et al., 2007). Under the IPCC Special Report on Emission Scenarios (SRES) A1B scenario by the mid-2090s global sea level will rise 0.22 to 0.44m above 1990 levels.

Satellite data, climate models, and hydrographic observations all show that sea level is not increasing uniformly around the world. Rates are up to several times the global mean rise in some regions, while sea level is falling in other regions (IPCC, 2007). However, sea-level rise particularly affects low-lying coastal areas and deltaic zones, with land elevations within a few meters above or below mean sea level and a high density of population.

Sea-level rise will impact on both quality and quantity of groundwater. Sea- level rise will affect on groundwater flow and water table levels by reducing hydraulic gradient. This will result in decrease in groundwater flow out from the system. As a result, the water table levels will be higher. Moreover, sea-level rise will cause permanent loss of land and water resources in coastal area and also accelerate sea water intrusion further inland.

1.2 Aims and Objectives of this Thesis

The aim of this research is to develop modelling tools to enable scientists to identify the most important factors affecting coastal aquifers over the next 100 years in the light of predicted climate change and sea-level rise. As climatic change predictions are inherently uncertain, the magnitude of the impacts of climate change may also be uncertain and this is a key aspect of the work presented here. This will contribute to the wider understanding of climate change impacts on groundwater systems in coastal areas.

Specific objectives are as follows:

- To develop modelling approaches and tools that will enable scientists to better understand the effects of anticipated climate change on coastal groundwater systems,
- To use these tools to identify the key mechanisms that affect the ability of coastal aquifers to provide a useful store of groundwater,
- To test the sensitivity of typical coast aquifer systems to changes in recharge using a model calibrated against known groundwater level observations,
- To investigate changes in the seasonal dynamics of coastal aquifer recharge under differing land uses as climate changes,
- To evaluate the effects of uncertainty in climate variability on the behaviour of groundwater systems,
- To identify the most important factors that will influence the recharge of coastal aquifers in the light of anticipated climate change and sea level rise.

1.3 Thesis Outline

The thesis consists of nine chapters. Firstly, a general overview of the importance of groundwater, groundwater in the hydrologic cycle, aquifers and coastal aquifers, climate change, and sea-level rise are presented. The aim and specific objectives of the thesis are stated.

Chapter 2 presents a review of the previous work carried out to investigate impacts of climate change and rise in sea level on groundwater. This chapter introduces related work including a review of the widely used theory of groundwater flow, basic groundwater and aquifers, importance of coastal aquifers and threats to coastal aquifers, climate change, sea-level rise, steady-state model of fresh/salt water intrusion, coastal erosion and modelling coastal aquifers.

Chapter 3 presents an overview of the methodology used and describes the sub models that are utilized. The first part of this chapter describes two case study areas chosen including Ainsdale National Nature Reserve in the UK and Samut Prakan in Thailand. The main components of the groundwater model construction are described including defining the aquifer system, developing a water balance model, data needed for the model, building, testing, and calibrating model, application of climate change into the water balance model, investigating impacts caused by climate change, and using the model to investigate other aquifer systems. Next the parameters and theory used in the model are described including water balance models, evapotranspiration, interception loss, groundwater flow, and Darcy's Law.

The water balance model development and calibration for Ainsdale NNR are described in chapter 4. Estimation of potential and actual evapotranspiration is described, together with the calculation of groundwater. The development and testing of the model are explained to show how the water balance model was refined for a short vegetation cover. This is then developed to include interception losses for large vegetation such as pine forests. Finally, the impacts of tree coverage change on the water balance model are described.

Chapter 5 describes modelling the impact of sea-level rise and coastal erosion on water table levels and its applications at Ainsdale NNR. The effect of sea-level rise on the conceptual groundwater model, results and sensitivity analysis are explained. Secondly, the effects of coastal erosion on the conceptual groundwater model and described together with a sensitivity analysis and results. The impact of sea-level rise and coastal erosion on the water balance model are described and the relative importance of sea-level rise and erosion in model compared with climate variables is explained.

In chapter 6, the impact of climate change on groundwater levels is presented by running the calibrated water balance model with climate change scenarios. In this chapter, the predicted data series is described, including UKCIP climate change scenarios, the Built Environment: Weather scenarios for investigation of impacts and extremes (BETWIXT) datasets, and the calculation of evapotranspiration for Ainsdale based on BETWIXT data. Uncertainty in model outputs is explored using a stochastic simulation of future time series of climate data. Finally, the impacts of expected climate change on the groundwater system are summarised.

In Chapter 7 the water balance model was also used to explore used to explore the possible impacts of climate change on groundwater systems in the other part of the world. Samut Prakan in Thailand was selected as a case study.

Chapter 8 contains a discussion on the modelling approach and outcomes and Chapter 9 presents the conclusions and recommendations of the thesis. It also includes a set of suggestions for additional research that could be done to improve the models is presented.

CHAPTER 2

Literature Review

This chapter reviews previous work which is relevant to investigation of impacts of climate change and sea-level rise on groundwater systems in coastal aquifers. Topics covered include a review of the fundamentals of groundwater flow and aquifers, the importance of costal aquifers and previous work on steady-state models of coastal systems including fresh/salt water intrusion. A review of the anticipated threats to coastal aquifers from climate change, sea-level rise and coastal erosion is made. It is shown that previous work in climate change and groundwater mainly used annual shifts in climate to predict impacts and the seasonal dynamic nature of aquifer recharge is poorly understood and the effects of the uncertainty of climate change are therefore not fully captured.

2.1 Groundwater and aquifers

Groundwater is water which has been stored underneath the ground surface in soil pore spaces and in the fractures of geologic formations for a month or several years depending on the geologcal properties. Freeze and Cherry (1979) stated that when a formation of rock/soil can yield a useable quantity of water, it is called an aquifer. The water table or phreatic surface, where water pressure is equal to atmospheric pressure, is the depth at which soil pore spaces become saturated with water. Groundwater is naturally refilled by surface water from precipitation, streams, and rivers when this recharge reaches the water table. The groundwater level is the level of water in a well depending on geological properties and depth of a well as shown in Figure 2.1.

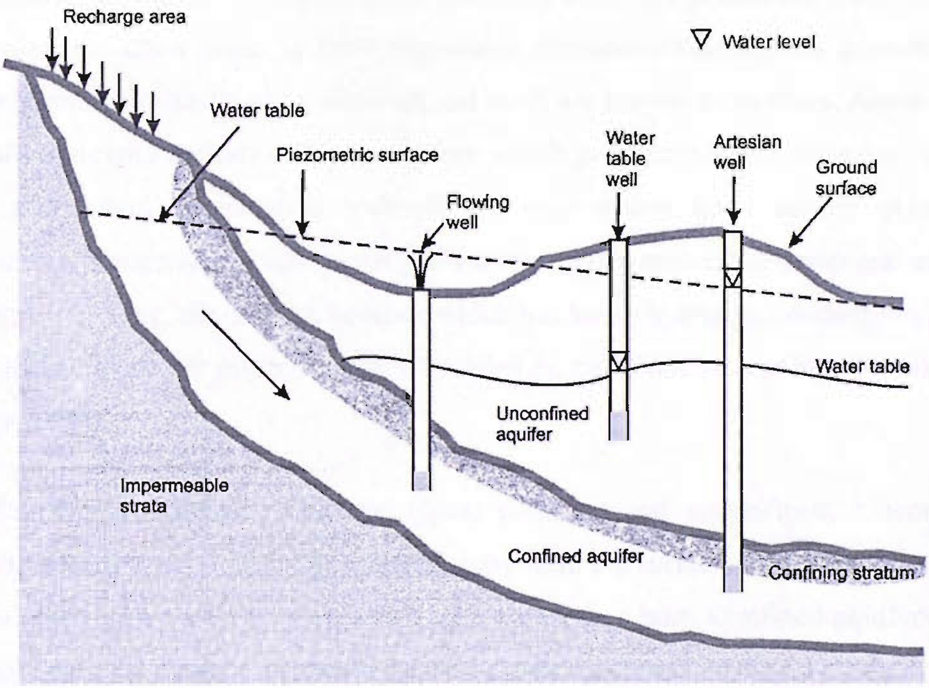


Figure 2.1: Groundwater and aquifer properties
(Modified after: Todd, 1980)

Todd (1980) stated that most rainfall will soak into the soil, which acts like a giant sponge. The part of the rainfall that flows over the ground is known as runoff. Part returns to the atmosphere though evaporation and part is taken up by vegetation and, through a process called evapotranspiration, returns to the atmosphere. The remainder infiltrates into aquifers and replenishes groundwater storage. Groundwater flows through aquifers to outlets in rivers, at springs and in the sea.

Groundwater contributes about 30% of the world's fresh water supply; moreover, the estimated volume of groundwater is about fifty times that of surface freshwater (UNEP, 2002). The icecaps and glaciers are the only larger reservoir of fresh water on earth. Groundwater is generally withdrawn for various purposes including agricultural, municipal, and industrial use by constructing and operating extraction wells. Groundwater abstractions are especially an important source of water for people and businesses that cannot, or would rather not, use water from the public mains. About 35% of all public water supplies in England and Wales come from groundwater which has undergone treatment (Environment Agency Facts and Figures).

Groundwater is almost universal; however, some geological formations are impermeable in which water can hardly flow, and some are permeable which contain fine holes that allow water to flow. Permeable formations that contain groundwater, which is enough quantity to be obtained and used, are known as aquifers. Aquifers are typically saturated regions of the subsurface which produce water to a well or spring. Sand and gravel or fractured bedrock generally makes good aquifer materials. Aquitards are materials which do not yield a sustainable amount of water and usually are formed by clay, silt or fresh bedrock which has lower hydraulic conductivity. If an aquitard is completely impermeable, it is called an aquiclude or aquifuge (Freeze and Cherry, 1979).

Aquifers can be divided into two types; confined and unconfined. Unconfined aquifers usually receive recharge water directly from the surface, from precipitation or from a body of surface water such as a river, stream, or lake. Confined aquifers have very low specific yield or storativity values (much less than 0.01 and as little as 10^{-5}). Unconfined aquifers have specific yield between 0.01 and 0.4 (Todd, 1980).

The earth's crust can be divided into the saturated zone and the unsaturated zone (also called the vadose zone) as shown in Figure 2.2. In the saturated zone, the pressure head of the water is greater than atmospheric pressure. The unsaturated zone is the zone above the water table where the pressure head is negative and the water which partially fills the pores of the aquifer material. The water table is the surface where the pressure head is equal to atmospheric pressure. In the unsaturated zone, the water content is held in place by surface adhesive forces and it rises above the water table by capillary action.

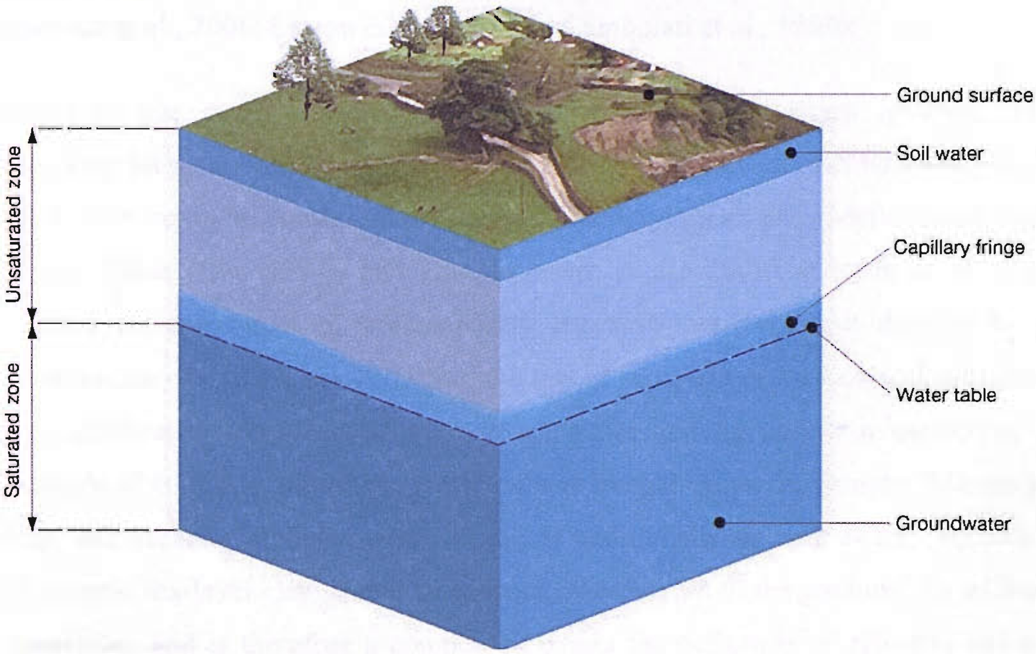


Figure 2.2: Saturated zone and unsaturated zone (Source: UK Goundwater Forum)

2.2 Importance of Coastal Aquifers and Threats to Coastal Aquifers

Many coastal zones in the world accommodate high density population, so freshwater is regularly a scarce resource in these regions. Progressive growth of coastal populations has led to an increasing demand for water use. Intense groundwater exploitation without precise planning has caused severe deterioration of water resources. Due to overexploitation of groundwater, many coastal areas have been threatened with problems such as salinisation and subsidence; for example, Cecina and Ravenna in Italy (Grassi et al., 2007; Giambastiani et al., 2007), Queensland in Australia (Narayan et al., 2007), Bangkok in Thailand (Phien-wej et al., 2006), Greece (Lambrakis and Kallergis, 2201; Voudouris, 2006), Jakarta in Indonesia (Abidin et al, 2001), and Taipei and Pingtung Plain in Taiwan (Chen at el, 2007; Hu et al., 2006). Salinisation occurs when the freshwater-saltwater interface is shifted further inland due to decrease in groundwater heads (usually caused by over-pumping of groundwater). Subsidence of unconsolidated deltaic sediments is a natural process.

Massive pumping of groundwater induces subsidence by dropping the piezometric level influenced in irreversible compaction of aquitard material and amount of presumably elastic compaction from compression of coarse-grained conglomerate and sand deposits in aquifers (Chen et al., 2007; Phien-wej et al., 2006; Chai et al., 2004; Pacheco et al., 2006; Larson et al., 2001 and Gambolati et al., 1999).

Sea-level rise could exacerbate saline intrusion and inundation in areas where seawater intrusion has already occurred due to groundwater withdrawal (Essink, 2001); for example, coastal areas along the Mediterranean Sea (Melloul and Collin, 2006), China (Liu, 1997), and Estonia (Kont et al., 2003). Ericson et al. (2006) present an assessment of contemporary effective sea-level rise defined by the combination of eustatic sea-level rise, the rate of sediment deposition and subsidence, and accelerated subsidence due to groundwater and hydrocarbon extraction, for example of 40 deltas around the world such as Bengal, Amazon, Danube, Mississippi, Nile, and Mekong. Relative sea-level rise is traditionally defined as the combination of eustatic sea-level change and subsidence, irrespective of the potential for sediment deposition, and is therefore a component within the definition of effective sea-level rise. It is found that direct anthropogenic effects determine effective sea-level rise in the majority of deltas studied, with a relatively less important role for eustatic sea-level rise.

Climate change is another possible threat to coastal aquifers by reducing aquifer recharge. Climate change impacts on recharge may occur by changing rainfall patterns, and evapotranspiration rates. Previous studies have typically linked climate change scenarios with hydrological models and have investigated the impact of climate change on groundwater resources in different areas; for example, East Anglia in the UK (Holman, 2006), Massachusetts (Kirshen, 2002) and Muchigan (Croley et al., 2003), Northrhine-Westfalia in Germany (Krüger et al., 2001), India (Panda et al, 2007), the Baltic Sea region (Schmidt-Thome, 2005), and Greece (Lambrakis and Kallergis, 2001).

2.3 Climate Change

IPCC (2007) stated that climate change describes changes in the average state of the atmosphere or weather over time scales varying from decades to millions years. The Earth's climate has continuously changed over time since ice ages. These changes are driven by two main categories: internal climatic process and external factors called "climate forcings" including such processes as variations in solar radiation, the Earth's orbit, volcanism, greenhouse gas concentrations, and human activities. The biggest human influence factor of concern is increases in CO_2 levels due to emissions from fossil fuel combustion, followed by aerosols which exert a cooling effect, but other factors, including land use, ozone depletion, and deforestation also impact on climate (IPCC, 2007).

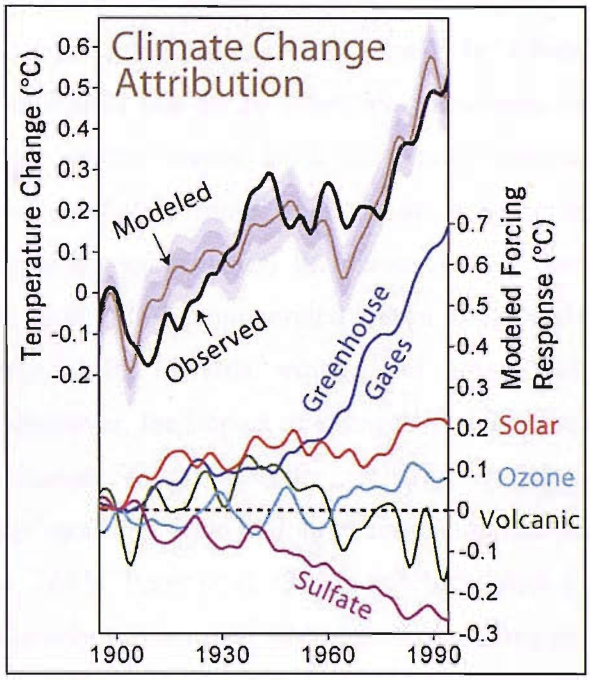


Figure 2.3: Attribution of recent climate change
(Source: Meehl et al., 2004)

Meehl et al. (2004) presented observed and modelled temperature changes from 1900 to 1990 with various factors forcing temperature change including greenhouse gases, solar, ozone, volcanic, and sulphate (Figure 2.3). The chart shows that temperature continuously increases; furthermore, greenhouse gases become more significant in forcing temperature increase.

The primary effect of climate change on the environment and human life is an increasing global average temperature which creates a variety of secondary effects including sea-level rise, altered patterns of agriculture, and extreme weather event increases. As the climate becomes warmer, evapotranspiration will increase. Secondary evidence of global warming such as reduced snow cover, rising sea levels, and weather changes provides examples of consequences of global warming that may affect not only human activities but also ecosystems. Moreover, increased extreme weather means more rainfall on hardened ground unable to absorb it leading to flash floods instead of a replenishment of soil moisture or groundwater level (Gille, 2002).

In the case of projected freshwater, there are the few studies of climate impacts on groundwater; for example: Arnell et al. (1994) studied impacts of climate change on groundwater recharge in the UK. The report shows that the winter season is important to groundwater recharge; furthermore, recharge will be adversely affected if the recharge period is shortened due to increased evapotranspiration and soil moisture deficits or the winter rainfall comes in shorter, more intense periods than now. Moreover, prolonged rainfall is more effective at recharge than shorter, intense storms. The work noted that summer base flow is sensitive to the response time of the aquifer. Kundzewicz et al. (2007) summarized that in many aquifers of the world the groundwater recharge shifts towards winter, and groundwater recharge in the summers declines. Moreover, the impact of changes in river levels on groundwater is much more than changes in groundwater recharge for an aquifer having low groundwater recharge rates and good hydraulic connection between the river and the aquifer (Arnell et al, 2003). Parry et al. (2007) concluded that groundwater recharge will decrease considerably in some already water-stressed regions, where population and water demand rapidly increase. This result agrees with Thomsen (1990) who presented that a decrease in winter rainfall could cause a major reduction in groundwater recharge in some parts of Europe, as a result of evapotranspiration rates are low in winter. In the same way, Kirshen (2002) summarized that the impacts on recharge are sensitive to actual evapotranspiration. Moreover, runoff and water availability are very likely to increase at higher latitudes and in some wet tropics. Areas in which runoff is projected to decline will face a reduction in the water resource availability (Parry et al., 2007). In the same argument, Arnell (2004) concluded that climate change increases water resources stresses in some parts of the world where runoff decreases, but decreases them in other parts. However, Döll and Flörke (2005) suggested that groundwater recharge increases less than increase in total runoff. Groundwater recharge increases by only 2%, whilst total runoff was estimated to increase by 9%.

Land use change may cause a change in groundwater recharge. Climate change may lead to vegetation and land use change which influences groundwater recharge (Kundzewicz et al., 2007). Ranjan et al. (2006) investigated the effects of climate and land use changes on groundwater resources in coastal aquifers. An interesting finding is that deforestation leads to increased groundwater recharge in arid areas due to reduced evapotranspiration although it increases runoff. Moreover, the review found that the fresh groundwater loss increases as the percentage of forest cover increases. Deforestation causes an increase in recharge and existing fresh groundwater resource in areas having low precipitation and high temperature. Ranjan's model was found to be very sensitive to hydraulic conductivity changes and groundwater recharge and hence it is important to understand the key mechanisms of recharge and their seasonal variation.

In the UK, the UK Climate Impacts Programme (UKCIP, 2002) produced a set of four possible alternative scenarios of climate change for the UK, the UKCIP02 scenarios. Each is based on a different greenhouse gas emissions profile (Low emissions, Medium-Low emissions, Medium-High emissions and High emissions). The UKCIP02 climate scenarios indicate that average annual temperatures across the UK may rise by between 2 and 3 °C by the 2080s. Annual average precipitation across the UK may decrease slightly, by between 0 and 15 per cent by the 2080s. Moreover, extreme winter precipitation will become more frequent; for example, an increase in the number of very warm summer months, very dry summers could occur in 50% of years by the 2080s, winter daily precipitation intensities that are experienced once every two years on average, may become up to 20 per cent heavier. For the Medium-High Emissions scenario, very dry summers (like 1995) may occur in half the years by the 2080s, while very wet winters (like 1994/95) may occur on average almost once a decade (UKCIP, 2002).

The Regional Climate Change Impact and Response Studies in East Anglia and North West England (RegIS) project is part of the UKCIP (Holman et al., 2002). The project studies both climate change and socio-economic trends and looks how these regions might response under two contrasting storylines. It is concluded that in the North West of England, mean annual temperatures are likely to rise by between 0.7 and 2.1°C by the 2050s, compared to 1961 to 1990. Higher temperatures will increase evaporation rates by 9-22%. Annual rainfall increases slightly, but winters will become wetter than at present and the summers drier. Under the high emission scenario in the 2050s, both groundwater recharge and average river flows in the North West are expected to decrease moderately (Holman et al., 2002). In 2003 a second phase of the RegIS project was funded (RegIS2). The Regional Impact Simulator using the UKCIP02 based on the Low and High emissions scenarios concluded that increases in mean annual temperature, relative to 1961- 90, range from 0.5 to 2.6°C by the 2050s. Annual rainfall varies from –9 to +7% by the 2050s. Winter precipitation increases in all regions, but summer precipitation decreases across virtually all of the UK (Holman et al., 2007).

2.4 Sea-level rise

In consequence of increasing average global temperature, sea levels will rise due to many processes including thermal expansion of ocean water, the loss of land-based ice due to melting of mountain glaciers and small ice caps and ablation (melting and subsequent runoff) of the polar ice sheets of Greenland and Antarctica. It might even be possible that a great part of the West Antarctic ice sheet disintegrates, and thus sea level might rise several meters in the order of millennia (FAO 1997). Nicholls (2002) and Nicholls and Lowe (2004) stated that apart from short-term variability such as tides and waves, relative sea-level rise is the sum of several components. Firstly, global mean sea-level rise caused by an increase in the volume of the ocean is primarily due to thermal expansion of Upper Ocean and the melting of small ice caps due to human-induced global warming. The contribution of ice melt in Greenland is less certain, but increased snowfall over Antarctica is expected to enlarge the Antarctic ice sheet. This will cause a sea level fall. The Antarctica and Greenland ice sheets receive snowfall at a rate of about 8 mm each year. If no ice returns to the oceans, sea level would drop 80 mm every 10 years. Approximately the same amount of water returns to the ocean in icebergs and from ice melting at the edges. The difference between the ice input and output (called the mass balance) is important as it causes changes in global sea level (IPCC, 2001; Douglas, 1997). Secondly, regional factors such as changes in ocean circulation, changes to long-term wind fields and atmospheric pressure, spatial variation in thermal expansion may cause deviations from the global mean sea-level rise. However, this component has been largely ignored in impact assessments to date. Lastly, vertical land movement causes by various geological and human-induced processes such as consolidation and water withdrawal. This component is expected to be less than the rise due to oceanographic changes; however, it will be important, especially in areas subject to human-induced subsidence (Nicholls, 2004).

The rate of sea-level rise has increased between the mid-19th and the mid-20th centuries; moreover, there is a strong evidence to support that global sea level gradually increased since the late 19th century (IPCC, 2007). Figure 2.4 illustrates annual averages of the global mean sea level (mm) from 1870 to 2003. An increase of 1.5 to 4.5 °C is estimated to lead to a sea level increase of 15 to 95 cm (IPCC, 2001).

The global sea level has risen more than 120 metres since the peak of the last ice age from 15000 to 6000 years ago (Nicholls, 2002). From the beginning of the 19th century to 3000 years ago, sea-level rise was almost constant at 0.1 to 0.2 mm/yr (IPCC, 2001). From 1961 to 2003, the average rate of sea-level rise was 1.8 ± 0.5 mm/yr and it was 1.7 ± 0.5 mm/yr for the 20th century (Bindoff et al., 2007). Nicholls et al. (2007) reviewed that the best estimate of the global mean sea-level rise scenarios based on thermal expansion and ice melt shows an acceleration of up to 2.4 times for the mean case compared to the 20th century. These projections, which are smaller than the previous estimate by Church et al. (2001), reflect improved understanding, particularly of estimates of ocean heat uptake (Bindoff et al., 2007; Nicholls et al., 2007).

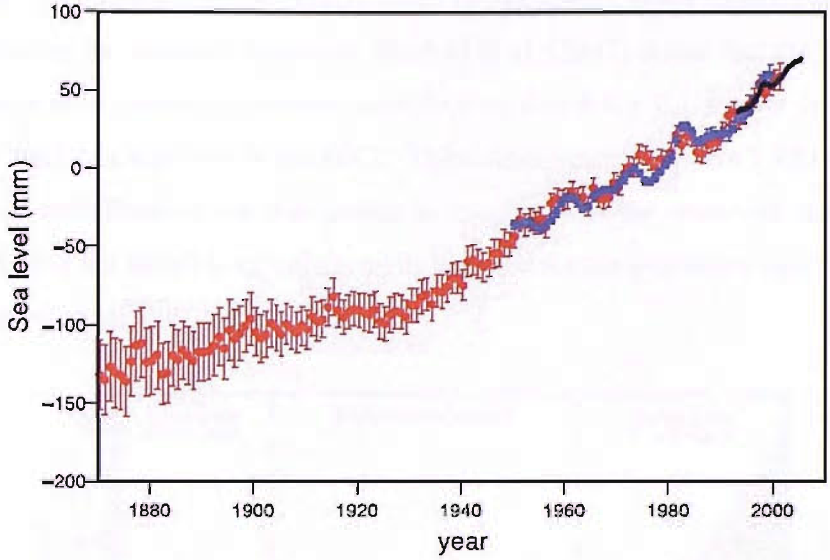


Figure 2.4: Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870; the blue curve shows coastal tide gauge measurements since 1950 and the black curve is based on satellite altimetry. Error bars show 90% confidence intervals. (Source: Bindoff, 2007)

There have been many reports of estimated global mean sea-level rise for the future; for example, The IPCC Special Report on Emission Scenarios (SRES) under A1B scenario presented that by the mid-2090s global sea level reaches 220mm to 440 mm above 1990 levels (Bindoff et al., 2007). Figure 2.5 shows time series of global mean sea level (deviation from the1980-1999 mean) in the past and projected for the future. Bindoff et al. (2007) stated that for the period before 1870, global measurements of sea level are not available, so the grey shading shows the uncertainty in the estimated long-term rate of sea level change. The red line is a reconstruction of global mean sea level from tide gauges, and the red shading denotes the range of variations from a smooth curve. The green line represents global mean sea level observed from satellite altimetry. The blue shading shows the range of model projections for the SRES A1B scenario for the 21st century. Beyond 2100, the projections are increasingly dependent on the emissions scenario (Bondoff et al., 2007). Rejecting some IPCC assumptions, Mörner et al., (2004) has argued that rise in sea level will not exceed 200 mm, within a range of either +100±100 mm or +50±150 mm depending on assumptions.

There are uncertainties in the contributions to sea level change estimation; however, understanding has recently improved. Bindoff et al. (2007) stated that the average sea-level rise due to thermal expansion contribution was 0.4 ± 0.1 mm/yr for the period 1961 to 2003. As reported in the IPCC Third Assessment Report (TAR), the sum of all known contributions for this period is smaller than the observed sea-level rise; therefore, it is not possible to satisfactorily account for the processes causing sea-level rise (Bindoff et al., 2007).

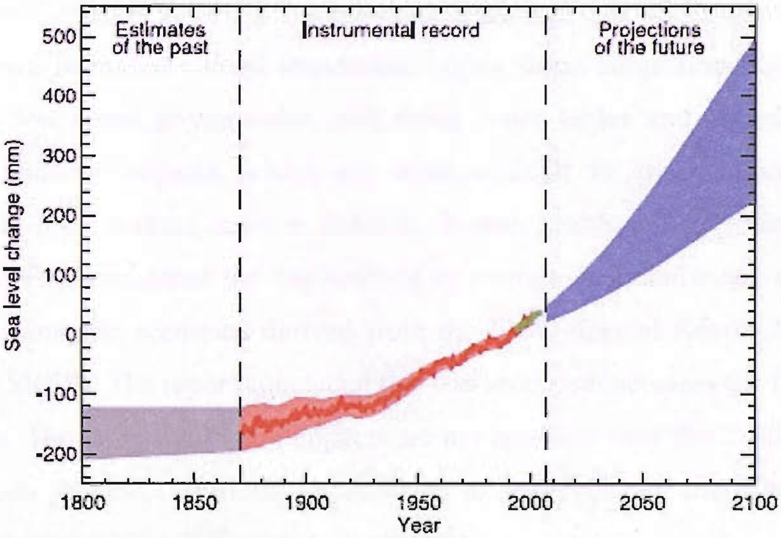


Figure 2.5: Time series of global mean sea level (deviation from the1980-1999 mean) in the past and as projected for the future. (Source: Bindoff et al., 2007)

The rise in global mean sea level is accompanied by considerable decadal variability. The rate of sea-level rise is estimated from observations with satellite altimetry from the satellites TOPEX/Poseidon as 3.1±0.7mm/yr for the period 1993 to 2003, significantly higher than the average rate (Douglas, 1997; Leuliette et al., 2004; Bindoff et al., 2007). The tide gauge record indicates that similar large rates have occurred in previous 10-year periods since 1950. It is unknown whether the higher rate in 1993 to 2003 is due to decadal variability or an increase in the longer-term trend.

Satellite data, climate models, and hydrographic observations show, in the same agreement, that sea level is not increasing uniformly around the world. Increasing rates are up to several times the global mean rise in some regions, while sea level is falling in other regions (IPCC, 2007). However, sea-level rise particularly affects low-lying coastal areas and deltaic zones, with land elevations within a few meters above or below mean sea level and a high density of population. There is evidence for an increase in the occurrence of extreme high water worldwide related to storm surges, and variations in extremes during this period are related to the rise in mean sea level and variations in regional climate.

Current and future sea level change would be expected to have a number of impacts, especially on coastal systems. These impacts can be divided into two categories. Firstly, direct impacts consist of morphological change (such as erosion and coastal wetland loss), increased coastal inundation, higher storm-surge flooding, salinisation of surface water and groundwater, and rising water tables and impeded drainage. Secondly, indirect impacts, which are more difficult to analyze, are potentially important in some sectors, such as fisheries, human health and etc (Nicholls, 2003). Nicholls (2004) considered the implications of a range of global-mean sea-level rise and socio-economic scenarios derived from the IPCC Special Report on Emissions Scenarios (SRES). The report concluded that sea-level rise increases the flood impacts in all cases. The most significant impacts are not apparent until the 2080s, and trends of the results suggest that flood impacts due to sea-level rise could become much more severe through the 22^{nd} century in all cases.

2.5 Sea water intrusion

Over abstraction of groundwater by human pumping can cause salt water movement into aquifers in coastal areas which affects the quality of the freshwater. For an aquifer near the coast, the recharge zone is likely to be inland. A lowered water table may induce sea water to reverse the groundwater flow toward the sea in coastal areas. The movement of sea water into inland is called a saltwater intrusion.

Many coastal aquifers have experienced a salt water intrusion caused by both natural as well as human intervention such as mining of natural resources (e.g. water, sand, oil, and gas) and land reclamation. (Essink, 2001) An accurate assessment of the impacts of sea-level rise on coastal aquifers is difficult to achieve. Importantly, the impacts of sea-level rise must be considered in relation to impacts of human activities.

Climate change and sea-level rise may have impacts on saltwater intrusion due to decrease in recharge (Kundzewicz et al., 2007). Moreover, coastal aquifers within the zone of influence of mean sea level will be seriously threatened by sea-level rise, and it will extend areas of salinisation of groundwater and estuaries, which could result in a decrease of fresh water resources (Parry et al., 2007).

The freshwater-saltwater interface generally seldom remains stationary because temporal recharge and withdrawal of water from the aquifer will cause the movement of the salt-freshwater interface. The movement of the fresh-saltwater interface will advance or retreat depending on groundwater recharge. Increases in groundwater recharge shifts the salinity interface downward to the sea and decreases in recharge shift the saltwater-freshwater interface further inland (Ranjan et al., 2006).

Sea-level rise will cause the mixing zone between fresh and saline groundwater to be shifted further inland (Ranjan et al., 2006). The distance of the movement of the interface caused by climate change and sea-level rise has been investigated; for example, Sherif and Singh (1998) studied the effect of climate change on sea water intrusion on coastal aquifers in Egypt and India which rely heavily on groundwater. Only 50 cm of sea-level rise in the Mediterranean will cause 9.0km additional intrusion in the Nile Delta aquifer and 0.4km in the Bay of Bengal which will significantly impact on the ecosystem located in these areas. Ranjan et al. (2006) investigated the effect of hydro-geologic factors including specific storage, porosity, and hydraulic conductivity on the movement of freshwater-saltwater interface. The result illustrated that a change in storage coefficient does not affect the position of the interface. In the same way, the change in porosity does not lead to a change in the position of the interface. The most important factor affecting the change in the position of the freshwater-saltwater interface is hydraulic conductivity and recharge. Additional pumping will cause serious seawater intrusion. Groundwater abstraction wells, which were previously located beyond the saline water zone, will be in areas where upconing of brackish or saline groundwater can easily occur. This can be considered as one of the most serious effects of sea-level rise for every coastal aquifer where groundwater is heavily exploited (FAO, 1997).

2.6 Steady state model of fresh/salt water intrusion

Modelling the process of saltwater intrusion into aquifer systems is still rather complex. Freshwater has a density of 1.0g/cm^3 whilst salt water is slightly denser 1.025g/cm^3. As a result of this, fresh water floats on top of the salt water. Rainfall that percolates the ground depresses the salty water found beneath it forming a profile that has the appearance of a lens which is called the Ghyben-Herzberg lens. This relationship principle was discovered independently by a Dutch scientist named Baden-Ghyben and a German scientist named Herzberg.

Essink (2001), based on the Ghyben-Herzberg principle, concluded that the two most important factors are the aquifer recharge and hydraulic gradient (Figure 2.6). Simple steady state models can be constructed to estimate the relative position of fresh and salt water in an aquifer; however, climate change, tidal range and sea-level rise produce interactions which complicate such simple models.

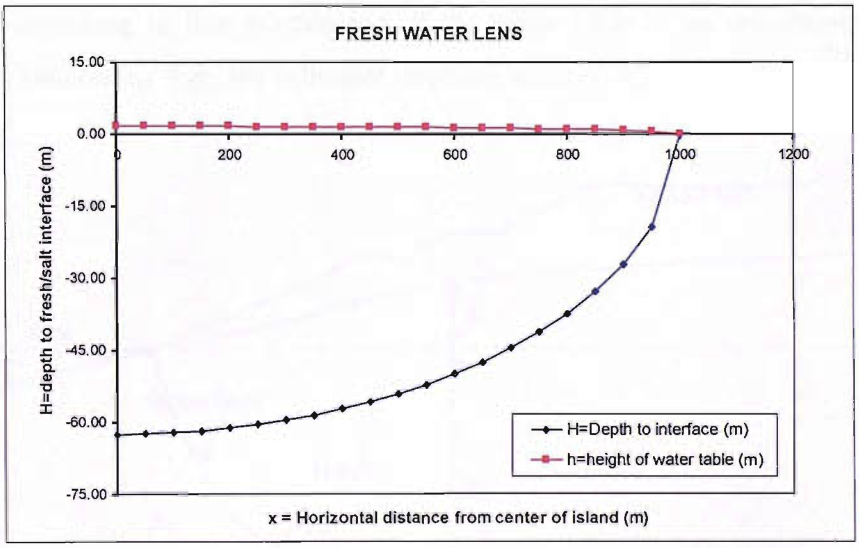


Figure 2.6: Example freshwater lens based on the Ghyben-Herzberg model using Essink's steady state calculation. (The upper line is the water table and the lower line is the theoretical interface between the fresh water on the left and the salt water on the right)

The boundary that separates the fresh water layer from the salt water is not a sharp line. In reality, this boundary is a transition zone of brackish water (fresh/salt mixture). This is caused by seasonal fluctuations in rainfall, tidal action, and the amount of water being withdrawn either by humans or by natural discharge.

The Badon Ghyben-Herzberg principle, equation (2.10), describes the position of an interface between fresh and saline groundwater as shown in Figure 2.7.

$$h = \frac{\rho_s - \rho_f}{\rho_f} H \Leftrightarrow h = \alpha H \qquad (2.1)$$

Where h = the piezometric head with respect to mean sea level (L)

H = the depth of the fresh-salt interface below mean sea level (L)

ρ_f = the reference density, usually the density of fresh water without dissolved solids (M/L^3)

ρ_s = the density of saline groundwater (M/L^3)

α = $(\rho_s - \rho_f)/\rho_f$ the relative density difference (dimensionless)

= 0.025 if ρ_f = 1000 kg/m^3 and ρ_s = 1025 kg/m^3

This analysis assumes hydrostatic conditions in a homogeneous, unconfined coastal aquifer. According to this relationship, if the water table in an unconfined coastal aquifer is lowered by 1 m, the saltwater interface will rise 40 m.

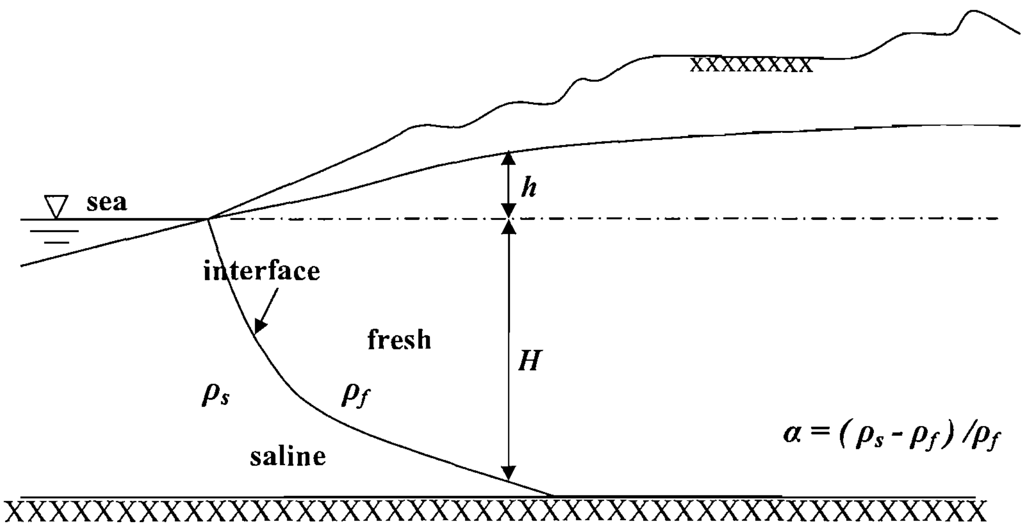


Figure 2.7: A fresh-salt interface in an unconfined coastal aquifer (Modified after: Essink, 2001)

According to Essink (2001b), freshwater lenses have evolved in unconfined aquifers due to natural groundwater recharge as shown in Figure 2.8. Analytical formulae can be derived such as equation 2.11 (Essink, 2001b).

$$H = \sqrt{\frac{-fx^2 - 2C_1 x - 2C_2}{k(1+\alpha)\alpha}}, \quad h = \alpha H, \qquad q = fx + C_1 \tag{2.2}$$

Where q = the groundwater flow per unit coast length (L^2/T)
H = the depth of the fresh-salt interface below mean sea level (L)
k = the horizontal hydraulic conductivity (L/T)
f = the natural groundwater recharge (L/T)
x = the horizontal position (distance from the axis of symmetry) (L)
C_1, C_2 = the constant number determined by setting boundary conditions

Using equation 2.11, if H_{max} (which is the deepest depth of the fresh-salt interface in the middle of the lens) is 62.5 m and the shoreline subsequently retreats 100m at each side due to sea-level rise whilst the natural groundwater recharge drops by 20% due to climate change, H_{max} becomes only 50.3 m. This illustrates that the thickness of the fresh-salt interface is partly controlled by the recharge rate, which is directly related to climate.

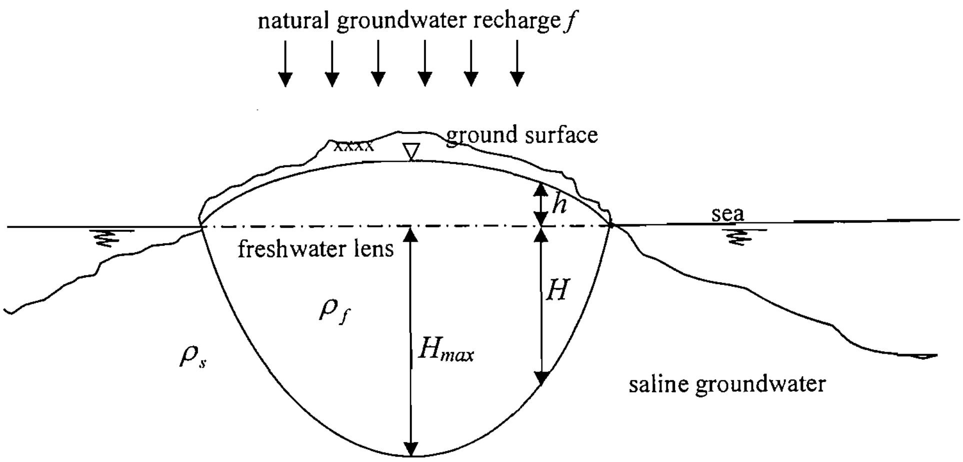


Figure 2.8: The position of a fresh-salt interface in an elongated island (Modified after: Essink, 2001)

The Essink model is a steady state model which assumes a constant recharge rate. As such it is not possible to use this model to simulate seasonal or monthly patterns of water table levels, nor can it deal with changes in climate. As a result it is clear that a dynamic water balance model is needed to generate aquifer recharge and thus simulate the seasonal water table variations caused by climate change and sea-level rise.

2.7 Coastal erosion

Coastal erosion refers to the loss of landmass into the sea, lakes, or rivers due to natural processes such as winds and tides, waves, or even human interference. There are many factors that drive coastal erosion; for example, geological structure, wave climate, water level change, geomorphology, weathering and transport slope processes, vegetation, coastal land use, resources extraction, and coastal management. Coastal erosion can result in dramatic rock formations in areas where the coastline contains stones and the coastlines become eroded much faster in the softer areas such as sand dunes.

Erosion is also affected by many other factors such as sea-level rise, sand mining, structures, mangrove clearance etc. Bruun (1962) showed that as a result of sea-level rises, the upper part of the beach is eroded and deposited just offshore in a fashion that restores the shape of the beach profile with respect to sea level. The "Bruun Rule" implies that a one meter rise would generally cause shores to erode 50 to 200 meters along sandy beaches, even if the visible portion of the beach is fairly steep.

Nicholls (2002) stated that Bruun (1962) suggested that there was a relationship between sea-level rise and shoreline recession on sandy beaches. In many parts of the world, sand dunes are an important component of coastal and flood defences. Dune systems can form in response to varying wind/wave climate, sea level change, and shoreline erosion. Changes in nearshore morphology are likely to be reflected by the erosion/accretion status changes. It is very important to predict the onset of erosion or accretion before it actually happens for planning and protection in the future.

Sea-level rise and coastal erosion may be important factors affecting groundwater in coastal aquifers. In many areas, the coastline retreat from the sea rising only one-meter would be much greater than expected by the area of land below the one-meter contour on a map, because shores would also be affected by erosion. Over the last 100 to 150 years, sea-level rise is contributing to coastal erosion in many places around the world (Rosenzweig et al., 2007). As a result of sea level change, coastal erosion is driven by other natural factors including land subsidence, wave energy and sediment supply (Saye et al., 2005).

A phase of coastal erosion at one of the study areas in this thesis (Formby Point, UK) began at the beginning of the 20th Century and has continued to the present day through a combination of human interventions associated with the Mersey and Ribble Estuaries and a change in storm conditions (Saye et al, 2005; Atkins, 2002; Pye and Neal, 1994). Coastal erosion predictions for this coast caused by sea-level rise were estimated for every 10 years time steps from 2025 to 2105 by Sefton Council (Lymbery et al., 2007). Applying the sea-level rise data estimated by Department for the Environment, Food, and Rural Affair (DEFRA) into Bruun's formula along with data relating to the topography at each study area enables the distance of the coast reposition itself in response to the sea-level rise. Coastal erosion prediction for Formby area due to sea-level rise is estimated to be about 13m in 2025 and 391m to 561m in 2095.

2.8 Modelling Coastal Aquifers

Many models, ranging from relatively simple analytical solutions to complex numerical models, are potentially available to study the impacts of climate change, sea-level rise, and saltwater intrusion on groundwater systems. Complex numerical models have been developed; for example, the three-dimensional groundwater model MODFLOW described in McDonald and Harbaugeh (1988) (Kirshen, 2002). The GIS-based HYLUC (HYdrological Land Use Change) soil water model has been used to investigate the impacts of land use change, particularly those relating to forest cover, on water resources in many countries. It was used to assess the potential impact of forest expansion on groundwater recharge. The finite-difference model SHELUC (System Hydrological European Land Use Change), combined HYLUC and SHETRAN, has been used to calculate long term recharge (Calder et al., 2002). AUTRA is a product of the US Geological Survey and is widely used to simulate density-dependent groundwater flow such as seawater intrusion (Narayan et al., 2007). Some models comprise various models together such as IHMS comprised DiCaSM, MODFLOW and SWI (Sea Water Intrusion) (Ragab, 2004), and MOCDENS3D (Essink, 2001) consists of two integrated codes: MOC3D and MODFLOW (Giambastiani et al., 2007). These numerical models are more complicated compared to water balance model; however, the modelling approach depends on the data availability and what kind of expected result from the model.

MODFLOW (and many of the other models described above) depend on good estimates of aquifer recharge. This thesis therefore concentrates on estimating recharge under a range of land use, climate change, sea-level rise and erosion scenarios. However all these scenarios have uncertainty in their input values e.g. projected sea-level rise between 6 and 63cm, air temperature change between 3 and 5 degrees C by the 2080's, uncertain emissions scenarios and unforeseen changes in land use.. The only way to practically deal with these multiple uncertainties is to run a Monte Carlo simulation of 1,000-5,000 instances of a recharge/groundwater model and analyse the multiple outputs in a probabilistic format. It would not be practical or effective to build and run MODFLOW-type models so many times because it is a complex model which needs many parameters and needs longer time to build and run compared with a simplified water balance model. Therefore, a simplified water balance model approach was considered for this work which could be rapidly implemented in a Monte Carlo simulator.

Water balance models have been widely used for estimating potential groundwater recharge in global; for example in the UK (Hough and Jones, 1998; Finch, 1998), Greece (Voudouris, 2006), and China (Kendy et al., 2003). These models combine an evapotranspiration model with a soil moisture deficit model. This approach has the advantage that it can be used to provide time series estimates of potential groundwater recharge from readily available meteorological data; moreover, it is strongly linked to climatic inputs such as rain and evapotranspiration which are expected to change in the future. Hence, the water balance method is selected to use in this study for investigating impacts of climate change on coastal groundwater.

2.9 Summary

Groundwater in coastal aquifers will be investigated in this thesis to explore the impact of climate change and sea-level rise. Most of the parameters in the water balance models are either directly or indirectly influenced by climate change due to global warming; for example, evapotranspiration increases as mean temperature increases; wetter winters and drier summers affects on amount of runoff which impacts on groundwater recharge; consequently, this may reduce groundwater table leading to seawater intrusion. Additionally, thermal expansion and melting of land ice contributed rising in sea level which exerts coastal erosion and jeopardises groundwater table depending on the geometry of the aquifer and the aquifer recharge rate.

Climate change will lead to changes in groundwater recharge which needs to be estimated. The above discussion has shown that, due to the large range of input parameters and uncertainties in the likely values due to climatic change and sea level rise, a stochastic approach to modelling future groundwater levels is a more appropriate approach rather than a traditional groundwater modelling approach.

CHAPTER 3

Overview of Methodology

This chapter presents the methodology and examines sub models developed to construct a quasi 1-D ground water balance model for an unconfined coastal aquifer. The model will be utilised to investigate sea-level rise and climate change impacts on coastal groundwater. The model is considered appropriate for locations where a rise in sea level and climate change will occur. The target sites chosen for the model construction are from different countries. The first site is in North West England at Ainsdale Sand Dunes National Nature Reserve (25km north of Liverpool). In Thailand where large relative sea-level rise is occurring, Samut Prakan (small province near Bangkok) and some parts of southern Bangkok are studied. These study sites were selected because they had long terms records (>20years) of groundwater data.

3.1 Case study areas

To calibrate a water balance model, long term observed water table level data are needed (30+ years). Data availability limited the choice of study sites. Two sites were chosen to be the case studies for this research. The reasons for site selection mainly depend on data availability and model simplicity. Firstly, Ainsdale National Nature Reserve (UK) was chosen because the aquifer system is simple and has uniform properties (ie a relatively homogenous, isotropic, and unconfined aquifer). Furthermore, water table level data has been collected since 1972 and three different zones of land use exist in the area. This will enable the investigation of scenarios of climate change and land use change on groundwater. The case study area in Thailand comprises more than half of Samut Prakan near southern Bangkok and it was selected to test that the modelling approach developed in for the UK system is sufficiently generalized to work in other systems/ climate/ countries. This region is affected by significant relative sea-level rise caused by over pumping of deeper aquifers in Bangkok.

3.1.1 Ainsdale Sand Dune National Nature Reserve (NNR)

The coastal sand dune system at the Ainsdale Sand Dunes is the site of a National Nature Reserve (NNR) (25km north of Liverpool, UK). A 30+ year set of observed water table level data are available.

Figure 3.1: Location map of Ainsdale Sand Dunes National Nature Reserve (Source: Google Earth)

The Ainsdale NNR has a total area of 492 ha and it is situated in the district of Sefton in the County of Merseyside, North West England. These dunes are located between Ainsdale village and Fresh field, along the Southport coastal road (Figure 3.2). The site is owned by English Nature.

Figure 3.2: Coastline at Formby-Ainsdale near Liverpool

(Source: *http://www.silver-images.co.uk/pages/panos2.htm* and Google Earth)

Ainsdale NNR was established on 10th August 1965 as an area closed to the public in an attempt to protect the environment in at least part of the sand dune system. It was the 112th National Nature Reserve to be declared by the forerunner of English Nature, the Nature Conservancy Council. The seaward margin and northern part of the Nature Reserve were not planted with trees. The coastal fore dunes have a cover of Marram grass (Figure 3.3). However, a high proportion of the area is covered by pine forest which has been planted since the 1920's (Atkins, 2004). The sand dunes aim to be a conservation area which provides a habitat for the rare natterjack toad and sand lizard which are found only in a few parts of the British Isles.

Ainsdale Sand Dunes NNR comprises foreshore, open dunes and fore dunes, neutral grassland, frontal pinewood, scrubs and rear woodland. The average height of the NNR is nearly 15 metres O.D.; however, these dunes fringe a low lying area of poorly drained land in south Lancashire and rise to about 25 metres O.D. The dunes form a coastal belt approximately 25 km wide, even though blown sand extends several kilometers further inland. Therefore, soil development on the sand dunes is poor. (Clarke, 1980) Sea-level rise at Ainsdale is expected by UKCIP (2005) to be about +3 to +63 cm under Low and High Emission Scenarios respectively.

Figure 3.3: The high fore dunes at Ainsdale Sand Dunes NNR

The Reserve area is partially covered by pine forest. The trees were planted in blocks from 1906 onwards in the higher dry slack floors and on dune ridges. However, the trees were not planted in the seaward margin and northern part of the Nature Reserve. The coastal fore dunes have covered by Marram grass. In the southern part of the NNR, coastal erosion is currently undercutting the fore dunes (Clarke, 1980). The coastline between Sefton's Lifeboat Road car park and the National Trust Victoria Road car park is expected to erode by about 150m by the year 2050 (Atkins, 2004). Pinewood support a healthy population of red squirrels *Sciurus vulgaris* and together with associated scrub, are also a habitat of birds, plants, and fungi (Atkins, 2004).

Pine plantation at Ainsdale has caused changes in the natural dynamics of the sand dunes. It results in the loss of dune habitat and associated species, and limits the ability of the coastal system to respond to environmental change. Once a woodland canopy is formed, the pine trees shade out the light from the surface; therefore, other plants are unable to grow. As a result of these changes, a project to recreate the natural dune landscape destroyed by the pine plantations was set up. An application for frontal woodland removal was submitted in 1990 (Atkins, 2004).

Pine clearance on the NNR was carried out in 4 phases. Phase 1 of the project, which involved the removal of 4.5 ha of pines and associated scrub, completed in 1992 and the second phase completed in 1997 involved felling 16 ha (Figure 3.4). In addition, a further two phases were planned to continue as a rolling programme of 9.3 ha and 8 ha for phase 3 and 4 respectively. The pine plantation removal programme aimed to restore wetland habitats associated with dune slack surroundings. Woodland clearance has led to an increase in the number of natterjack toads on site and created new sand lizard habitat (Atkins, 2004).

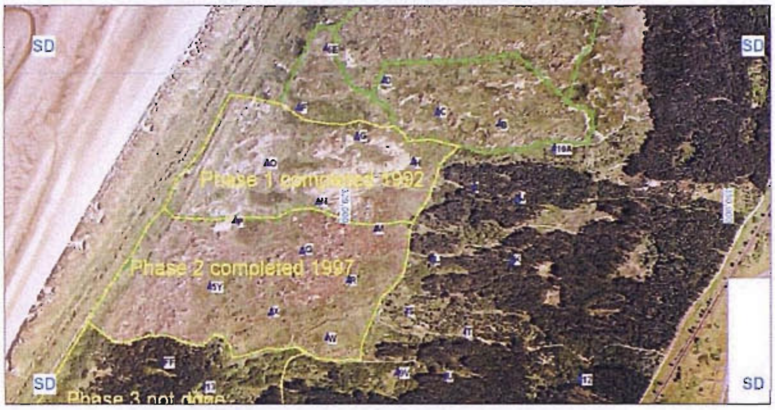


Figure 3.4: Map of area of pine clearance project phase 1 and phase 2 (Atkins, 2004)

These changes will be valuable in calibrating and testing the response of the groundwater system to changes in land use. To explore the impacts of changes in land use on water table levels, Ainsdale NNR model will be divided into 3 zones consisting of open sand dunes with no trees, the area of pine trees, and an intermediate area where pine trees were cut down in 1992 and 1997.

3.1.2 Samut Prakan, Thailand

Samut Prakan is one of the central provinces of Thailand. It is located at the mouth of the Chao Phraya River to the Gulf of Thailand (see Figure 3.5). The borders to the north and west join the Metropolitan of Bangkok (25 kilometres from Bangkok). To the south is the sea and the east is Chachoengsao Province. It occupies an area of 1,004 km^2. The province has a coastline of approximately 47.2 kilometres. The part of the province located on the western side of the river consist mostly of rice and prawn fields as well as mangrove forests, while the east part is the urban center - including industrial factories.

To investigate the impacts of sea-level rise on coastal groundwater, Samut Prakan was chosen to be a representative of an area where relative sea-level rise has already occurred. Data availability is very important to the study area selection because the limiting factor of selecting a site is groundwater level data. Although this site does not comply with all criteria of aquifer properties because it is not a uniform, homogeneous, and isotropic aquifer, it is used as a site study due to water table level data availability.

Figure 3.5: Location map of Samut Prakan, Thailand (Source: Google Earth)

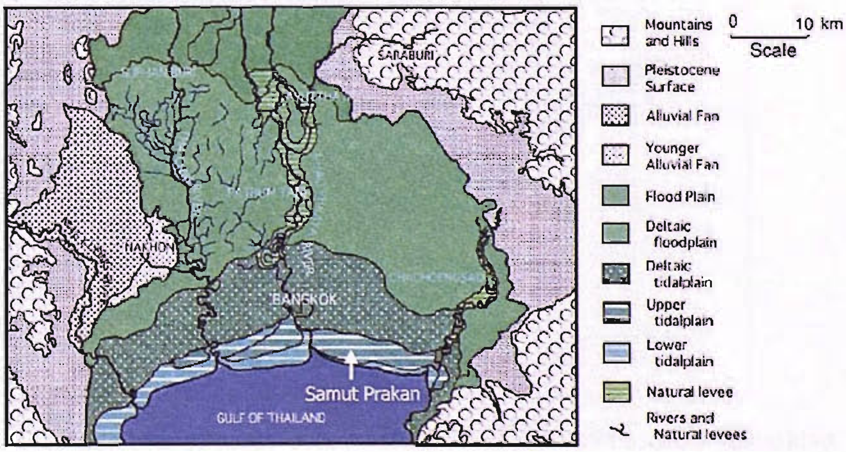


Figure 3.6: Landform classification map of the Chao Phraya Delta (Umitsu, 2000)

Landforms of the Chao Phraya Delta are classified into three regions (see Figure 3.6): the deltaic floodplain in the north, the tidal plain in the southernmost regions of the plain, and the deltaic tidal plain in the central and south where Samut Prakan is located. Elevation of the tidal plain is around 1-2 m a.s.l., and its surface is very flat and low (Umitsu, 2000). The sediments of this area consist of very soft silt or clay. In addition, this elevation is almost the same as the high tide level of the Gulf of Thailand.

Relative sea-level rise is a significant problem in this area, as it is a low and deltaic region. The rise in relative sea level after 1960 (Figure 3.7 and Figure 3.8) is a result of lands subsidence significant over pumping of aquifers in Bangkok. As a result of relative sea-level rise, many processes already on-going will be accelerated, and this area previously unthreatened will then become vulnerable to impacts such as increased risk of inundation, seawater intrusion, erosion and recession, etc. If sea-level rise continues in the future, severe coastal erosion will then be the most serious problem. Although sea-level rise is less than 1m, horizontal retreat of the coastline will be a considerable distance from the present coast. Soft silt and clay deposits of this area also rapidly accelerate erosion. Long-term yearly mean sea level data in Samut Prakan, Thailand are collected at Fort Phrachula Chomklao station by the Permanent Service for Mean Sea Level (PSMSL), hosted by the Proudman Oceanographic Laboratory [POL].

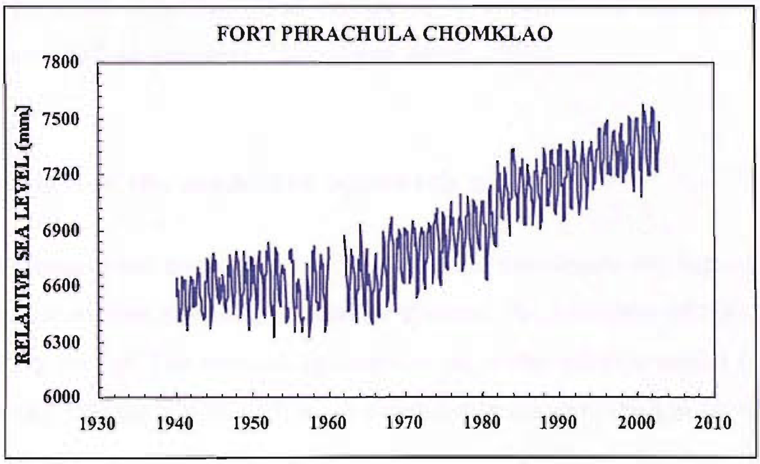


Figure 3.7: Variations of monthly relative sea level at Fort Phrachula Chomklao station near Samut Prakan, Thailand (Modified after: pol.ac.uk)

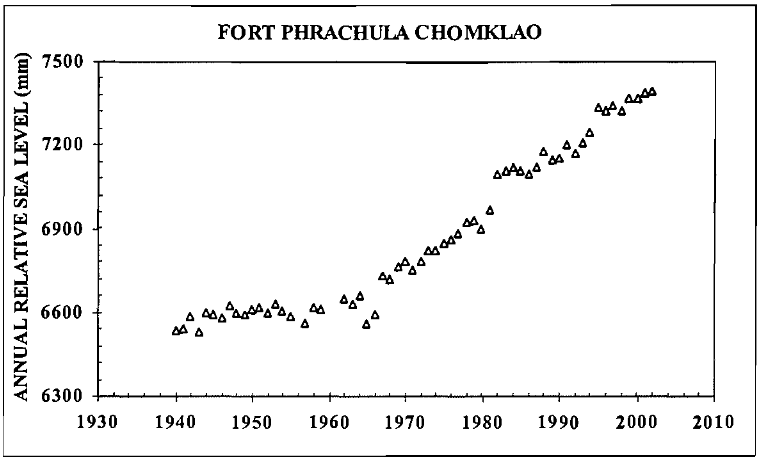


Figure 3.8: Variations of annual mean relative sea level at Fort Phrachula Chomklao station in Samut Prakan, Thailand (Modified after: pol.ac.uk)

A range of scenarios will be investigated to explore climate change and sea- level rise impacts on the groundwater system in coastal aquifers in Thailand. Data sets of groundwater level in Thailand have been collected by the Department of Groundwater Resources in Bangkok. However, the water table data are collected in many field sites and different types of boreholes. There are some short period data sets and also some long-term groundwater data.

The differences in sea-level rise between the case study in the UK and Thailand is that the rapid rise of mean sea levels in Thailand were caused by the large extraction of groundwater which also causes land subsidence. The variation of annual mean relative sea level is 16.4±0.85 mm/year (Yanagi and Akaki, 1994).

3.2 Overview of the modelling approach used

A coastal groundwater model will be constructed to investigate the impact of climate change on unconfined coastal groundwater systems. An overview of the approach is shown in Figure 3.9. The main components of the water balance model construction and the water balance model with main components are described in section 3.3 and 3.4.

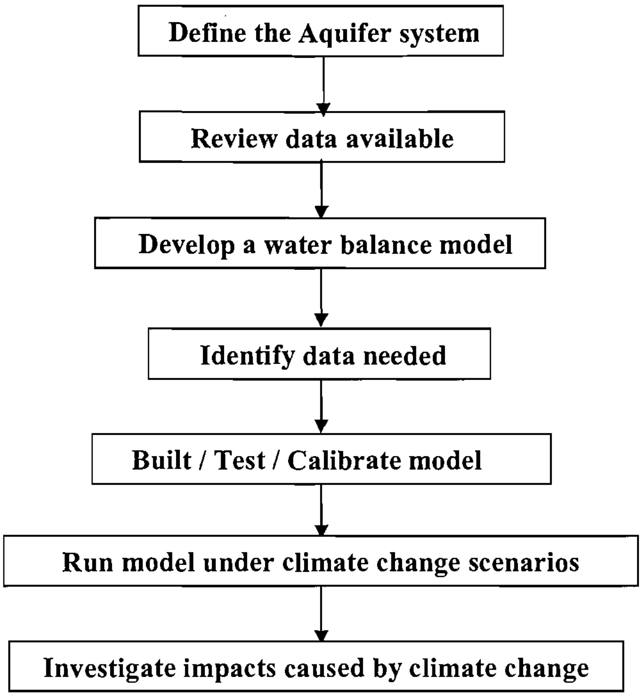


Figure 3.9: Flow chart of summarized modelling approach for a case study site

3.3 The water balance model construction

According to the main flow chart of the modelling approach used in Figure 3.9, the main components of the groundwater model construction are described below.

3.3.1 Define an aquifer system

The beginning of the model is defining an aquifer system which makes the model construction easier. Criteria for selecting an aquifer property in this model consists of:-

- Unconfined aquifer – Where groundwater is in direct contact with the atmosphere through the open pore spaces of the overlying soil or rock, then the aquifer is said to be unconfined. The upper groundwater surface in an unconfined aquifer is called the water table. Conversely, confined aquifers are permeable rock units that are usually deeper under the ground than unconfined aquifers. They are overlain by relatively impermeable rock or clay that limits groundwater movement into, or out of, the confined aquifer. Groundwater in a confined aquifer is under pressure and will rise up inside a borehole drilled into the aquifer. Unconfined aquifers are usually recharged by rain or stream water infiltrating directly through the overlying soil. Typical examples of unconfined aquifers include many areas of coastal sands and alluvial deposits in river valleys. Therefore, water balance components are calculated more easily if an aquifer is unconfined.

- Uniform aquifer properties– The uniformity of an aquifer is very useful when considering the movement of groundwater; however, aquifers are not always uniform either horizontally or vertically. Assuming a uniform aquifer is necessary to simplify the model construction.
- Homogeneous and isotropic medium – it is an aquifer property which affect directly to groundwater flow. Homogenous means aquifer properties are uniform in space and isotropic means aquifer properties are the same in all directions. Using an aquifer of this type will simplify the modelling scenarios.
- Data availability also controls the choice of aquifer; to be able to develop and calibrate the model.

3.3.2 Develop a water balance model

With the purpose of understanding impacts of climate change on groundwater system in coastal aquifers, it was decided to develop a water balance model to determine which hydrological variables were most likely to be affected by changing climate. Simple water balance models are often used to estimate direct groundwater recharge and they may be written to understand easily by using input and output terms (equation 3.1). This is based on a comparison of the amounts of water entering and leaving the system.

$$\text{INPUTS} - \text{OUTPUTS} = \text{STORAGE CHANGE} \qquad (3.1)$$

The term "inputs" include rainfall and groundwater flow into the coastal aquifer, whereas "outputs" include actual evapotranspiration, groundwater flow out of the system, and surface drainage. "Storage change" represents soil moisture in soils (0-0.8m), water table level, and also water levels in flooded area (linked to water table level).

Having determined that the water balance model is a simple conservation of mass equation, water which goes into a system is distributed via the physical environment into an output form, therefore leaving the system, or into a store, and increasing the water contained within the system. It is necessary to define the boundaries of the system when quantifying these parameters in order to ascertain the accurate amount of water entering and leaving it. Therefore the exact area of the basin is important when water balance parameters are calculated.

Importantly, Clarke (1980) established that "the Nature Reserve at Ainsdale is a system almost completely separated from adjacent groundwater systems. This means that the Reserve can be studied in isolation as a separate entity, and a water balance for the area can be constructed." Moreover, Clarke (1980) concluded that the main difference between a drainage basin and the Ainsdale NNR is the form of its boundaries, thus the bulk of outflow does not occur at one particular point as in a conventional drainage basin but as a gross translation of water through the sand dune medium. As a result, it is not possible to directly measure the outflow from the Reserve as is normally accomplished in conservative drainage basin systems. It will then be necessary to determine the rate of outflow from the Reserve by using indirect methods.

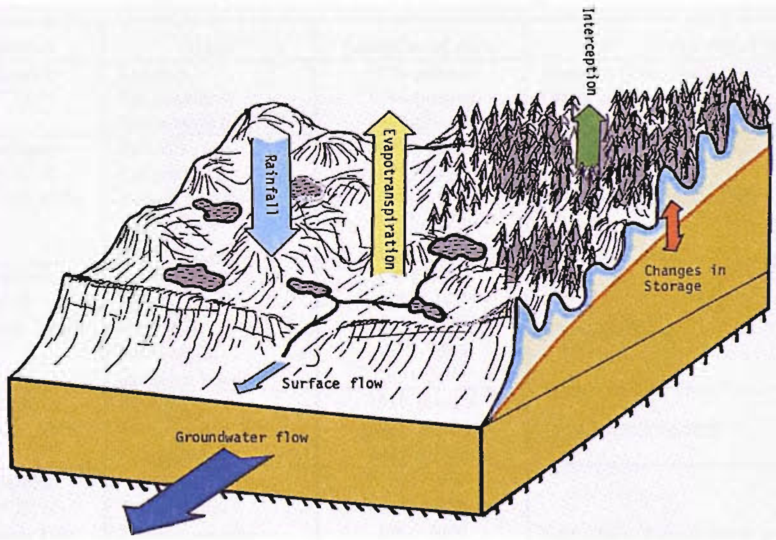


Figure 3.10: Schematic view of the water balance parameters for Ainsdale (Source: Clarke, 1980)

To apply a water balance to the Ainsdale Nature Reserve, it will be necessary to consider the assumptions made and their validity to the sand dune system. The shape of the Reserve's water table is initially assumed as being uniform in cross-section. Figure 3.10 shows a schematic representation of the Ainsdale NNR groundwater system, and the major water balance parameters acting upon it.

3.3.3 Data needed for the water balance model

To enable the calculation of the water balance and the testing of the model against groundwater observations requires data. It has proven difficult to obtain a consistent long term climate data set. At Ainsdale NNR, some climatic data are collected, but some months lack data; therefore, climatic data from other weather stations located around Ainsdale were adjusted to create a consistent data set.

Data are available from 5 sources as shown in Table 3.1. In March 2004, the student visited the Ainsdale NNR to understand the case study area and collect groundwater data. The NNR supplied data from Ainsdale consisting of climatic data (rainfall and temperature) and groundwater level data. Types and lengths of data availability in each station are also presented in Table 3.1

Table 3.1: Types and lengths of data availability for Ainsdale and sources of data

Station	Data	Lengths of data	Sources of data
Ainsdale 53°35' N	Rainfall Temperature Water table levels	1970-present 1980-present 1972-present	Ainsdale Sand Dunes NNR Direct contact
Blackpool 53°46' N 20 miles North	Rainfall Temperature Vapour pressure Wind speed Sunshine hours	1951-1979 1951-1979 1951-1979 1951-1979 1951-1979	PhD Thesis (Clarke, 1980)
Bidston 53°24' N 15 miles South	Rainfall Temperature Humidity Wind speed Sunshine hours	1951-2003 1951-2003 1975-2003 1951-2003 1951-2003	*www.pol.ac.uk*
Valley 35 miles West	Rainfall Temperature Sunshine hours	1930-present 1930-present 1930-present	*www.metoffice.co.uk*
Ringway* 53°35' N 25 miles East	Rainfall Temperature Vapour pressure Wind speed Sunshine hours	1961-1990 1961-1990 1961-1990 1961-1990 1961-1990	*www.cru.uea.ac.uk/cru/projects/betwixt/*
* predicted climatic data for 2020s, 2050s, 2080s are also available			

The water balance equation used shows that necessary data are separated into four groups consisting of:-

Measured water table level data: the water balance model will be tested against observed water table level data. Observed water table level data are also be used to investigate the causes and effects of the climate change and land use change on groundwater. Water table level data are available directly from the Ainsdale Nature Reserve Office staff.

Figure 3.11: Map of the observed groundwater wells location at Ainsdale NNR

A network of eleven 6.3cm by 2 metres long perforated plastic tubes were inserted into selected slack floors in 1972 to monitor the water table changes in Ainsdale NNR (excluding one observation well which is located at pond) . Then, three more tubes were added since 1991. Figure 3.12 shows the average groundwater level data at 4 observation wells including Wells 7, 9, 10 and 11 collected every month since 1972. These wells were arranged to form a rectangular network with an average spacing of about ½ km, although extra wells (Wells 1, 2 and 3) were sited in Massam's Slack near the coast. The observed water table levels for all wells are shown in Figure 3.13. Among these 15 wells, there are only seven observation wells have been monitored each month from 1972 to present, because 8 additional borehole data sets collected approximately from 1972 to 1987.

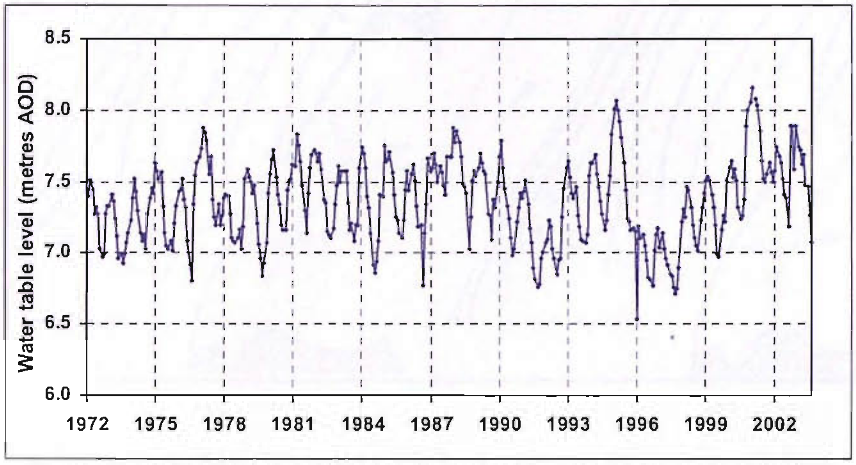


Figure 3.12: Water table variations at Ainsdale NNR 1972-2001
(Based on the average of 4 boreholes including Wells 7, 9, 10 and 11
in the dune slacks spread across the NNR)
Source: the Ainsdale NNR

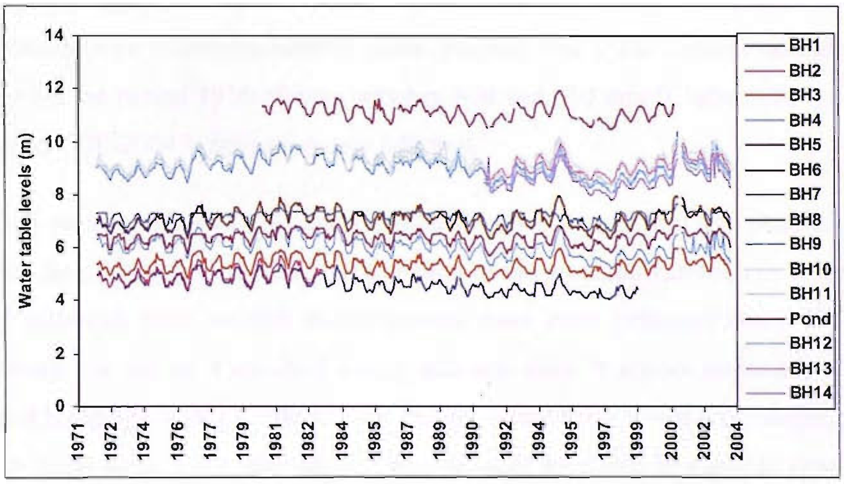
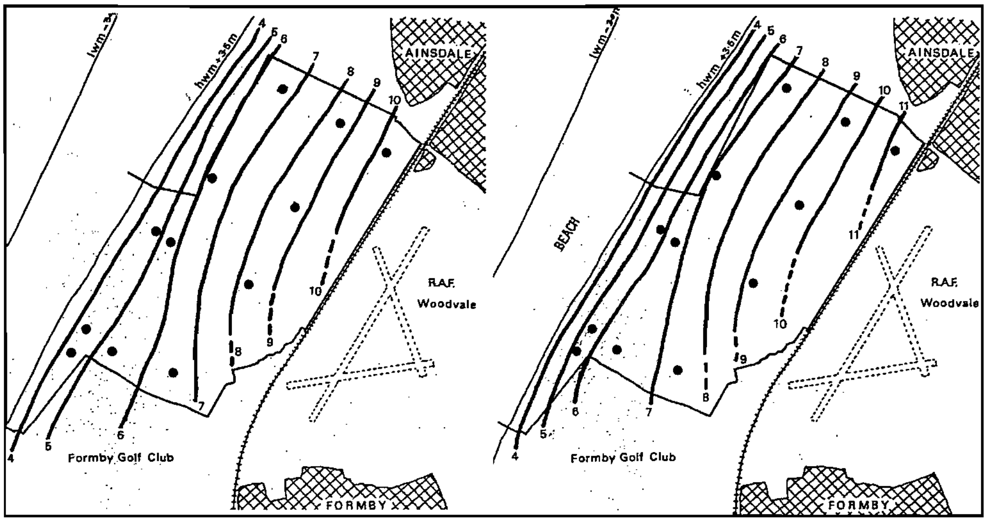


Figure 3.13: Water table levels from 1972 to 2004

Water table contour maps illustrated in Figure 3.14 demonstrate an inland curvature of the water table contours in the southern part of the reserve. Clarke (1980) concluded that possible explanation for this are the coastal erosion effects, the ditch network, and the increased evapotranspiration from the pine forest which is the greatest effect.



(a) (b)

Figure 3.14: Water table contour maps (a) Dry condition: August 1976 (b) Wet condition: February 1975 (Source: Clarke, 1980)

Rainfall: rainfall is the easiest of the water balance parameters to measure. The previous section (3.3.2) demonstrated that there is no groundwater flow into the NNR and also no significant surface flow. Therefore, all incoming water must enter as precipitation (which includes rainfall, snow, hail and sleet). The average rainfall at the Reserve for the period 1916-50 was between 800 and 850 mm (Clarke, 1980) and for the period 1970-2004 is approximately 840 mm.

Although annual rainfall totals can be used to describe wet and dry periods in the Reserve, they do not provide a good indication of the seasonal variation in water table levels. Although daily rainfall measurements have been collected since 1968, the gauge used was not of a standard design and was sited in a poor exposure, close to trees and buildings (Clarke, 1980). Furthermore, water table levels were recorded as a monthly basis since 1972 and climatic data are also available in monthly time steps. Therefore, the water balance model requires long term monthly rainfall data. A graph of monthly rainfall totals at the NNR is shown in figure 3.15.

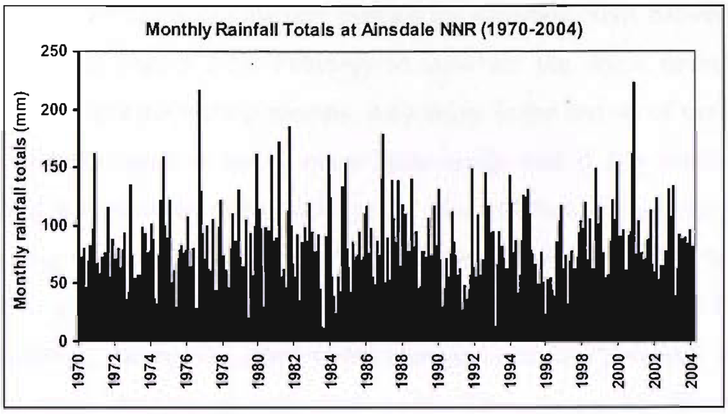


Figure 3.15: Monthly rainfall totals at Ainsdale NNR in 1970-2004

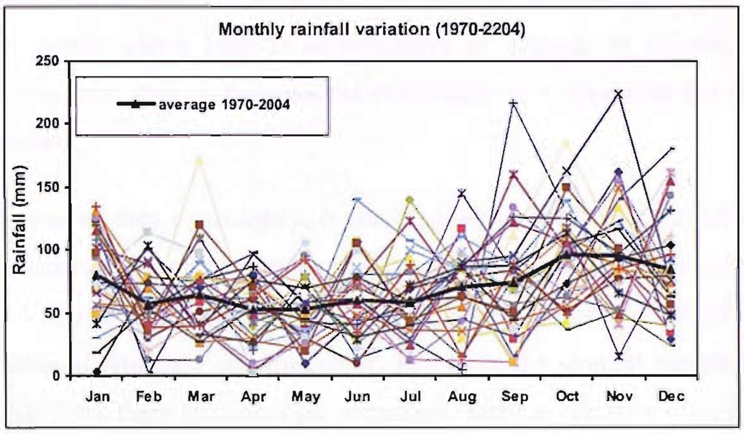


Figure 3.16: Monthly rainfall variations at Ainsdale NNR in 1970-2004

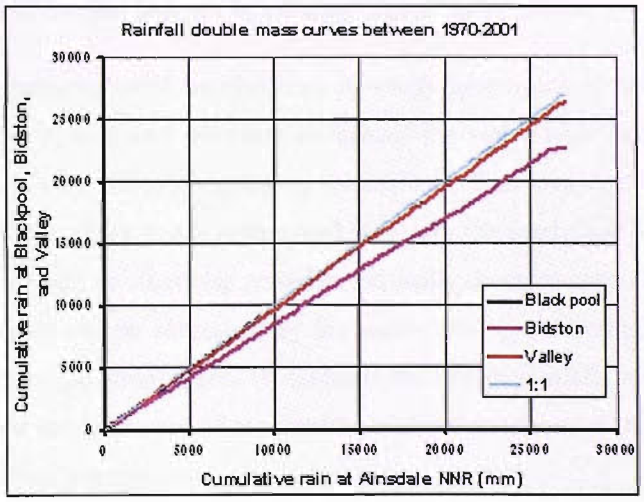


Figure 3.17: Rainfall double mass curves of Ainsdale, Blackpool, Bidston and Valley

Monthly rainfall variations and average rainfall for Ainsdale NNR between 1970 and 2004 are shown in Figure 3.16. February to June are the driest months, whereas August to January are the wettest months. Any delay in the arrival of the autumn and winter rainfall will result in lower water table levels and if this trend were to be continued over a number of consecutive years, this will result in a drop in the water table depending on amount of rainfall during winter. Therefore, it can be concluded that rainfall is a main factor in controlling the changes in water table levels at the Reserve. However, the rainfall alone is not enough to explain precisely the seasonal groundwater level changes in individual years. The amount of effective rainfall entering the groundwater store in the sand dunes is affected by the interaction of rainfall, interception, and evapotranspiration. Hence, to understand the changes in water table levels which lead to investigation of impacts of climate change on groundwater system, data on the seasonal distribution of evaporation and transpiration will be required.

To test for rainfall data consistency, it was decided to check the rainfall at Ainsdale against the others by using the double mass curve technique as shown in Figure 3.17. Blackpool, Valley and Ainsdale rainfalls were similar but Valley rainfalls were a little less than those at Ainsdale and Blackpool. However, the straight double mass curve indicates that these three records were consistent. Bidston rainfalls were considerably less than Ainsdale rainfalls by approximately 17%. There was break in the slope at almost the end of the line because of missing rainfall data in 2001.

Climate parameters: It will be necessary to verify how much of the rainfall enters the groundwater system and therefore influences the water table levels in the sand dunes. Rainfall may be intercepted by plants and then evaporated back to the atmosphere. Water which is not intercepted goes into the sand dune and will then be either held in the soil or otherwise percolate vertically down to enter the groundwater store. Some water will be consumed by the plants root and the remainder transpires from the leaves to the atmosphere. To calculate the loss of rainfall, soil moisture, and groundwater via the processes of evaporation and transpiration, "evapotranspiration" or ET, climate data are required.

The rate of evapotranspiration depends in part on the surface of the ground, the vegetation type, the prevailing meteorological conditions, and the availability of water for transpiration for the plant. Pine forest covers approximately 40% of the Reserve, dune and scrub about 45% and the remaining 15% comprise slack floors (Clarke, 1980). Water loss by interception is related to the height and leaf cover of the plant and the frequency of rainfall (Ward, 1975). Interception losses may be as high as 50% of the incoming rainfall in pine forest (Leyton et. al., 1967). Therefore, to calculate the ET rate it will be necessary to evaluate ET in each vegetation zone individually.

Potential evapotranspiration (PET), defined by Penman (1948), is "evaporation from an extended surface of short green crop actively growing, completely shading the ground, of uniform height and not short of water". This definition was made in order to simplify the evapotranspiration calculation by reducing as many as possible of plant and soil variables. A simplified form of PET is the Reference crop evapotranspiration (ET_o), which is an estimate of potential evapotranspiration for a short green crop such as grass which is not short of water.

Potential evapotranspiration rate can be estimated several methods. Firstly, an evaporation tank is the simplest method to measure the data but this method is not available in the Reserve. Another choice is using empirical formulae which use climatic data. The Food and Agriculture Organization of the United Nations (FAO) compared many equations with observed field data and recommended the Penman-Montieth equation. The original form of the Penman-Montieth equation is described in previous section (Allen et al, 1998).

The calculation of reference evapotranspiration by means of the FAO Penman-Montieth method requires various climatological and physical parameters. Some of the data are measured directly in weather stations. Other parameters can be derived with the help of a direct empirical relationship from other climate observation. Climatic data sets, which consists of humidity, wind speed, sunshine hours, maximum and minimum temperature, were assembled to calculate potential evapotranspiration at Ainsdale. The different lengths of recorded data available made direct comparison difficult, thus it was decided to adopt the double mass curve technique to test for some data consistency between 1961 and 2003.

To create the climatic data sets to be representative data sets at Ainsdale Sand Dunes from 1961 to 2003, correlation and regression were used. Sunshine hour data is shown as an example of the approach. Figure 3.18 presents a sunshine comparison at Blackpool against Bidston and Valley and it also shows the correlation and regression equation which was used to generate a new extended sunshine hour data set for Ainsdale. Sunshine hour data in Bidston fit to Blackpool better than Valley. Therefore, a new sunshine hour data set for Ainsdale was created by using sunshine hour data from Blackpool between 1961 and 1979 combined with those data of Bidston generated by regression equations from 1979-2003. Then the new sunshine data was assumed as Ainsdale sunshine data. The chart of the new sunshine hour data from 1961 to 2003 is shown in Figure 3.19.

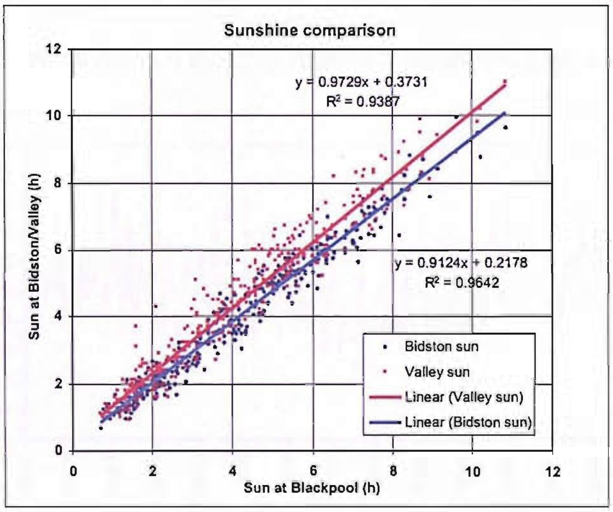


Figure 3.18: Sunshine comparisons at Blackpool against Bidston and Valley.

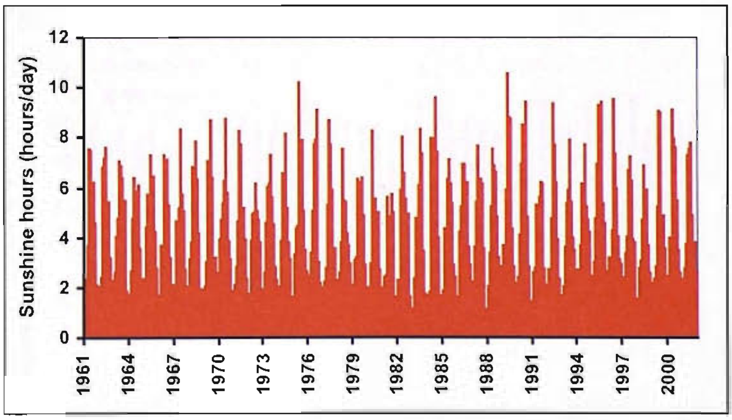


Figure 3.19: Generated monthly sunshine hours data set for Ainsdale

Other climatic data series were assembled including relative humidity (%), wind speed (km/d), and maximum and minimum temperature (°C) are presented in Figure 3.20, Figure 3.21, and Figure 3.22 respectively.

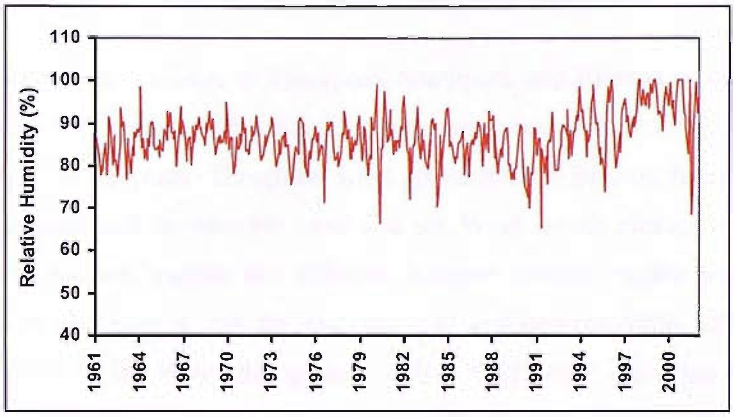


Figure 3.20: Generated monthly relative humidity (%) for Ainsdale

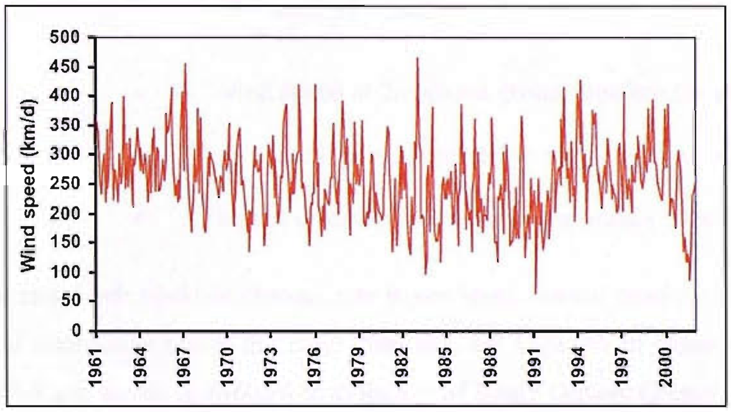


Figure 3.21: Generated monthly wind speed (km/d) for Ainsdale

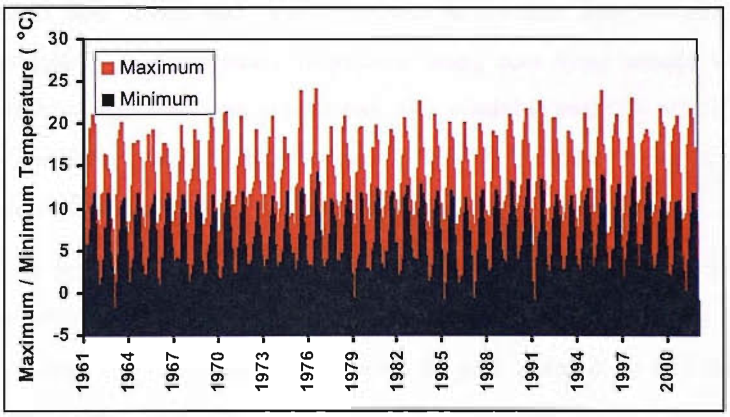


Figure 3.22: Generated monthly maximum and minimum temperature for Ainsdale

Similar to the sunshine hour data, the humidity data required the formation of a new data set by using correlation and regression. Maximum and minimum temperatures were collected at Ainsdale NNR since 1980 and data before 1980 were generated using correlation and regression equations similar to the other climatic data.

Wind speed data are available in Blackpool, Southport, and Bidston weather stations but Blackpool and Southport data have many missing data and are available only for approximately 10-15 years. Therefore, wind speed data at Bidston from 1951-2003 were used to generated an Ainsdale wind data set. Wind speeds measured at different heights above the soil surface are different, because surface friction tends to slow down wind passing over it. For the calculation of evapotranspiration, adjusted wind speed measured at 2m above the ground surface is required (equation 3.2) (FAO, 1990).

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \qquad (3.2)$$

Where	u_2	=	wind speed at 2m above ground surface (m/s)
	u_z	=	measured wind speed at z m above ground surface (m/s)
	z	=	height of measurement above ground surface (m)

Other data required: land use change, rise in sea level, coastal erosion, soil property and physical characteristics of the dune sand etc. are required to support the water balance model and its use in evaluating to impact of future climate change.

Initially, the water balance model was constructed and calibrated based on monthly observed water table levels and monthly measured climatic data, because daily data were not available. A daily water balance a using root zone model was used to calculate *SMD* and *AET* for open grass areas. The available monthly rainfall data were interpolated to daily rainfall data using CROPWAT model using a polynomial interpolation method.

To investigate impacts of land use change on groundwater system in the Ainsdale Sand Dunes NNR, 3 zones of the land use types are set as shown in Figure 3.23 consisting of zone A: sand dunes area, zone B: pine plantation, and zone C: area where trees have been cut down.

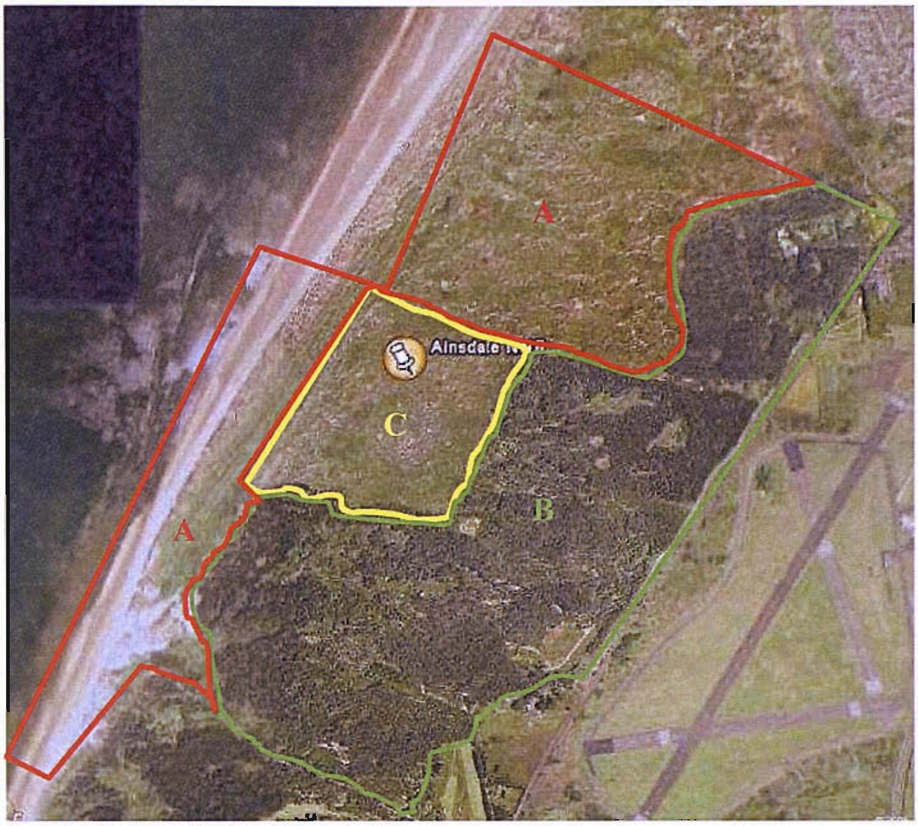


Figure 3.23: Map of 3 zones of land use change scenarios consists of zone A: sand dunes, zone B: pineforest, zone C: pine trees clearance

Relative sea level rise. The movement of the freshwater-saltwater interface causes by changes in groundwater recharge. Not only a decrease in groundwater recharge affects the interface position, but also rise in sea level will do the same. To investigate whether a rise in sea level or change in groundwater recharge is the largest influence on saline intrusion, sea-level rise data are needed. As shown in figure 3.24, the trend line of measured sea-level rise at Liverpool increases from approximately 55 mm in 1900 to 175 mm in 2000 or annual rate is about 1.2mm/year. UKCIP (2005) concluded that net sea-level change for North West England under High Emission scenario in 2080s is +63 cm and under Low Emission scenario +3 cm; whereas, regional isostatic uplift in this area is 0.6 mm/year.

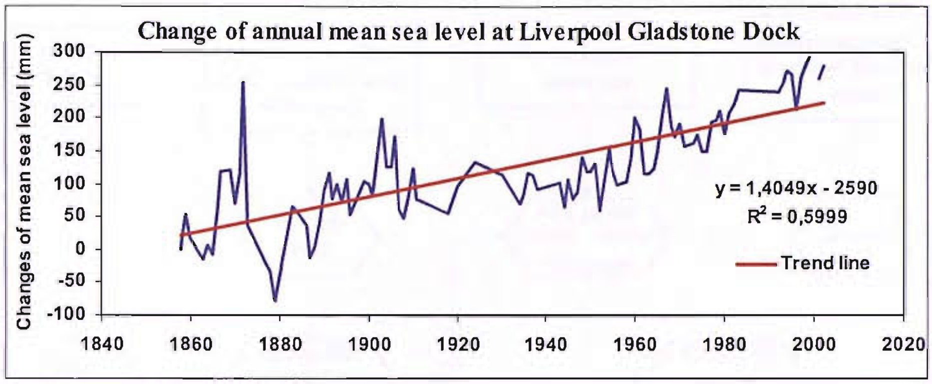


Figure 3.24: Changes of annual mean sea-level at Liverpool 1850-2000 (Source: Permanent Service for Mean Sea Level of Proudman Oceanographic Laboratory)

3.3.4 Building the model for Ainsdale

The key climatic components of the water balance were described in the previous section, so that an estimate of the amounts of water entering and leaving the sand dune system may be quantified. A flow chart of water balance model constructing procedure is shown in Figure 3.25.

Meteorological data including rainfall, temperature, sunshine hour, wind speed, and relative humidity were collected from several sites in monthly to investigate the seasonal change caused by climate change. Potential evapotranspiration was calculated using the FAO Penman-Montieth equation for surfaces with albedo of 0.05 (water), 0.15 (heath), and 0.25 (grass) (FAO, 1990). The climatic variables input into the Penman-Montieth equation have to be the mean values for each period. The PET calculation needs crop type information such as grass, pine forest and sand dunes.

Monthly effective rainfall and PET were interpolated into a daily format using CROPWAT model to run the daily soil moisture deficit model. Then, the soil moisture depletion and actual crop evapotranspiration were calculated. When runoff is not significant, the amount of water leaving the dune system depends on evapotranspiration and groundwater flow. AET was calculated using equation 3.3 and 3.4. Recharge and groundwater flow were estimated in the next step.

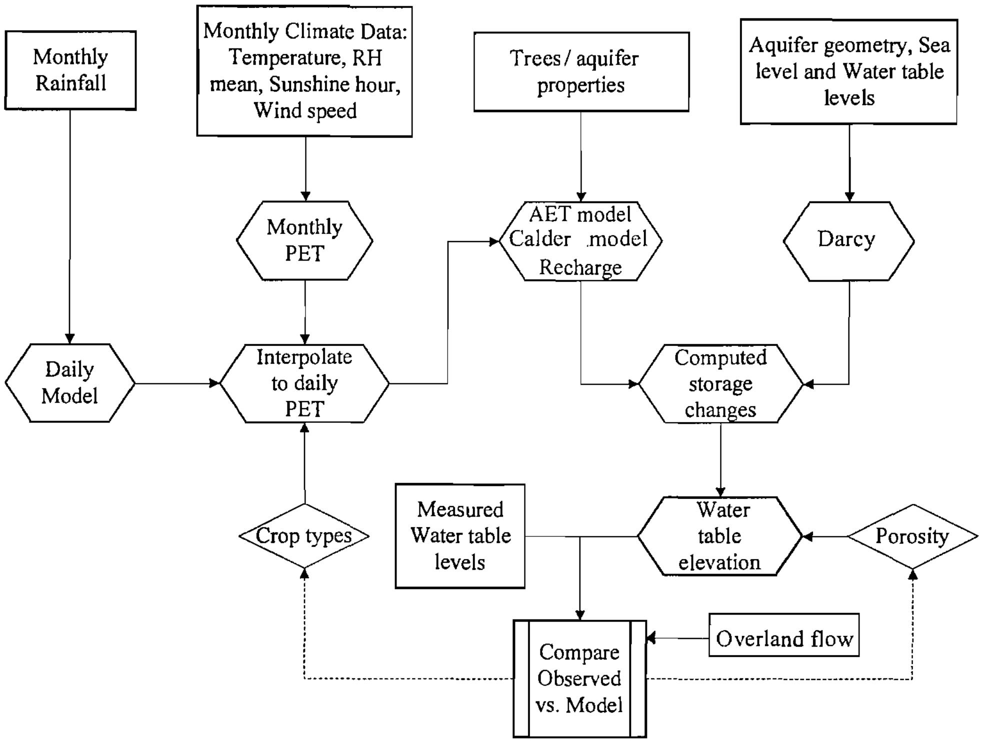


Figure 3.25: Flow chart of water balance model construction

Outflow of water from the Reserve occurs mainly by groundwater flow across a seepage face because the volume of water moved by channel flow was negligible in terms of the annual water balance. To calculate the rate of flow of water through the system, it was necessary to obtain information on the physical characteristics of the aquifer, the aquifer geometry, the properties of the aquifer, the slope of the water table to the sea, and the depth of the sand dunes. The property of a medium to allow water to flow through it has named hydraulic conductivity (K) or permeability described in previous section. Clarke (1980) summarized hydraulic conductivity values of the Reserve by using 3 methods including formulae, parameter, and slug tests. The result indicated that the measured values of K are in the range 10 to 15 metres/day at 10°C.

Clarke (1980) concluded that the overall head loss from the inland boundary of the NNR to mean sea level is about 10 metres. Dividing this by the distance between the peak of the water table and mean sea level gives the hydraulic gradient out of the Reserve system. The sloping base of the sand is almost parallel to that of the water table and so a constant thickness of the aquifer can be assumed in calculations. This value is approximately 12 metres, even though it will be less in dry periods and greater in wet periods when the water table is high. The rate of groundwater flow was calculated by using Darcy's Law. The groundwater flow calculation based on hydraulic conductivity, water table level and hydraulic gradient of the Reserve.

Monthly rainfall, *AET*, and the rate of groundwater flow were calculated. The change in water storage was calculated. The storage change was converted to water table elevation (m AOD) by using the previous month level change in storage and porosity functions (previous month water level + storage change * effective porosity). Clarke (1980) concluded that the regional effective porosity of the dune sand is nearer to 30% than 40%, although it increases when the water table is above the ground level. Not only porosity varies by the depth above or below ground level, but also overland flow.

Clarke (1980) summarised that when the slacks and adjacent slacks are flooded, overland flow can be an important water removal component in the water balance model. In adjacent slacks, the only possible mechanism for the removal of surface water in the central part of the NNR is the ditch system. It was unfortunate that there was no direct method of quantifying overland flow. The amount of water the ditch carried out of the Reserve was approximated by assuming the average flow rate to be about 10-30 litres/second. Flow in the ditch began when the water table level at Well 9 rose above -80cm and stopped when it fell below -70cm. If it is further assumed that the ditch drains about ½ km^2 of the reserve, and it removed about 200 mm of water from the central part of the NNR. It is assumed that overland flow from the dunes begins before the water table is above ground level, because the drainage ditches become active when the water table is <80cm below ground level (Clarke, 1980).

To test whether the values of the water balance components are accurate, the time series of computed water table levels was compared against observed water table levels at Ainsdale. Model calibration and testing will be described in more detail in the following chapter

3.3.5 Running the model under climate change scenario

The scenario which was chosen to investigate climate change as NNR is the "**Medium-high**" scenario. Beck (2001) stated that this is the scenario which is most often quoted. This scenario assumes a future increase of 1 per cent annum in greenhouse gas concentrations. In the same way, summary report of UKCIP98 concluded that "where only a single scenario is used, say the "**Medium-high**" scenario, should be exercised when interpreting the results of the assessment".

The raw data for use in climate impacts studies were accessed via the UKCIP website at *www. ukcip.org.uk/scenarios/*. Completion of a license form was needed to access the UKCIP data. Most of data available via the website are an observed climate data set at 50 km resolution for the UK. Although there are some variables at 5 km resolution, only daily mean temperature and total precipitation rate are available. To calculate the water balance model for the future time periods 2020s, 2050s, and 2080s, climatic variables at 50km resolution were accessed from the UKCIP data as shown in table 3.2.

Table 3.2: Climate variables contained in the UKCIP02 used in the research

Variable	**Code**	**Model-Simulated 1961-1990 Climate (50 km)**	**Climate-Change Scenarios(50 km) 2020s, 2050s, 2080s**
Maximum temperature	TMAX	°C	Δ°C
Minimum temperature	TMIN	°C	Δ°C
Total precipitation rate	PREC	mm/day	%
10 m wind speed	WIND	m/s	%
Relative humidity	RHUM	%	%
Total cloud in longwave radiation	TCLW	%	%

Figure 3.26 illustrates 50 km grid square resolution for the UK map. Ainsdale Sand Dunes NNR locates in the UKCIP grid square 294. The obtained UKCIP climate data file contains monthly and seasonal average climatic variables with respect to simulated 1961~90 average, simulated by HadRM3 with SRES (Medium-High) emissions scenario.

The predicted climate change data in grid square 294 for the future time periods 2020s, 2050s and 2080s including rainfall and other climatic variables as shown in Table 3.2 were applied into the water balance model. After predicted climate change data were applied as Ainsdale data, the water balance model will be repeated to explore change in groundwater recharge caused by changing in climate.

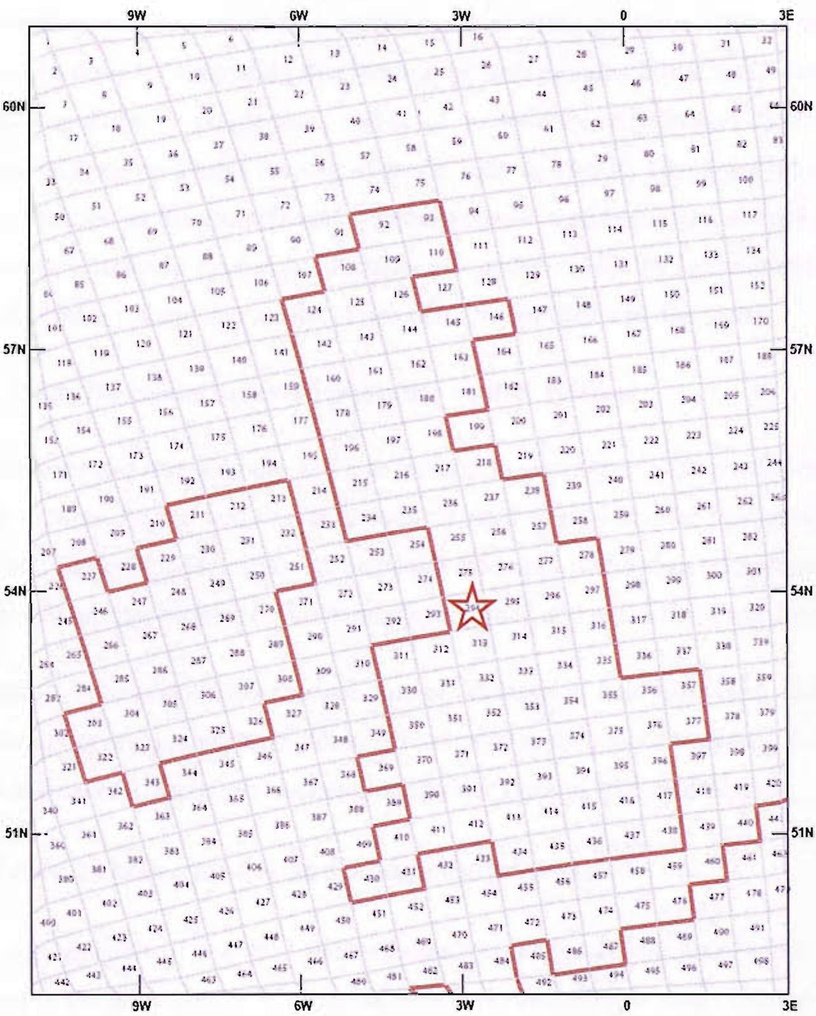


Figure 3.26: The 50 km grid square resolution map for the UK

3.3.6 Investigation by climate change impacts on groundwater

The likely impact of climate change on groundwater will be evaluated by using the calibrated model at Ainsdale. As there are many factors which can affect the groundwater system (many of which are affected by climate), it will be necessary to deal with uncertainties in the input data. A sensitivity analysis of the model would give some information on the effect of varying single model variables, but a better understanding will be obtained by carrying out at using a Monte Carlo simulation. This will be done by simulating the varying the uncertainties of the input parameters by sampling from a pre-defined series of probability distribution functions. A statistical analysis on a large number of model runs to identify which factors have the largest influence on the groundwater system in coastal aquifers. Then, actions that can be undertaken to avoid irrevocable damage to aquifers caused by saline intrusion as a result of climate change and sea-level rise will be identified and discussed.

3.3.7 Using the model to investigate other aquifer systems

The calibrated and tested model will also be used to investigate a range of scenarios to explore climate change and sea level impacts on a coastal aquifer in Thailand. The model will be developed, improved, and calibrated until it will then be appropriate for the different aquifer properties; for example, confined and unconfined aquifers.

The effects of sea-level rise, climate change, changes in land use types, changes in groundwater extraction patterns will be investigated and methods to reduce the impact human and natural change on coastal groundwater systems will be described.

3.4 Water balance model and main components

To identify impacts of sea-level rise and climatic change on the water table changes observed in the dune system, a water balance is needed. Simple water balance models are often used to estimate potential groundwater recharge.

The major components of water balance are shown in Figure 3.10 and the main terms may be written as equation (3.1).

$$(R - RO) - ET - I + SM - GW = \Delta S \qquad (3.1)$$

Where R = Rainfall or precipitation

RO	=	Runoff
ET	=	Actual evapotranspiration
I	=	Interception loss
SM	=	Change in stored water within the soil
GW	=	Groundwater flow in/out of the system
ΔS	=	Change in groundwater storage (water table level).

In agricultural science, SM is normally expressed as the soil moisture deficit (SMD) which changes dynamically in response to the inflows and outflows of water in the field (Smethurst et al., 2004; Blight, 2003).

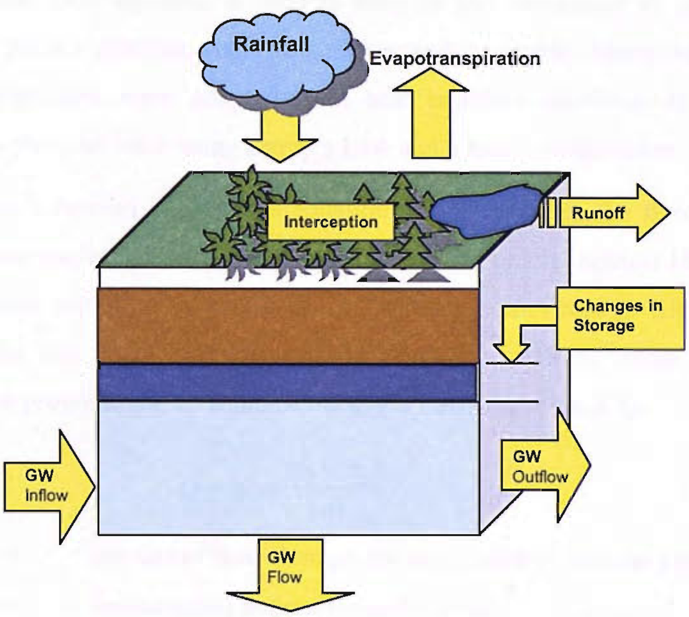


Figure 3.10: Water balance components

Water will enter the soil through the ground surface from rainfall and leave as evapotranspiration. Rainfall is easier to measure compared with evapotranspiration; furthermore, it can be very site specific and available in long records. By using the Penman-Montieth equation and the crop coefficient and soil moisture balance model, actual evapotranspiration can be estimated. Thus, if a study site is assumed to have no runoff, the soil moisture deficit can be estimated from the relation between rainfall and evapotranspiration by using a simple water balance model, as shown in equation (3.3). However, the complete water balance equation requires additional data which is more complicated to measure and takes a long period of time to collect.

$$R - ET - I + SM - GW = \Delta S \quad (3.3)$$

Where R = Rainfall or precipitation
ET = Actual evapotranspiration
I = Interception loss
ΔS = Change in groundwater storage (water table level)
GW = Groundwater flow in/out of the system
SM = Change in stored water within the soil

3.4.1 Groundwater flow

The groundwater flow equation is used to describe the movement of groundwater flow through porous medium such as aquifers and aquitards. Many solutions for groundwater problems were adapted from heat transfers solutions. It is usually derived from a physical basis using Darcy's Law and a mass conservation.

Darcy's Law is a derived constitutive equation which describes the flow of a fluid through a porous medium. The law was formulated by a French engineer Henry Darcy who investigated the flow of water in the vertical homogeneous filters for the fountains of the city of Dijon, France in 1856 (Bouwer, 1978). From his classic experiments, he proposed the now famous Darcy's Law (Equation 3.4).

$$Q = K.A.\frac{(h_1 - h_2)}{dx} \quad (3.4)$$

Where Q = the rate of flow through the sand (units of volume per time)
K = the saturated hydraulic conductivity
A = the cross-sectional area to flow
$(h_1 - h_2)$ = the hydraulic head difference between inlet and outlet across the sand
dx = length of the sand column

The Dupuit approximation is one of the most simple and worldwide tools available for estimation of groundwater flow within unconfined aquifers. It is widely quoted in textbooks as the basis of most methods employed for computing unconfined flow.

The Dupuit-Forchheimer model is predicated based on the observation that in most groundwater flow, the slope of the phreatic surface is very small approximately

1/1000 to 10/1000. The Dupuit assumptions can be summarized as: (1) the horizontal hydraulic head gradients are equal to the slope of the water table and are invariant with depth and (2) the equipotential lines are vertical and the streamlines are essentially horizontal (Al-Thani, 2002).

Analytic solutions to the unconfined-flow equations can be developed using the Dupuit assumptions. The well-known equations for the discharge and phreatic-surface for rectangular-flow systems are shown in equation (3.5) (Clement et al., 1996; after Bear, 1979).

$$Q = K\frac{(h_1^2 - h_2^2)}{2L} \tag{3.5}$$

Where	Q	=	the discharge per unit width of the aquifer
	K	=	the saturated hydraulic conductivity
	h_1	=	the hydraulic head at the position $x=1$
	h_2	=	the hydraulic head at the position $x=L$
	L	=	length of the sand column

3.4.2 Evapotranspiration

Evapotranspiration (*ET*) is the sum of evaporation from open water and transpiration from vegetation. Water is evaporated from ponds, or lake surfaces, wet soil and from rain droplets caught in the leaves of trees. Transpiration takes water out of plants by the evaporation of water through the pores in leaves. Thus, types of vegetation and land use significantly affect evapotranspiration. Water transpired through leaves comes from the roots; therefore, plants with deep reaching roots can transpire more water (Shaw, 1994).

It is difficult to measure evapotranspiration directly. Evaporation pans can be used to estimate lake evaporation, but transpiration and evaporation of intercepted rain on plants cannot be reliably estimated using this method. Both evaporation and transpiration occur simultaneously and there is no easy method to separate the two processes. Moreover, it is difficult to get a good measurement of actual evapotranspiration. In general, to avoid the problems associated with quantifying actual evapotranspiration, potential evapotranspiration (*PET*) is often used as a starting point in estimating evapotranspiration (Shaw, 1994).

Potential evapotranspiration is the evapotranspiration that occurs if the soil/plant has plenty of water to evaporate and transpire. Potential evapotranspiration is usually measured indirectly, from climatic parameters (such as temperature and sunshine), but also depends on the surface type, the soil type, and the vegetation. Furthermore, it can be estimated using approximate equation such as Thornthwaite equation, Blaney Criddle equation, Penman equation and Penman-Montieth equation.

The potential evapotranspiration rate is normally calculated for a reference surface, conventionally short grass, called the reference crop evapotranspiration (ET_o). The reference crop evapotranspiration is the evapotranspiration rate from a hypothetical reference crop with an assumed crop height of 0.12 m, an albedo of 0.23, and a fixed surface resistance of 70 s m^{-1}, actively growing, well-watered, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, and completely shading the ground (Penman, 1948; Allen et al., 1998). If the potential evapotranspiration rate is greater than precipitation, the soil will dry out, unless irrigation is applied. Empirically, the potential reference crop evapotranspiration can be estimated using meteorological data. Factors that affect evapotranspiration include the plant's growth stage, percentage of soil cover, solar radiation, humidity, temperature, and wind.

Although various methods have been developed to estimate evapotranspiration, the Penman-Montieth formula has become accepted as the world standard for calculating the potential reference crop evapotranspiration (Allen et al., 1998; Allen, 2000). In the same way, the Food and Agriculture Organization (FAO) compared the statistics and ranking for monthly estimates of evapotranspiration using 20 methods and recommended that Penman-Montieth is the best methods in both humid and arid locations (FAO, 1990).

The modified FAO Penman-Montieth equation (Equation 3.6) presented in FAO paper 56 has been widely used to estimate the hourly, daily, and monthly potential evapotranspiration from meteorological data (Allen et al., 1998). Although this empirical equation has been tested and approved widely, it requires accurate climatic data. This empirical equation is used by the FAO CROPWAT computer model for windows (Clarke et al., 1998).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (3.6)$$

Where	ET_o	=	reference evapotranspiration (mm d^{-1})
	R_n	=	net radiation at the crop surface (MJ $m^{-2}d^{-1}$)
	G	=	soil heat flux density (MJ $m^{-2}d^{-1}$)
	T	=	air temperature at 2 m height (°C)
	u^2	=	wind speed at 2 m height (m s^{-1})
	e_s	=	saturation vapour pressure (kPa)
	e_a	=	actual vapour pressure (kPa)
	e_s-e_a	=	saturation vapour pressure deficit (Pa)
	Δ	=	slope vapour pressure curve (Pa $°C^{-1}$)
	γ	=	psychometric constant (Pa $°C^{-1}$)

The reference crop evapotranspiration can be converted to an actual evapotranspiration by multiplying with a surface coefficient called a crop coefficient. The crop coefficient factor (K_C) is defined as the ratio of crop potential evapotranspiration (ET_c) to a grass reference evapotranspiration (ET_o). The crop coefficient factor is affected by the crop characteristics, length of growing season, soil moisture, the time of planting, and the local climatic conditions (Doorenbos and Pruitt, 1977).

Based on the total available water in the active root zone (*TAW*) and readily available water (*RAW*), the effect of stress is then calculated in a two stage process. Both total and readily available water are stated as volumes of water per unit area within the drying zone practically the same as the soil moisture deficit (*SMD*). Evapotranspiration is assumed to take place at the potential rate on condition that the soil moisture deficit is less than readily available water. Evapotranspiration decreases below the potential rate in proportion to the ratio of non-readily available water (*TAW – RAW*) extracted when the soil moisture deficit goes above readily available water (Smethurst et al., 2004).

$$AET = PET \: x \: K_C \qquad \text{for } 0 \le SMD \le RAW$$

$$AET = PET \: x \: K_C \: x \: \frac{(TAW - SMD)}{(TAW - RAW)} \qquad \text{for } SMD > RAW \qquad (3.7)$$

Equation (3.7) is the basis of the CROPWAT computer model for windows, which has been widely used in soil moisture budgeting and irrigation (Clarke et al., 1998). Although the FAO Penman-Montieth approach offers the best method for estimating crop water requirements for irrigation planning purposes, further research is needed on the application of FAO-56 crop coefficient factors (El-Magd, 2004).

When the soil moisture deficit is large, potential evapotranspiration will overestimate the actual evapotranspiration because the remaining soil moisture is not readily accessible to the vegetation. Actual evapotranspiration can be estimated in two stages, at first by scaling potential evapotranspiration by a crop coefficient, specific to the vegetation and then by calculating the effect of stress on the plants caused by the soil moisture deficit (Allen et al., 1998).

The actual rate of evapotranspiration is constrained by water availability. Arnell and Reynard (1996) estimated for a sample of UK catchments that the rate of actual evaporation would increase by a smaller percentage than the atmospheric demand for evaporation. In addition, the local effects of climate change on soil moisture will vary not only with the degree of climate change but also with soil characteristics. The water-holding capacity of soil will affect possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change (Arnell et al., 2001).

3.4.3 Interception loss from trees

Trees have the ability to use more water than other types of vegetation. Evergreen conifers tend to have a greater water use because high interception losses are maintained throughout the year (Nisbet, 2005). Calder et al., (2003) demonstrated that broad leaved trees intercept and evaporate 10-25% of annual rainfall in the UK and conifer intercept and evaporate 25-45% of annual rainfall.

Interception is one of the important parts of the water balance model. After the water balance model for well in sand dune area was successfully calibrated, the water balance model for well in the zone of pine trees was constructed. Thus, interception was included to the water balance model for areas covered by pine trees.

Interception is needed in the model because tree cover may intercept rainfall. Not all of the precipitation which falls to the land reaches the soil surface to become available for vegetation growth, stream flow or groundwater recharge. Interception loss is the portion of gross precipitation retained by the canopy and lost from the watershed as evaporation before reaching the soil surface. Once precipitation reaches the soil surface, the process of interception is complete and the process of infiltration begins (Calder, 2005). Interception of rainfall by conifers can account for between 11 and 47% of the total rainfall (Penman 1963).

There are two major factors affecting interception capacity consisting of trees and precipitation. First, trees serve a role on interception loss by tree species, canopy density, leaf area, seasonal characteristics (deciduous vs. evergreen), and leaf surface and bark roughness. Factors that affecting precipitation properties include the precipitation amount, storm frequency, precipitation intensity, and storm duration, type of precipitation, wind during storm, and wind during evaporation are influenced on the amount of interception (Gash, 1979).

After precipitation occurs, some water is gathered due to interception by canopy and litter (interception loss equals the sum of canopy interception loss and litter interception loss). The rest of the precipitation which reaches the soil surface is called Net precipitation, theoretically measured under the canopy and litter. Throughfall is the precipitation which reaches litter, or bare soil, by passing directly through or dripping from the canopy. Stemflow is the precipitation which reaches litter or bare ground by flowing down the stems of trees, shrubs, forbs, and grasses. In some cases stemflow can pipe water directly into the soil (Gash, 1979).

Interception loss can be estimated by using either direct or indirect method. Direct method requires direct measurement of gross precipitation, throughfall, stemflow, and change in litter moisture content before, during, and after storms. Although throughfall and stemflow occur with grasses, they are almost impossible to measure accurately in the field. Indirect methods normally estimate interception loss by using the interception model such as the semi-empirical Calder-Newson model, Rutter model, Gash's model (Calder, 2005).

There have been several studies of the interception loss by forest which are frequently expressed in the form of empirical regression equations between interception loss and rainfall. However, these results are empirical and can be extrapolated only to similar forest condition in areas where the original data were collected. In contrast, the Rutter model is a physically based model producing an estimate of the interception loss by input rainfall and meteorological variables to calculate a water balance model of a forest canopy. Nevertheless, the Rutter model has practical disadvantages because it requires hourly meteorological data and a complex computer programme (Gash, 1979).

The storm-based analytical model described by Gash (1979) is one of the most popular models estimating forest rainfall interception. Gash's analytical model demonstrated that the evaporation of rainfall intercepted by forest canopies can be estimated from the forest structure, the mean evaporation and rainfall rates and the rainfall pattern. Gash's model considers rainfall to occur as a series of discrete events.

Calder (2005) presented a daily model to estimate interception and transpiration for forest, heather and grass. The model is operated on a daily time step and incorporates the two-parameter exponential relationship (Equation 3.8). The Calder model was found to fit well with pine forest interception losses recorded in the UK.

$$I = \gamma(1 - \exp(-\delta P) \qquad (3.8)$$

Where I = the daily interception loss (mm)

P = the daily precipitation (mm)

γ = interception parameter; from observations this depends on land use (about 6.1-7.6 mm)

δ = interception parameter (0.099 mm^{-1})

Seasonal evaporative losses were obtained by summing the daily evaporation estimates (E_d) estimated in terms of transpiration and interception loss, as given by;

$$E_d = \beta E_T(1 - w) + \gamma(1 - \exp(-\delta P)) \qquad (3.9)$$

Where E_d = the daily evaporation

β = the transpiration fraction

E_T = the daily Penman evaporation estimate

$(1-w)=$ the fraction of the day that the canopy is dry and is able to transpire

w = the fraction of the day the canopy is wet (0.045P for $P<0.22$mm, w=1 for $P \geq 22$mm)

The Calder seasonal model is appropriate only for areas with conditions similar to the UK uplands where soil moisture stress is an infrequent occurrence. Moreover, it is strictly applicable only to mature stands of trees (Calder, 2005).

Both the Gash and Calder models were implemented in the water balance model. The water table levels calculated by these two models gave similar results. Therefore the Calder model was used to simplify the generally applicable water balance model, because it is easy to use and only a few parameters are required.

The following chapter describes how the model components explained above were assembled into a waterbalance model for use at Ainsdale.

CHAPTER 4

Developing and Testing the Model at Ainsdale

The development and calibration of the water balance model at Ainsdale NNR is described in this chapter. The main components needed to construct the water balance model consist of rainfall, evapotranspiration, groundwater flow, storage change and surface runoff. Some of these components were available as a long recorded data such as rainfall; however, calculations were needed for some components such as evapotranspiration and groundwater flow. A summary of the model components and how they were evaluated is given in Table 4.1 and the model structure was described in Figure 3.26. The sequence of steps used to test and calibrate the model is given in Table 4.2.

The main differences between the water balance model used in this work and the Clarke model (Clarke, 1980) are discussed as follows:-

- Use of the Penman Montieth equation to calculate evapotranspiration instead of the Penman equation in the Clarke model.

- Calculation of daily soil moisture deficit and actual evapotranspiration. This required sub models for vegetation type, soil water capacity and daily soil moisture deficit. The Clarke model did not include this calculation.
- Use of the Calder Model to simulate tree interception. The Clarke model did not simulate tree interception.
- Use of a 30 years run of climate data to calibrate the model for groundwater flow instead of 3 years in the Clarke model.

The remainder of this chapter describes the incremental steps used to calibrate the model against a 30 year runoff observed water table levels both in the open dunes under a short grass cover and in an area of pine trees.

Table 4.1: Summary of model components

Parameter	**Obtained from**	**Calculation method**	**Approximate range of uncertainty**
Daily Rainfall	Measured data	n/a	+/- 2%
Actual Evapotranspiration from short vegetation	Potential ET, and root zone model	Penman Montieth, FAO 56 Kc for short grass and CROPWAT root zone model	PET +/-7% AET +/-15%
Groundwater Flow	Initially from annual water balance and then refined during model development by varying K	Darcy's Law and Dupuit equation, saturated thickness of aquifer, hydraulic conductivity of sand and gradient of water table	Aquifer thickness assumed constant at 20m. Hydraulic conductivity varied during model testing. Hydraulic gradient calculated from simulated water table levels. Flow +/-50%
Changes in water table levels	Simulated water balance at end of previous time step	Water balance change (mm) converted to water table level change (m) using depth dependent porosity functions	Saturated sand effective porosity measured in the range 28-32%. Depth dependent porosity functions assumed a standard profile under slack floors.
Water table levels in slacks	Porosity assumed to be 100% in open slacks and 30% under dune ridges	Water table level varied as a function of change in storage and porosity weighted by ratio of flooded slack : dune ridge in well vicinity	Ratio of areas +/- 10%

Surface runoff	Heuristic based on field observations of water levels in flooded slacks and drain flow rate	Calculated water table level from end of previous month used to evaluate functioning of drain system	Surface flow +/- 50%
Interception of rainfall from trees	Calder's models using daily rainfall and PET	Varying interception parameters	Interception +/-20%

Table 4.2: Steps used in model verification

Step	Calculation method	Notes
Initial water balance	Annual Rain-Annual PET to estimate magnitude of groundwater and surface flow	Did not account for seasonal variations and assumed potential ET
Monthly water balance	As above using monthly data	Shows some seasonal variations but overestimates recharge
Daily Water balance using root zone model	Calculated soil moisture deficit and actual evapotranspiration for open grass areas	Shows seasonal variations but predicted water table levels not stable : groundwater flow needed refinement
Daily water balance, root zone model, groundwater calculated as a function of hydraulic gradient	Hydraulic gradient calculated from predicted water table levels at the end of the previous time step	Better performance but long term stability poor
Daily water balance, root zone model, groundwater function of hydraulic gradient. Variation in dune sand permeability.	Hydraulic conductivity varied using sensitivity analysis to stabilise long term model performance.	Long term stability obtained but modelled winter summer amplitude of water table changes poor
Daily water balance, root zone model, groundwater function of hydraulic gradient. Tuned dune sand permeability. Depth dependent porosity functions	Porosity of dune sand varied with depth. Reducing from28% at depth to 50% near surface and 100% at surface	Better performance of winter summer amplitude
Daily water balance, root zone model, groundwater function of hydraulic gradient. Tuned dune sand permeability. Depth dependent porosity functions. Surface flow heuristic.	Model performed well in dry years but in very wet years it stored too much water. A drain flow heuristic was added.	Drain flow triggered when water table above a level observed to coincide with activation of surface drains.
Tree Interception / evapotranspiration	Application of Calder model	Reduced annual recharge, and lowered water table gradient and hence outflow.

In the following sections, the estimation of potential and actual evapotranspiration is described and followed by the calculation of groundwater flow. Model development and testing are explained to show how the model was refined and calibrated against the observed water table levels in the open dunes with a short vegetation cover. Finally interception loss for large vegetation is described. Interception loss is calculated by Calder's interception model for large vegetation such as pine forest and the impacts of tree coverage change on the water balance model are described.

4.1 Estimating Potential and Actual Evapotranspiration

Actual evapotranspiration is one of the main components needed to construct the water balance model. As a first approximation, it was considered that the Penman-Monteith equation estimate of *PET* for the unforested areas of the NNR would be representative of actual conditions. Because the water table is close to the ground surface in the slacks throughout the year, the roots of the transpiring vegetation will then be well supplied with water at all times.

The main parameters needed to estimate *PET* based on Penman-Monteith equation as described in Chapter 3 consist of long term recorded temperature, wind, humidity and sunshine. The variations of monthly *PET* at Ainsdale for year 1972-2007, using meteorological data sets for *PET* calculation described in Chapter 3, are shown in Figure 4.1 and illustrates that the highest rates of *PET* at Ainsdale are between May and August, and the lowest *PET* months start in November until February.

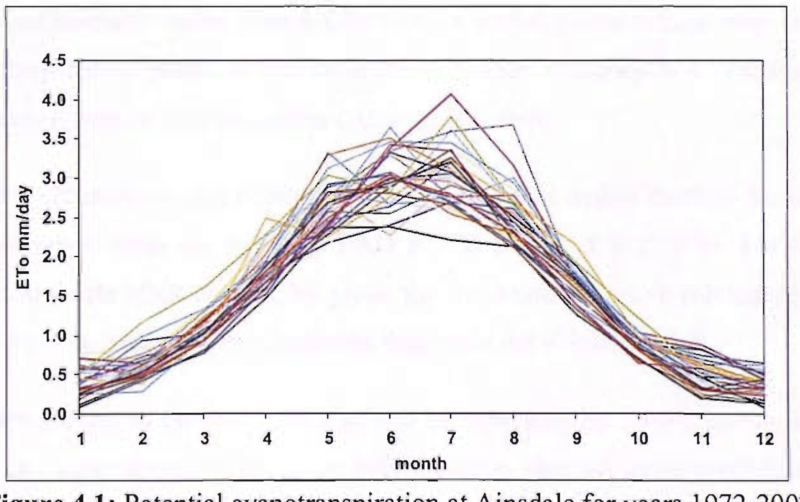


Figure 4.1: Potential evapotranspiration at Ainsdale for years 1972-2007

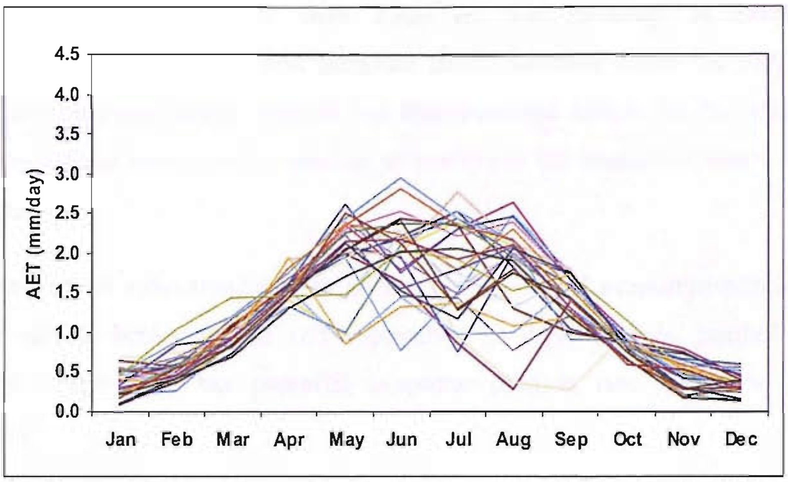


Figure 4.2: Actual evapotranspiration at Ainsdale for 1972-2007

Actual evapotranspiration at Ainsdale, shown in Figure 4.2, were estimated based on a soil moisture deficit model which uses soil and vegetation properties. Figure 4.3 shows the variations of *PET* and *AET* at Ainsdale from 1972 to 2004. This shows typically that AET = PET between October and April, and *AET* is less than *PET* in May to September.

As described in Chapter 3, the water stress coefficient (K_s) depends on the total available soil moisture (*TAM*), readily available soil moisture in the root zone (*RAM*), and soil moisture deficit in the previous month (*SMD*). Moreover, *RAM* can be estimated by multiplying an average fraction of *TAM* that can be depleted from the root zone before moisture stress occurs (*p*). The factor *p* differs from one crop to another and normally varies from 0.3 for shallow rooted plants at high rates of *AET* to 0.7 for deep rooted plants at low rates of *AET*. The fraction *p* is a function of the evaporation power of the atmosphere (Allen et al., 1998).

Maximum effective rooting depth (Z_r) and soil moisture deficit fraction for no stress (*p*) for common crops are listed by FAO no. 56 (Allen et al., 1998). For the sand dunes at Ainsdale NNR covered by grass, the maximum effective rooting depth was set as 0.5-1.0 m. and soil water depletion fraction is 0.4 (Clarke, 1980).

The water content in the root zone can also be expressed by its soil moisture deficit (*SMD*), i.e., water shortage relative to field capacity. The soil moisture deficit is zero where the soil is at field capacity. The depletion increases and stress will be induced when *SMD* becomes greater than *RAM* as soil moisture is extracted by evapotranspiration. When the soil moisture deficit exceeds *RAM*, the *SMD* is high enough to limit evapotranspiration to less than potential values. At this stage, actual evapotranspiration begins to decrease in proportion to the amount of water remaining in the root zone.

In general, actual evapotranspiration is less than potential evapotranspiration in the summer months between June and September. In these periods, rainfall is lower (typically 1.5mm/day), but potential evapotranspiration rate is higher (typically 3mm/day).

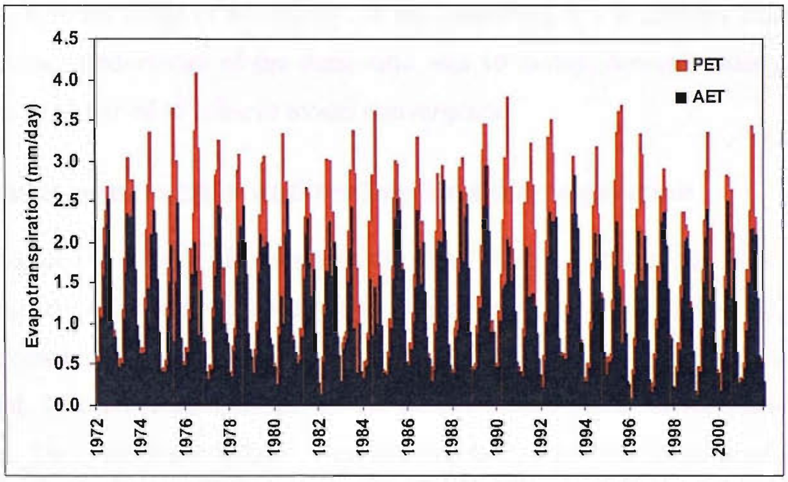


Figure 4.3: *PET* and *AET* at Ainsdale for years 1972-2004

4.2 Calculating groundwater flow

Groundwater flow is one of the major components required in the water balance model. Outflow from the Reserve occurs mainly by groundwater flow across a seepage face. Water enters the area as precipitation, and eventually leaves the system as groundwater flow. Clarke (1980) stated that there are no lateral boundaries in the sand dune system. Therefore, it can be assumed that the groundwater system continues infinitely in each direction (North & South), because groundwater flow moves along the streamlines and so cannot move laterally into or out of the system. Water table contour maps for dry seasons and wet seasons are shown in Figure 3.15 (Chapter 3). An annual water balance was used to estimate the preliminary groundwater flow rate. At Ainsdale, the average rainfall is about 840 mm/year and reference potential evapotranspiration is approximately 436 mm/year; thus, the rest of the water (about 34 mm/month) was initially assumed to be groundwater flow.

One of the most common equations (Darcy assumptions as described in Chapter 3) was used to estimate the rate of groundwater flow from the Reserve. Parameters needed to estimate groundwater flow using Darcy's Law consist of hydraulic conductivity *(K)*, length of the sand column *(L)*, the hydraulic head difference between inlet and outlet across the sand $(h_1 - h_2)$, and cross-sectional area to flow *(A)*.

To estimate the groundwater flow out from the system, it was necessary to derive a value for hydraulic conductivity of the sand as described in Chapter 3. Clarke (1980) measured K in the range of 8-15m/day. In the modelling, it was initially assumed that the hydraulic conductivity of the dune sand was 10 m/day; however, this parameter may have to be varied to achieve model convergence.

4.3 Model construction and testing for short vegetation

It was decided to choose the observations from Well 11 to test the water balance model because it is located in open dunes where there are no trees. Rainfall data are readily available, and the rates of evapotranspiration and groundwater flow have been calculated. The major components of the water balance model at Ainsdale are now available. Thus, the water balance equation can be solved. The steps used in testing and calibrating the model against a 30 years run of measured water table levels are discussed below:-

Table 4.3: Summary of model calibration processes

Run order	Method
First run	Assume AET = PET
Second run	Apply AET
Third run	Vary K to 10.0 m/day 10.5 m/day 11.0 m/day 15.0 m/day
Forth run	Vary effective porosity to 20 % 30 % 32 % 40 %
Fifth run	Adjusted surface porosity
Final run	Allow surface flow to 10 mm/month 15 mm/month 20 mm/month

4.3.1. First run of the model – *PET = AET*

It was decided to run the first water balance model assuming actual evapotranspiration was equal to potential evapotranspiration. Potential evapotranspiration was estimated by using the Penman-Monteith equation. The hydraulic conductivity was initially assumed to be constant at 15 m/day and the effective porosity of the dune sand was assumed to be 35%, the same as the total porosity. The result is shown in Figure 4.4 and indicates that the modelled water table level drops rapidly and continuously. This indicates that too much water is leaving the model. This is probably because potential evapotranspiration is often higher than actual evapotranspiration and assuming that actual evapotranspiration is equal to potential evapotranspiration resulted in too much water leaving the system. Another possible cause is that the calculated groundwater flow (a function of the hydraulic conductivity) was too high.

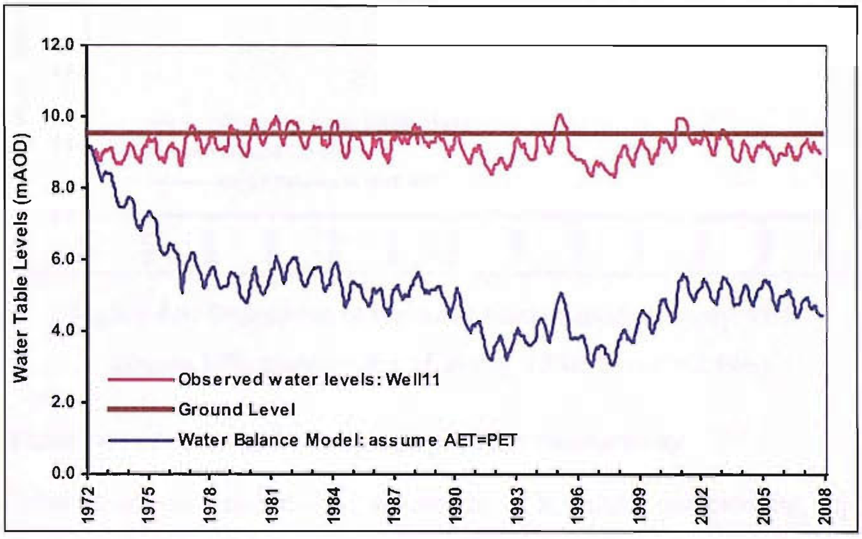


Figure 4.4: First run of the water balance model - *PET = AET*
: assume 35% porosity, K=15m/day (*RMS Error =4.04m*)

4.3.2. Second run of the model – apply *AET*

Potential evapotranspiration is generally higher than actual evapotranspiration as shown in Figure 4.3; therefore, the second water balance model was run by using actual evapotranspiration estimated using soil moisture deficit model. The groundwater flow calculation was left unchanged with K=15m/day. The water balance model was re-run including actual evapotranspiration is shown in Figure 4.5.

The calculated water table levels decrease over the first 5-10 years of the simulation then stabilise. This suggests that the initial situation calculated a higher loss of water from the model until the lowered water table has decreased the hydraulic gradient (and hence groundwater flows out of the system). Once the groundwater flow had been reduced, the model the stabilises and produces modelled water table levels comparable in pattern to the observed data but approximately 3m lower than observed.

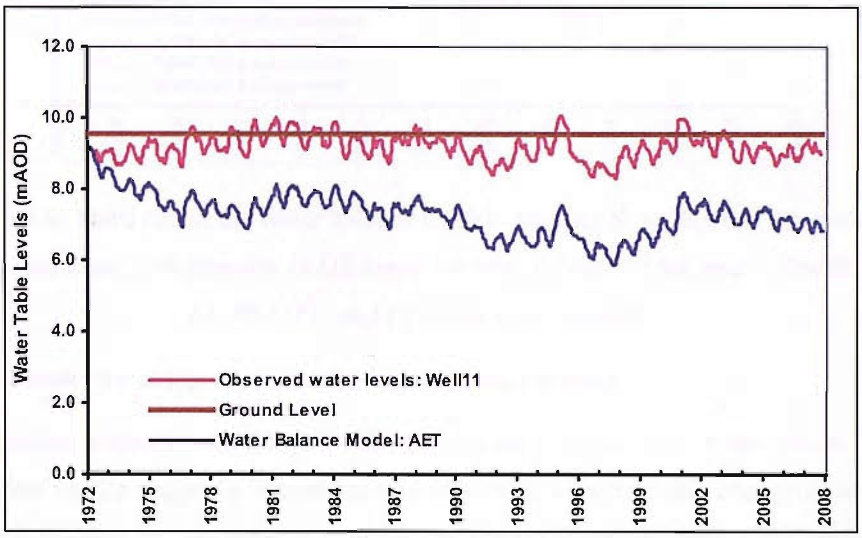


Figure 4.5: Second run of the water balance model - apply AET : assume 35% porosity, K= 15 m/day. (*RMS Error =2.39m*)

4.3.3. Third run of the model – varying hydraulic conductivity

Groundwater flow was calculated as a function of hydraulic conductivity, aquifer saturated thickness and the hydraulic gradient. The saturated thickness and hydraulic gradient are functions of the water table level, which is the output of the model, so these relationships were unchanged. The model was re-run varying the assumed hydraulic conductivity. Values chosen were 10, 10.5, 11, and 15 m/day. The best results were obtained using hydraulic conductivity = 10.5 m/day with a Root Mean Square Error (RMS Error) between observed and modelled water table levels of 0.88m. (Figure 4.6) This simulation produced long term stability in the model and showed some seasonal variations in the water table simulation. However, the winter-summer amplitude of simulated water table changes was significantly smaller than those observed.

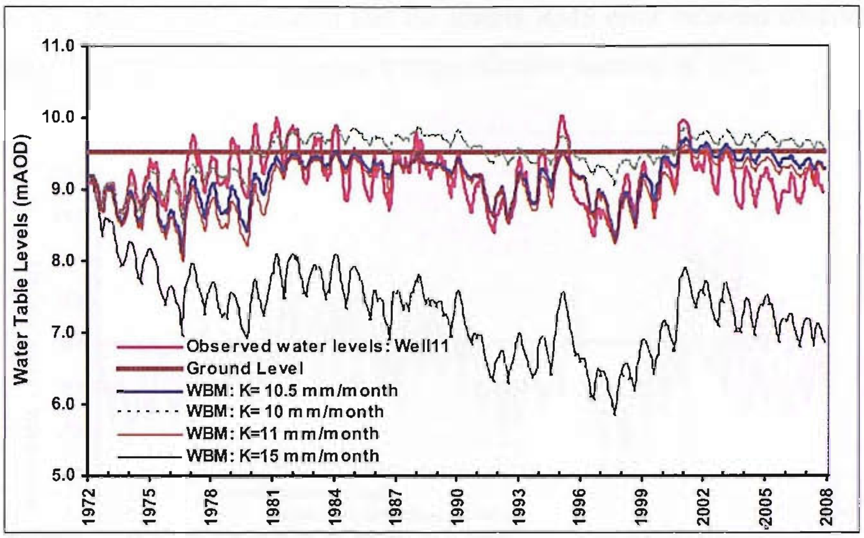


Figure 4.6: Third run of the water balance model - varying K to 10, 10.5, 11, and 15 m/day: assumed 35% porosity (*RMS Error =0.66m, 0.26m, 0.34m, and 2.39m for K 10, 10.5, 11, and 15 m/day respectively*)

4.3.4. Forth run of the model – varying effective porosity

The effective porosity was assumed to be 35% in the previous runs of the model. The simulation results suggest a winter-summer amplitude of water table change of about +/- 0.3m, whereas the observed amplitude was higher (about +/-0.6m). Until now, the model used an effective porosity equal to the dry sand porosity (35%). A sensitivity analysis was carried out by varying the dune sand effective porosity between 20% and 40%. The graph shows that 40% effective porosities is too high, and an effective porosity at 20% and 30%. The amplitude of the winter peaks and summer minima are closest when the effective porosity is about 32%. This is similar to the "drainable porosity" quoted for the dune sand by Clarke (1980). Clarke (1980) stated that the total porosity of the dune sand is approximately 39%, calculated when a sample of saturated sand is dried at 100°C for 24 hours. In the real soil, the specific retention is the amount of water left in the sand after it has drained under gravity. The specific retention for Ainsdale Sand Dune is about 7%; therefore, if the saturated sand was allowed to drain under field conditions then it will drain from 39% moisture content to about 7% content. The difference is 32%, which is the effective porosity (or storage capacity) of the dune sand in the natural environment, and is the same as the best value found during the model calibration. Figure 4.7 shows the results of the sensitivity analysis and indicated that the lowers RMS error between observed and modelled water table levels occurred with an effective porosity of 32%.

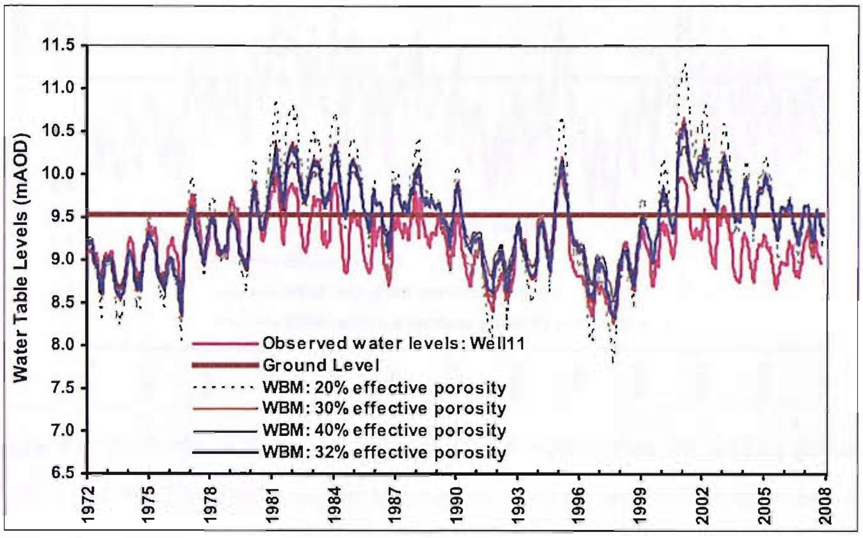


Figure 4.7: Forth run of the water balance model - varying the effective porosity: *(RMS Error =0.36m, 0.27m, 0.23m and 0.29m for porosity 20, 30, 32, and 40%)*

The model performance is still not stable in the long term. It behaves well for the first 5-10 years but then over estimates water table levels, especially in times of high observed water table conditions. This was due to the fact that water table levels were scaled from water balance water storage values using a constant porosity. When the water table level rises above ground level the "porosity" of the air is 100%, not the assumed value of 32%. This would result in modelled changes in water table levels being 3 times higher than those observed.

4.3.5. Fifth run of the model – correction for surface porosity

The effective porosity for the dune sand (32%) will not apply to the flooded slacks in the open dunes. This assumption leads to the fifth run of the water balance model by including a change of porosity to 100% when the water table rises above ground level. The water balance model result is shown in Figure 4.8. The results are an improvement but the model still performs poorly at high water table levels after 1980.

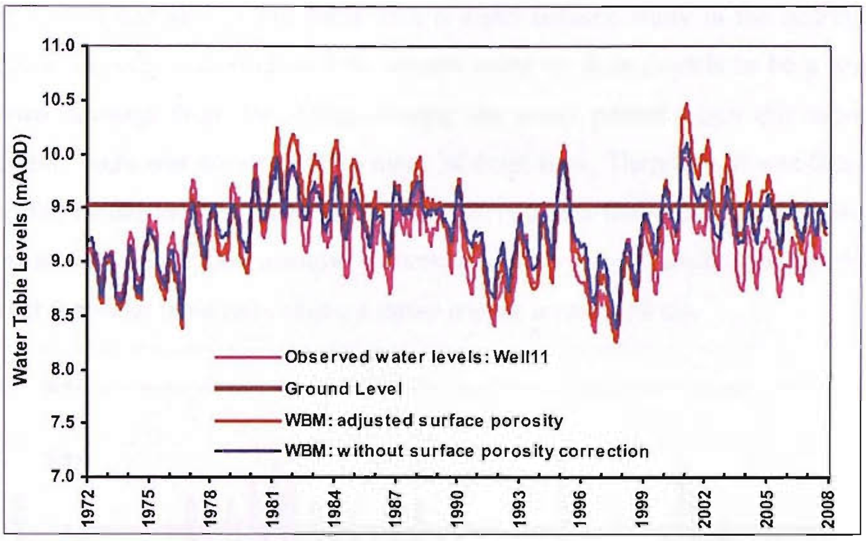


Figure 4.8: Fifth run of the water balance model - correction for surface porosity: (*RMS Error =0.23m before adjust the surface porosity and 0.20m after adjusted surface porosity*)

Clarke (1980) noted that if all the slacks in the open dunes are flooded, then 40% of the area has an effective porosity of 100%, while the dune ridges retain the original effective porosity. Therefore, the effective porosity of a flooded slack area was re-calculated as (40% of flooded slacks area*100% porosity) + (60% of the rest area*32% porosity) = 59.2%. As shown in Figure 4.8 the model adjusted surface porosity illustrates that the error after 1980 is reduce but some errors still exist after 1980, especially in times of high water table levels

4.3.6. Final run of the model – allowance for surface drainage

The model errors present after 1980 can be explained as a result of surface flow occurring from the flooded slacks through a shallow intermittent drainage system that removes water onto the beach. Clarke (1980) summarized that the mechanism for the removal of surface water in the central part of the NNR is the ditch system, and flow in the ditch began when the water table at Well 9 rose above 9.23 m and stopped when it fell below 9.33 m. Moreover, Clarke (1980) recorded field events of overland flow in 1976-1977 when the water table at Well 9 rose above 9.6 m. The measured flow was about 30litres/second or 20,000m^3/week. The measured drain flow was in a ditch raining an area of about 1000m x 1000m for about 1-2 weeks, so the flow discharged was approximately equivalent to 20-40mm for that month.

Atkins (2004) had similar problems with a water balance study in the nearby dune systems at Formby and attributed the excess water in their models to be a result of unknown drainage from the dunes. During the study period when this work was carried out, there was no observation made of drain flow. Therefore, it was decided to amend the model using a simple heuristic rule: assume that the drainage flow from the open dunes is approximately 20litres/second or 12-24mm/month which only occurs if the water table rises above a stated trigger level (9.38 m).

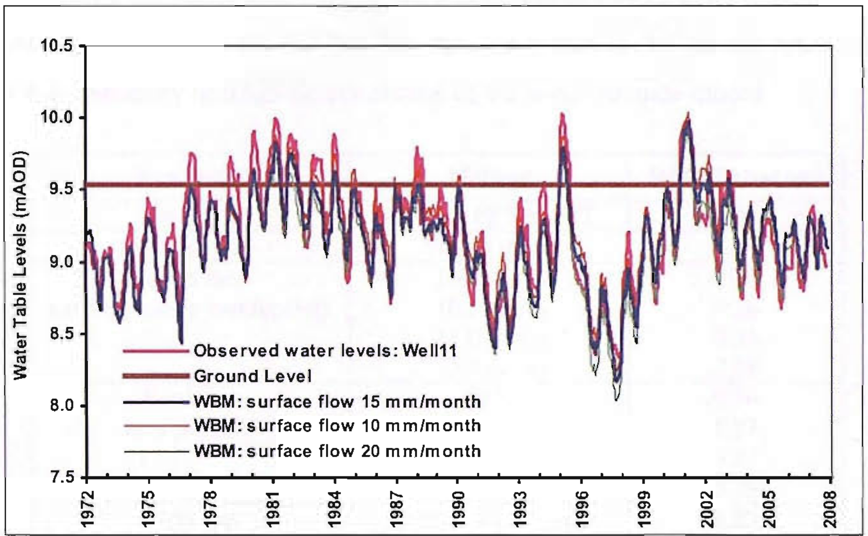


Figure 4.9: Sixth run of model – allowance for surface drainage (*RMS Error =0.16m, 0.11m and 0.13m for surface flow 10, 15 and 20 mm/month respectively*)

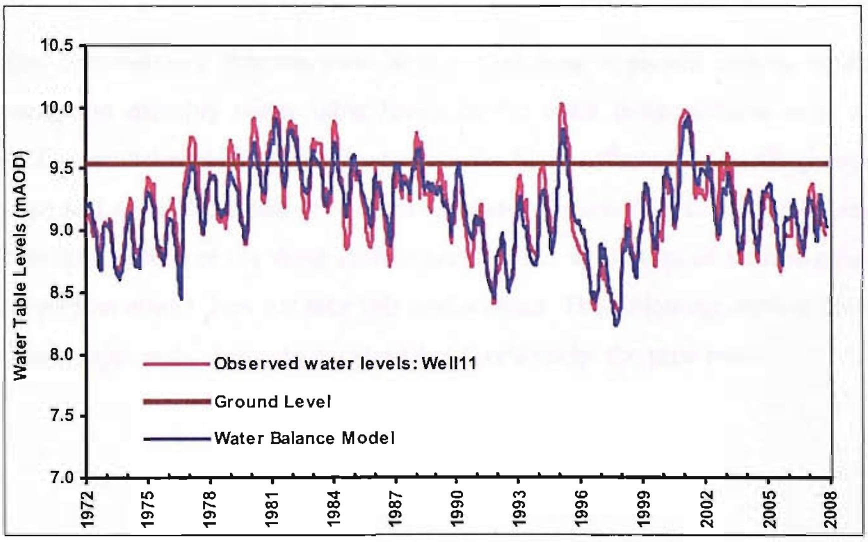


Figure 4.10: Final run of the water balance model for short vegetation: allowance for surface drainage *(RMS Error = 0.11m)*

The sixth model was run implementing this heuristic with surface drainage equal to 10, 15, and 20 mm/month when the water table is above ground level (Figure 4.9). The best water balance model result was obtained when 15 mm/month surface runoff was applied in the heuristic. The final run of the water balance model for Well 11 for short vegetation is shown in Figure 4.10.

Table 4.4 summarizes the Root Mean Square Error from the water balance model testing. Adding processes and making the water balance model more realistic reduces the RMS error from 4.04m for the first runs of model to 0.11m the final version.

Table 4.4: Summary of RMS Errors of runs of the water balance model

Run order	Method	RMS Error (m)
First run	Assume PET = AET	4.04
Second run	Apply AET	2.39
Third run *vary hydraulic conductivity*	10.0 m/day 10.5 m/day 11.0 m/day 15.0 m/day	0.66 0.26 0.34 2.39
Forth run *vary porosity*	20 % 30 % 32 % 40 %	0.36 0.27 0.23 0.29
Fifth run *adjusted surface porosity*	Before adjustment After adjustment	0.23 0.20
Final run *allow surface flow*	10 mm/month 15 mm/month 20 mm/month	0.16 **0.11** 0.13

This has demonstrated that we now have a modelling approach that is capable of simulating the monthly water table levels in the open dune systems over a long period. This model will be used to investigate the likely effects of climatic change, sea level rise and coastal erosion on the groundwater system of the dunes at Ainsdale. However some areas of the dune system are covered with areas of mature pine trees and the present model does not take this into account. The following section described a modelling approach to simulate water table levels under the pine trees.

4.4 Interception losses from large vegetation

To calculate the groundwater levels in the sand dunes, it will be necessary to determine what proportion of the rainfall incident on the Nature Reserve finally enters the groundwater system. Rainfall may be intercepted by plants and re-evaporated back to the atmosphere. At Ainsdale NNR, Pine forest covers more than 30% of the Reserve area; therefore, potential evapotranspiration calculated by the Penman-Montieth equation is unlikely to be appropriate for the pine forest area.

Well 9, which is located in the centre of the Reserve, was selected to represent the pine tree area. Calder's interception model (Calder, 2005), described in Chapter 3, was applied to the water balance model to calculate the amount of interception loss from pine forest. Figure 4.11 shows a comparison of water table levels calculated by water balance model and observed levels at well 9. It was again calibrated by allowance for varying in hydraulic conductivity (*K*), effective porosity, adjusted surface porosity, and also surface drainage. The result shows that the water balance model fits acceptably before 1997, but the water table levels are considerably higher than the observed data after 1997.

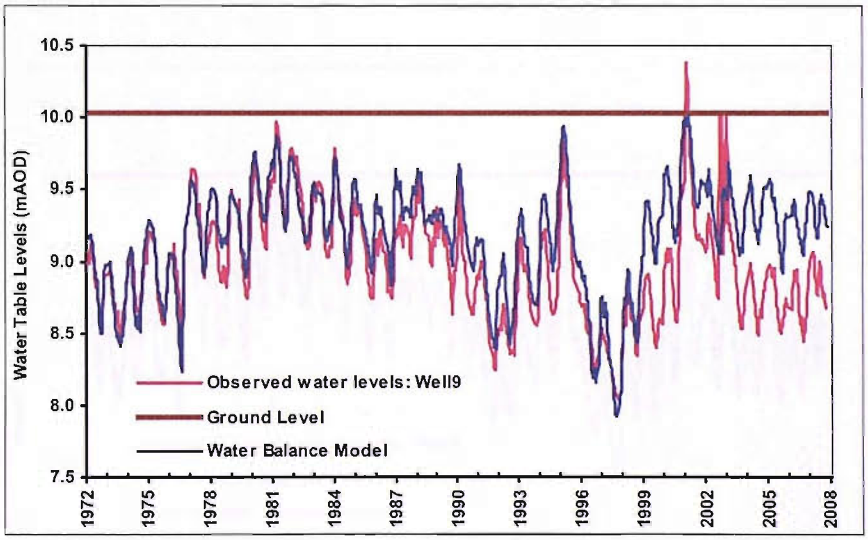


Figure 4.11: The water balance model for Well 9 - included interception loss and tree coverage change

Although well 9 was chosen to represent an area of the pine trees, this area is situated near the intermediate area where pine trees were cut down. Therefore, groundwater levels might be affected by tree coverage change. Atkins (2004) concluded that clearfell operation can have an impact on the water levels in the area immediately surrounding the site. The water balance model was run again by varying surface drainage after 1997 as shown in Figure 4.12. The physical basis for this is that when trees are felled the actual evapotranspiration is reduced because the trees are cut and other vegetation is destroyed, leaving only a soil surface. In this situation K_c would probably become much smaller for the year after the trees were cut down, and surface drainage might also change due to the disturbance caused by the logging operations. Clarke (1980) recorded evidence of subsurface clay drain pipes in this part of the Nature Reserve but no flow observations have been made.

Figure 4.12 shows the water balance model for Well 9 which incorporates and increases the surface drainage from about 20mm to 40mm/month after 1997 when the pine trees were cut down. This is at present no firm explanation for this except that if the surface drains were blocked by tree roots the perhaps the felling operations have rejuvenated the rain system in this area. However there are still problems with unexplained peaks in February 2001, October and November 2002, and January 2003.

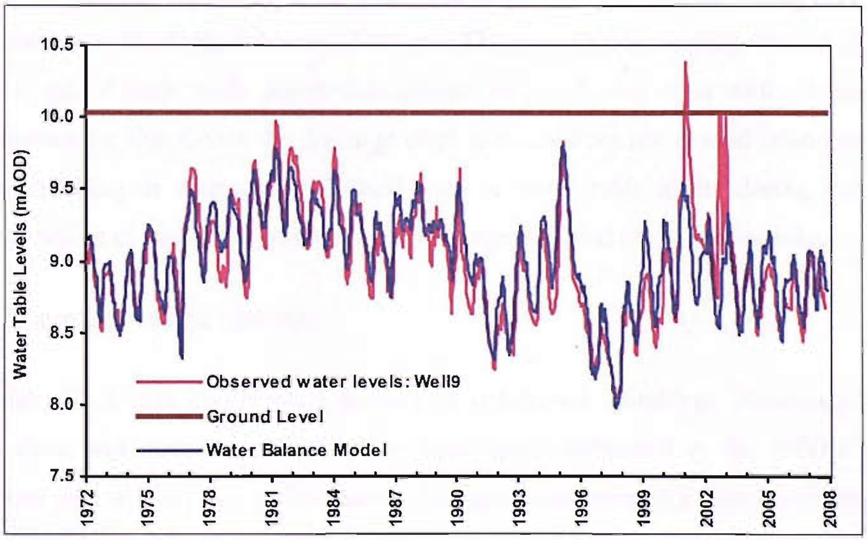


Figure 4.12: The water balance model for Well 9 - varying groundwater and surface flow after 1997

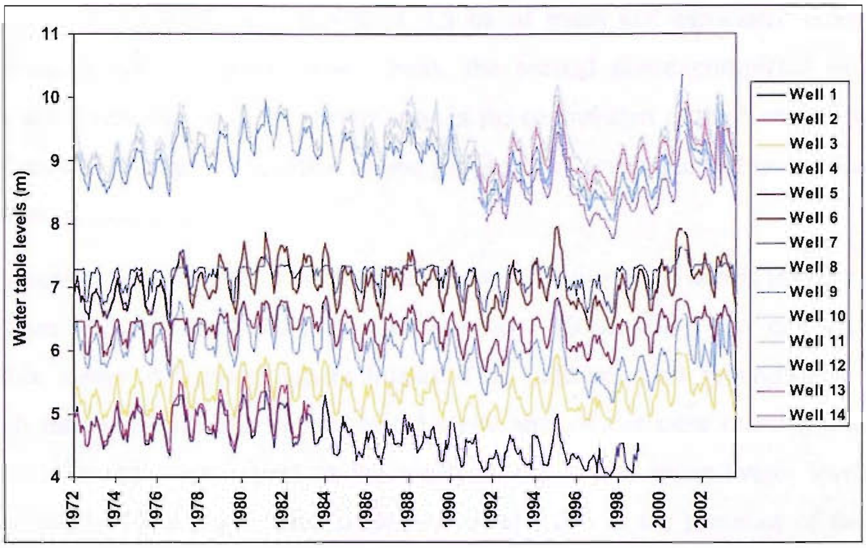


Figure 4.13: Observed water table levels Well 1 to Well 14 in Ainsdale NNR

Discussions with the staff at Ainsdale NNR has not been able to arrive at a satisfactory explanation for this extreme behaviour and it can only concluded that the tree felling has significantly altered the surface drainage in this area. To investigate these uncertainties, the levels in a series of wells in the southern part of the reserve were examined.

The observed water level data are shown in Figure 4.13. Some of these data show extreme water levels in February 2001 and October 2002 including Well 9, 10, 12, and 14. All of these wells are further inland compared with other wells. A possible explanation for this is that the drainage ditch network does not extend inland to these wells, resulting in temporary localised rises in water table levels during very wet periods which dissipate by groundwater flow over a period of several months.

4.5 Tree coverage change

Ainsdale NNR area comprises a mixture of coniferous woodland, deciduous scrub, fixed dune and dune slack. Pine plantations were established in the 1930's in the southern part of the area, and it causes changes in the natural dynamics of the sand dunes as described in Chapter 3. Moreover, the forested areas coincide with an area of lower water table levels. Management to increase biodiversity in the dune system has resulted in the removal of some areas of the pine trees. The removal of the pine plantation programme has been established in 1990. Phase 1 of the pine clearance project which involved the removal of 4.5 ha of pines and associated scrub was completed in 1992 (Atkins, 2004). Next, the second phase completed in 1997 involved the removal of 16 ha of pine trees in the central area of the Nature Reserve, therefore, this change might effect on the groundwater levels more than the clearfell operation in 1992.

The typical pattern of water table contours shown in Figure 4.14 shows that the water table rises from sea level (+0.2m) to a maximum +10.5m at the east side and then probably slopes downward gently inland. This indicates that groundwater flows through the dunes towards the sea in the study area. Water table contour lines run parallel with the coast except in the southern end where groundwater levels are approximately 50cm lower. This is closely correlated with the presence of the pine trees. This relationship was confirmed in the 1990's when selective tree removal took place in the central part of the Reserve and water table levels rose by approximately 30cm in the following years. (Atkins, 2004)

Figure 4.14: Typical pattern of water table contours

To explore the impacts of changes in land use on groundwater at Ainsdale, the NNR area was divided into 3 zones consisting of open sand dunes with no trees, the area of pine trees, and an intermediate area where pine trees were thinned and removed in 1992 and 1997.

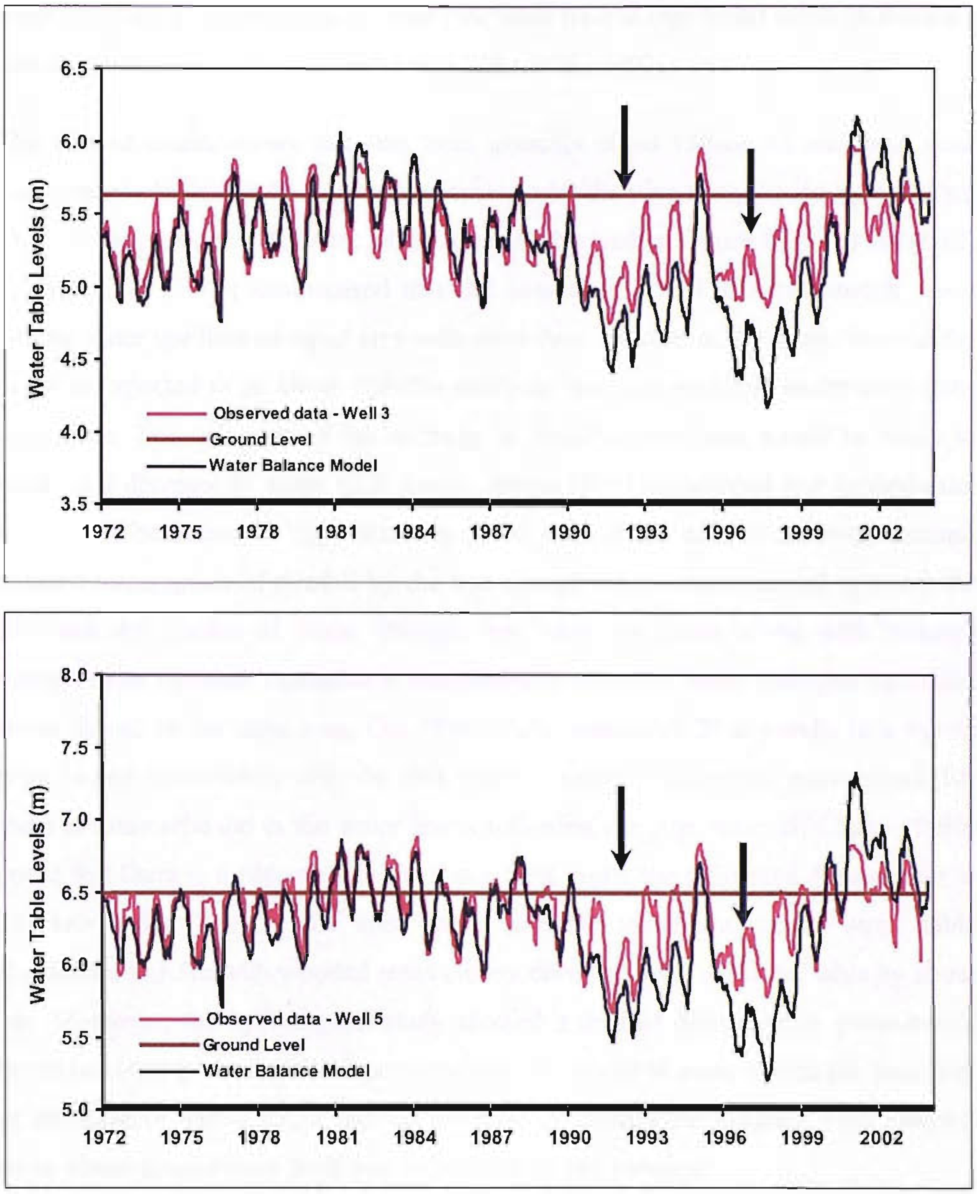


Figure 4.15: Impact of the pine removal in 1992 and 1997 on water table levels in Well 3 and Well 5.

Figure 4.15 shows the revised water balance model was applied to Well 3 and Well 5 in the areas where trees were removed. Interception losses were calculated based on models suggested by Calder (2005) and incorporated into the water balance model to investigate the effect of pine trees on the water system. Results up to 1990 show good agreement but the observed water table levels diverge from the model following the clearance of the trees. This is in accordance with observations in the field and supports other work that suggests that pine trees have a significant effect in reducing aquifer recharge in temperate climates (Calder et al., 2002).

The revised model shows that pine trees intercept about 150mm of rain each year, equivalent to lowering the water table levels under the pine trees should by 0.5-0.6m. This is in agreement with water table contours observed in Figure 4.14 and also CEH (2006). CEH (2006) summarised that the coniferous forest at Newborough has a greater water use than an equal area with short dune vegetation. Recharge beneath the forest is expected to be about 100-200 mm/year less than recharge under short dune vegetation. The reduction of the recharge in the afforested area would be likely to result in a decrease in water table levels. Atkins (2004) concluded that groundwater levels will be increased approximately 30cm as a result of tree removal, because reduced interception of rainfall by the tree canopy allows more rainfall to reach the soil and the uptake of water through tree roots decreases along with reduced transpiration. Clearfell operation is considered to result in wetter soils and increased water fluxes. In the same way, Gee (1991), who monitored 25 dip wells in a matrix prior to and immediately after the first phase of clearfell operation, summarised that there is some rebound in the water levels following the pine removal. Clarke (1980) noted that there is a reduction in the water table under the afforested dunes of up to 1m below that seen in the open dunes and the maximum annual water table fluctuation is 1.5m with wooded areas clearly drawing down the water table by about 1m. Moreover, the hydrological study showed a distinct difference in groundwater levels in existing locations of dune restoration compared to areas around the boundary of the Reserve. However, it was not possible to identify the distance from clearfell areas where groundwater level was influenced by tree removal.

4.6 Summary

The Water Balance model prepared in Chapter 3 was tested and refined by calibrating it against observed water table levels over a 30 year period at the Ainsdale case study site. The calibration included validating parameters for groundwater flow, deep and surface level effective porosity, actual evapotranspiration, and surface runoff. The RMS error of the water balance model for the short vegetation was reduced from 4.04m at the first run of the model calibration to 0.11m at the final run of the water balance model which adding processes and making the model more realistic reduces ever. The effects of interception losses from the pine trees were also incorporated using the Calder Model. The model shows that pine trees intercept about 150mm of rain each year, equivalent to lowering the water table levels under the pine trees should by 0.5-0.6m. The model appears to work very well except for some inland wells at times of extremely high water table levels.

CHAPTER 5

Modelling the Impact of Sea-level Rise and Coastal Erosion

Coastal zones are vulnerable to climate change and variability in sea levels. As a result of climate change, a rising sea level may cause permanent inundation of wetlands and other lowlands, increase of the salinity of rivers, bays and groundwater tables, intensification of flooding, and coastal erosion. Some of these effects may be further compounded by other changing factors such as erosion of the coastline which may accelerate saline intrusion (Essink, 2001). Rising sea levels may increase the salinity of both surface water and ground water through salt water intrusion, and the increase in water depths and increased tidal flood volumes. A shift of the saline boundary inland may affect water supply intakes and it could harm aquatic plants and animals that do not tolerate high salinity.

Shallow coastal aquifers are also at risk (IPCC, 2001). Aquifers in low-lying areas are recharged by fresh water which may become saline in the future. Groundwater usually flows out from the land to the sea; therefore, an eroded shore would change the amount of groundwater flow through increasing the hydraulic gradient; therefore, increasing the flow rates of groundwater as shown in Darcy's Law i.e. dh/dx will increase because dx is decreased.

Erosion is also an important factor potentially affecting groundwater systems in coastal aquifers. Coastline retreat from a rise of only one-meter would be much greater than expected by the area of land below the one-meter contour on a map, because shores would also be affected by erosion. Bruun (1962) showed that as a result of sea-level rises, the upper part of the beach is eroded and deposited just offshore in a fashion that restores the shape of the beach profile with respect to sea level. The "Bruun Rule" implies that a one meter rise would generally cause shores to erode 50 to 200 meters along sandy beaches, even if the visible portion of the beach is fairly steep.

5.1 Rise in sea levels

Global mean sea level has risen by 1.0-2.0 mm per year during this century (UKCIP, 2002). The sea-level rise relative to the land will be greater than the global average in southern and eastern UK because the land is sinking. On the other hand, land in northern England is rising due to the re-adjustment of land to de-glaciation following the last ice age and localized sediment consolidation due to land drainage.

In terms of climate change, the SRES scenarios translate into six greenhouse-gas emission marker scenarios including the A2, B1, B2, the A1 world –A1T (non-fossil fuel sources), A1B (balanced fuel sources) andA1FI (fossil-intensive fuel sources). B1 produces the lowest emissions and A1FI produces the highest emissions (Nicholls et al, 2007). In the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4), the best estimate of the global mean sea level rise scenarios based on thermal expansion and ice melt shows an acceleration of up to 2.4 times compared to the 20th century. The projections are in the range between 0.28 and 0.43 m for B1 and A1FI for the coming century. According to the IPCC, current model projections indicate substantial variability in future relative sea-level rise between different locations. Some locations could have a rise in relative sea level higher than the global average projections, while others could experience relative sea level fall.

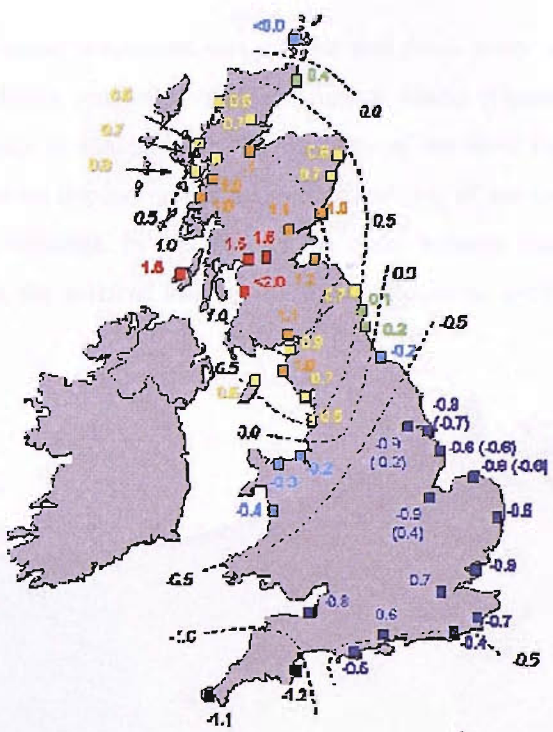


Figure 5.1: Late Holocene relative land/sea-level changes (mm/yr) in Great Britain (Positive values indicate relative land uplift or sea-level fall, negative values are relative land subsidence or sea-level rise) (Source: UKCIP, 2005)

Figure 5.1 illustrates the new estimates of relative land/sea-level changes (mm/yr) in Great Britain over the last few thousand years from UKCIP (2005) after Shennan and Horton (2002). The effects of sediment consolidation are not included. UKCIP (2005) concluded that net sea-level change relative to 1961-1990 for North West England under High Emission scenario in 2080s is +63 cm and under Low Emission scenario +3 cm; whereas, regional isostatic uplift in this area is 0.6 mm/year.

DEFRA guidelines conclude that an allowance of the design of any coastal defense schemes must be made for 4 mm per year of sea-level rise in the North West (Flood and Coastal Defense Project Appraisal Guidance No.3). However, the major threat for the next century is not change in the mean sea level, but rather the effect of climate change upon tidal surges, winds and storms. Climate change will affect sand dunes by changing sediment supply and through alterations in wind driven supply of sand (Atkins, 2002).

Sea-level rise will cause permanent loss of land and fresh water resource in coastal area and also accelerate sea water intrusion further inland (Figure 5.2). These will affect all living things in coastal zone. The impacts of sea-level rise on groundwater systems will depend on depend on the magnitude and rate of sea-level rise relative to changes in aquifer recharge. In this chapter the water balance model at Ainsdale is used to investigate the relative impacts of these effects on groundwater levels in coastal aquifers.

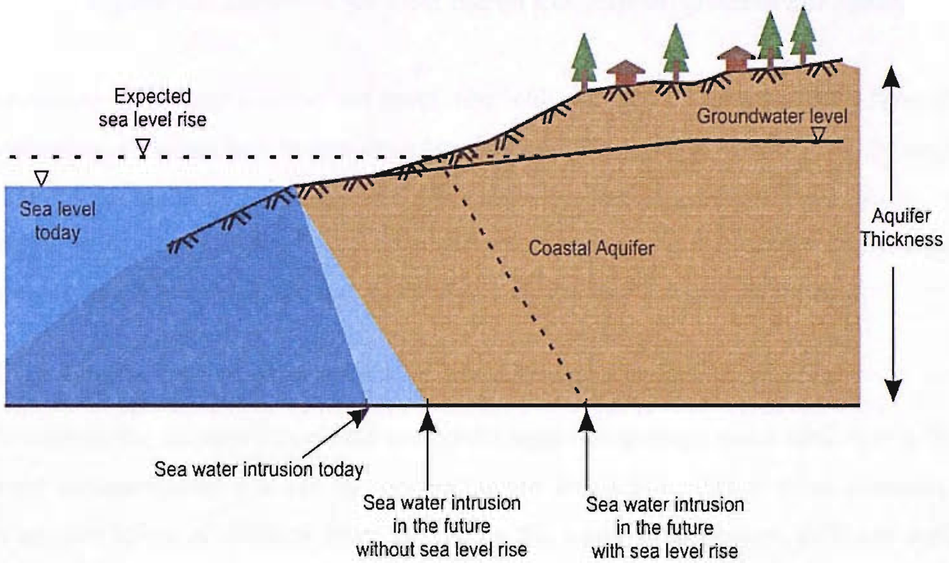


Figure 5.2: Seawater intrusion with and without sea-level rise in coastal aquifers to explore impact on sea-level rise on saline intrusion.

5.1.1 Effect of sea-level rise on the groundwater balance

This section will calculate predicted water table levels using the water balance model, and applying rising in sea level to investigate water table levels by reducing groundwater flow. Figure 5.3 illustrates the effects of sea-level rise on a conceptual model of the groundwater flow.

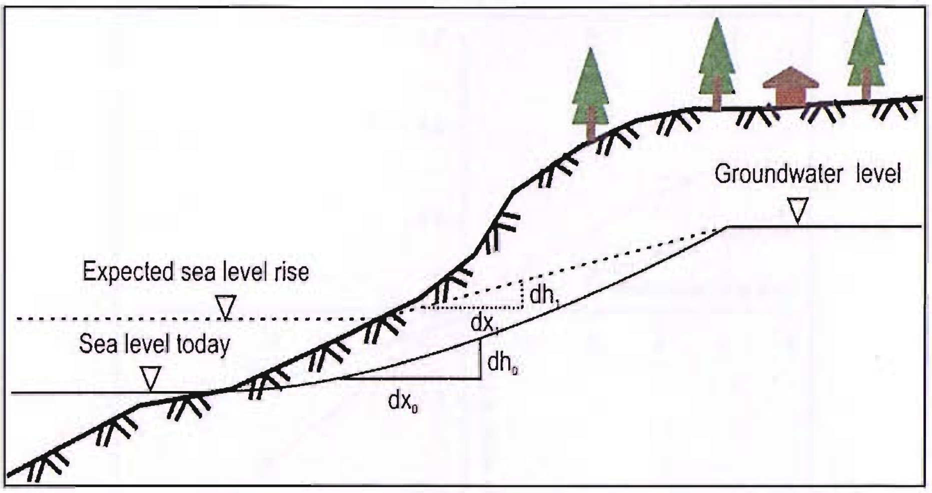


Figure 5.3: Effects of sea-level rise on a conceptual groundwater model

According to Darcy's Law, sea-level rise will impact on groundwater flow by decreasing *dh* which will in turn decrease the hydraulic gradient (*dh/dx*). As shown in Figure 5.3, expected sea-level rise will reduce hydraulic gradient from dh_0/dx_0 at present to be dh_1/dx_1 in the future. This will result in decrease in groundwater flow out from the system. As a result, the water table levels would be expected to rise.

5.1.2 Sensitivity of groundwater level change to sea level rise

To explore the impacts of extreme sea-level change on average water table levels, the water balance model was run by varying the sea levels from -5m to +5m. Moreover, to explore effect of distance from the sea on the water table change, different wells were simulated. The distance from the coast to Well 7 is approximately 750m; whereas, distance to Well 11 is farther inland (about 1450m).

Figure 5.4 shows the result of the impact of relative sea-level rise on average water table levels at Ainsdale. A rise in sea level causes an increase in water table levels and vice versa. Furthermore, wells closer to the coast show greater impacts from sea-level rise than those further away. For example, increasing sea-level about 1m will cause an average water table level rise of approximately 0.12m for well 11 and 0.28m for well 7. According to the UKCIP02 climate change scenario, the expected rise in sea level in 2080 will be about 63cm for northwest England. This affects modeled water table levels by about +18cm and +6cm for well 7 (750m from the sea) and well 11 (1450m from the sea), respectively.

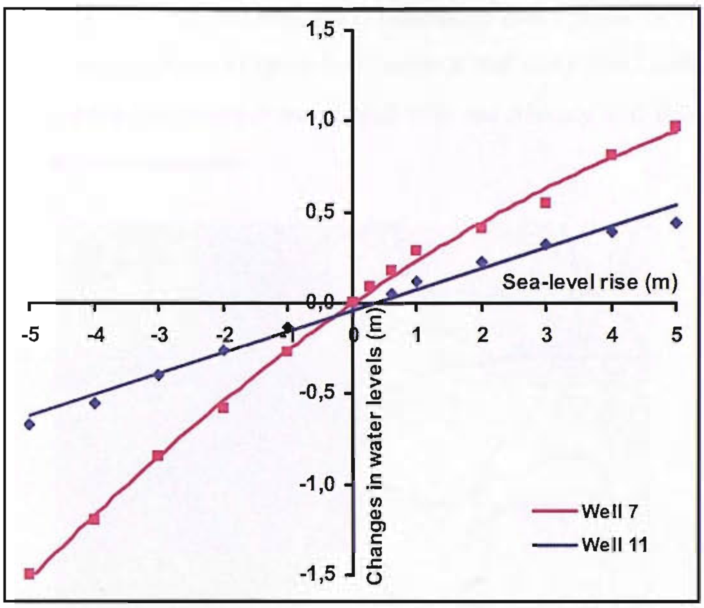


Figure 5.4: Impact of relative sea-level rise on average water table for well 7 and 11 based on the water balance model

Figure 5.4 shows that a rise in sea level will cause an increase in of water table levels and the greater the rate of sea-level rise, the greater change in water table levels. The water balance model shows that increasing mean sea level by +1, +2, and +3m causes the water table levels to rise by about 0.12, 0.22, and 0.32 m respectively.

5.2 Coastal erosion

The following section is a summary of the conclusions published by Atkins (2002) and Saye et al. (2005). It gives an overview of coastal erosion in NW England. The Sefton coast is located between the Mersey and Ribble estuaries in northwest England. The mean spring tidal range of the coast is approximately >8m. Tidal currents can be strong, and the coast is exposed to prevailing southwesterly and westerly winds. Wave climate is moderate (Saye et al., 2005). Storm surges of 2m or more can produce tidal levels in excess of 6.0m ODN, and storm waves combined with storm surges result in severe dune erosion (Pye, 1991).

The erosion occurring along most of the frontal dunes on the Reserve is caused by both natural and man induced marine processes. This is reducing the already narrow frontal dune area by around 1.5ha between 1996 and 2000 (Atkins, 2002), particularly at the southern end of the site. Atkins (2002) concluded that a phase of coastal erosion in the vicinity of Formby Point (Figure 5.5) began at the early 20th Century through a combination of human intervention associated with the Mersey and Ribble Estuaries and a change in storm conditions.

Figure 5.5: Formby Map

Saye et al. (2005) presented that changes in foreshore level and frontal dune erosion/accretion have been recorded since 1958 by measurements relative to fixed points. The frontal dune is accreting south of Formby point and erosion is occurring between Formby Point and south of Ainsdale, with the greatest recent loss to the frontal dunes occurring near Massam's slack. A second accreting section is between north of Ainsdale and Southport, and a transitional zone is identified between this section and the eroding section to the south (Saye et al., 2005).

Figure 5.6: Formby Map with erosion locations

As dune material is removed from Formby Point and deposited on the frontages to the north and south, the erosion of Formby Point is causing major coastline realignment and straightening. Erosion at Formby Point will cease or at least reduce significantly, and the dunes are likely to then stabilize. It should reach a position of natural equilibrium. Although erosion is still active at Formby Point, historically the annual rate of erosion has slowed and the system might be beginning to reach this equilibrium (Halcrow, 2002).The coastline between Sefton's Lifeboat Road car park and the National Trust Victoria Road car park (Figure 5.6) is expected to erode by approximately 150 metres by the year 2050. The coastline at North of Victoria Road is likely to erode up to 270 metres along the Formby Golf Club frontage. The "hinges" between erosion and accretion, located approximately at the

Formby/Ainsdale boundary 1200 metres north of Fishermans Path, are unlikely to change significantly. This represents a total loss of 91 hectares of land (Atkins, 2004).

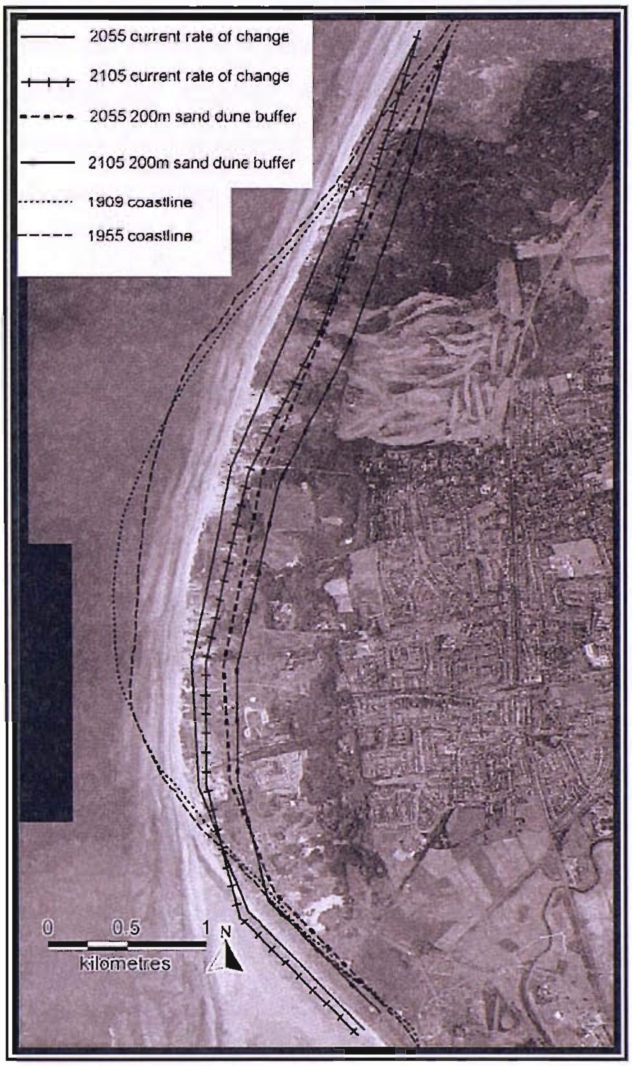


Figure 5.7: Estimated coastline by extrapolation of current trends
(Source: Lymbery et al, 2007)

Almost all of the land gained at Formby during the 18th century had been lost by erosion in the 19th century. It has been estimated that Formby Point lost 700m between 1920 and 1970 with the erosion front having already reached the southern boundary of the NNR by 1945. At this area, up to 200m of dunes were eroded during the next 35 years, and the width of the erosion front extended to 500m north of Fishermans Path. The Engineer and Surveyors Department Sefton MBC since 1958, measured the rate of erosion, and stated that the most rapid rates of erosion have been between Dale Slack Gutter and Fishermans Path, with more than 40m of erosion since 1981 (Atkins, 2002). Around 1900 erosion began at Formby Point and has continued to the present (Saye et al, 2005; Pye and Neal, 1994; Lymbery et al, 2007). The northern erosion limit has extended northwards towards Southport and now lies mid-way between Freshfield and Ainsdale. As a result of erosion, much of the dune frontage around Formby Point is scarped (Saye et al., 2005). Lymbery et al. (2007) presents estimated coastline in the future by extrapolation of current trends as shown in Figure 5.7.

5.2.1 Effect of coastal erosion on the water balance model

Coastal erosion can cause changes in groundwater flow and water table levels by changing the hydraulic gradient of the water table and increasing groundwater flow. Figure 5.8 illustrates the effects of coastal erosion.

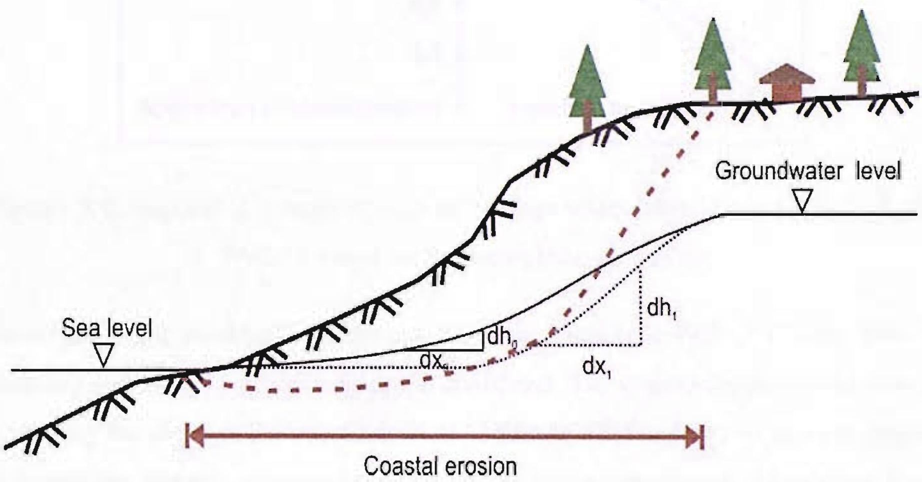


Figure 5.8: Effects of coastal erosion on the conceptual groundwater flow model.

Coastal erosion is expected to decrease *dx* in Darcy's Law from dx_0 at present to dx_1 in the future as shown in Figure 5.8. This will cause an increase in the hydraulic gradient (*dh/dx*) used in the groundwater flow calculations. As a result, groundwater flow out from the system will increase, causing the water table levels to lower.

5.2.2 Sensitivity of groundwater levels to coastal erosion

The water balance model was used to investigate the effect of different coastline erosion scenarios. These varied from -500m (i.e. erosion) to +500m (i.e. accretion) to explore the impacts of coastal erosion on average water table levels.

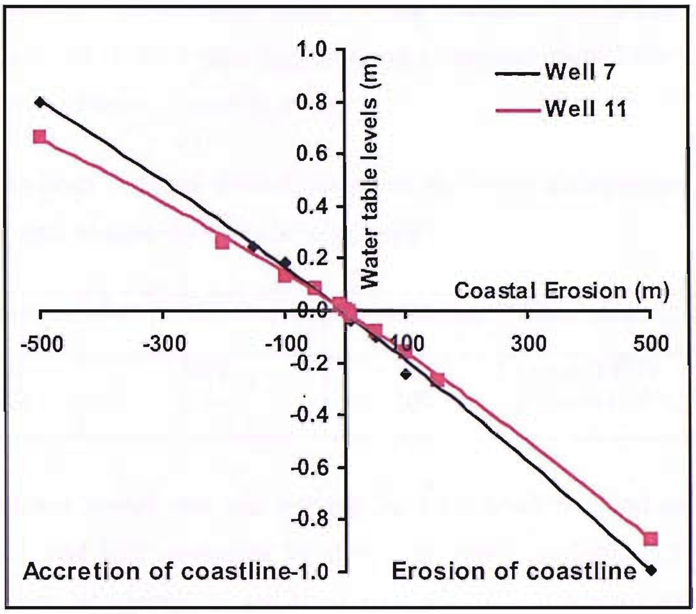


Figure 5.9: Impacts of coastal erosion on average water table levels for Well 7 and Well 11 based on the water balance model.

The effects were modeled at different distances inland, at Well 7 (750m from the coastline) and Well 11 (1550m from the coastline). The water balance model was run by varying the average the coastline from -500m to +500m from its present position to explore the impacts of coastal erosion and accretion on average water table levels. Erosion and accretion will vary along the coastline but the model results suggest that the effect will be to raise water table levels by +0.14m by every 100 meters of accretion and decrease it by 0.18m for every 100m of erosion (Figure 5.9). Furthermore, wells nearer to the sea show larger impacts from erosion and sea-level rise than those further inland.

5.3 Combined impact of sea-level rise and erosion on the water balance model

To investigate impact of climate change and coastal erosion on water table levels, the water balance model was run under different combinations of scenarios by varying sea-level rise and erosion shown in Table 5.1; for example, SE1 is that sea level was risen at 0.63m in 1975 for 1 year and returned to normal since 1976 together with coastal erosion at 100m for 1 year in 1975.

Table 5.1: Sea-level rise and erosion scenarios for investigating impact of climate change and coastal erosion on water balance model

Scenarios	Sea-level rise (m)	Erosion (m)	Time taken (years)
SE1	0.63	100	1 year (1975)
SE2	0.63	100	27 years (1975-2001)

The water balance model was run varying both sea-level rise and coastal erosion scenarios (SE1 and SE2 scenarios as shown in detail in Table 5.1) together to investigate effects of change in sea level and erosion on groundwater levels. The result for SE1 and SE2 scenarios were shown in Figure 5.10. Impacts of 0.63m sea-level rise and 100m erosion occurring instantaneously in 1975 on the water balance model (SE1) are shown in Figure 5.10 (a). This indicates that the groundwater level would fall slightly for about 3-4 years and it then returns back to levels similar to those at present. In the SE2 scenario, which explores effects of changes in sea-level rise (0.63m) and coastal erosion (100m) extended over a long time period (1975-2001). In this case the groundwater level is expected to decline by up to 40cm.

(a)

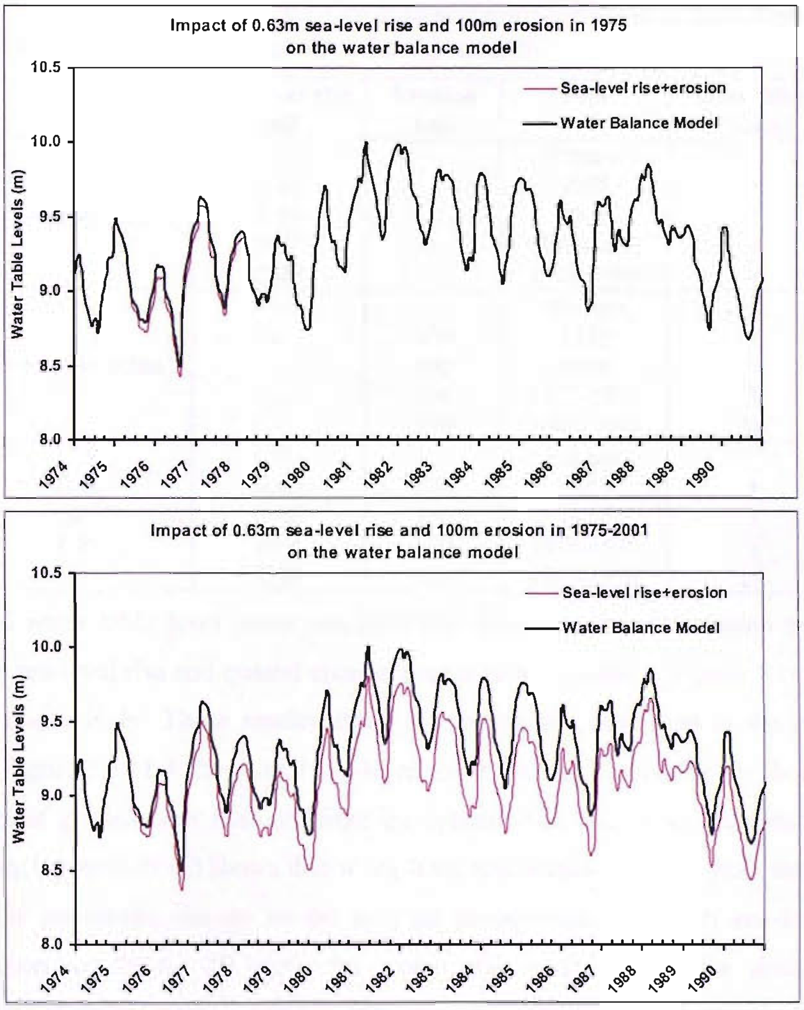


Figure 5.10: Effects of change in sea-level rise and coastal erosion on the Well 11 model (a) scenario SE1 (b) scenario SE2

To evaluate the effects of coastal erosion and the uncertainty in their magnitude, the water balance model was re- run in a Monte Carlo simulation of several hundred combinations of sea level rise and coastal erosion patterns. The selected scenarios of sea-level rise and coastal erosion are shown in Table 5.2. Rainfall and evapotranspiration were assigned a normal probability distribution. The, mean and standard deviation of rainfall (73±30mm/month) and evapotranspiration (41±6mm/month) were estimated from observed data 1972-2002. Other parameters such as hydraulic conductivity and crop coefficient were held constant to consider only the variations of sea-level rise and coastal erosion. The results are shown in Figure 5.11.

Table 5.2: Sea-level rise and coastal erosion scenarios for running the water balance model using Monte Carlo simulation in the Crystal Ball

Scenarios	Sea-level rise (m)	Erosion (m)	Year	Time taken (years)
Sea-level rise	-	-	Present	
	0.63	-	1975	1
	2.00	-	1976	1
	0.63	-	1977-1979	3
	2.00	-	1980-1999	20
Coastal Erosion	-	-	Present	
	-	100	1975	1
	-	300	1976	1
	-	100	1977-1979	3
	-	100	1980-1999	20
SLR & CE	-	-	Present	
	0.63	100	1975	1
	2.00	300	1976	1
	0.63	100	1977-1979	3
	2.00	100	1980-1999	20

Expected water table level under sea-level rise scenarios, coastal erosion scenarios and both sea-level rise and coastal erosion scenarios are shown in Figure 5.11 (a), (b) and (c) respectively. These results agree wit the pattern discussed in the previous section. Figure 5.11 (a) shows that sea-level rise increases water table levels due to a reduction of groundwater flow out from the system. The rate of sea-level rise is also important. Figure 5.11 (a) shows that if sea-level rise occurs in only 1 year, there is no immediate noticeable change in the average groundwater levels. If sea-level rise occurs continuously for 20 years, the water table levels would rise about 0.5m. Conversely, coastal erosion causes a reduction of water table levels. Figure 5.11 (b) shows that the water table levels would drop by 30cm (100m of erosion) and by 1m (300m erosion) in 1 year. With coastal erosion occurring over an extended time scale (3 years or 20 years) the water levels would drop by 60cm and 80cm respectively. These results show that both magnitude and rate of coastal erosion influences groundwater levels. Figure 5.11 (c) shows expected water table levels caused by sea-level rise combined with erosion. Both the scale and magnitude of sea-level rise and coastal erosion are important factors, but when they occur in combination it is difficult to distinguish which factor is the more important. The following section compares the relative importance of erosion and sea level rise with the other key variables that affect groundwater recharge.

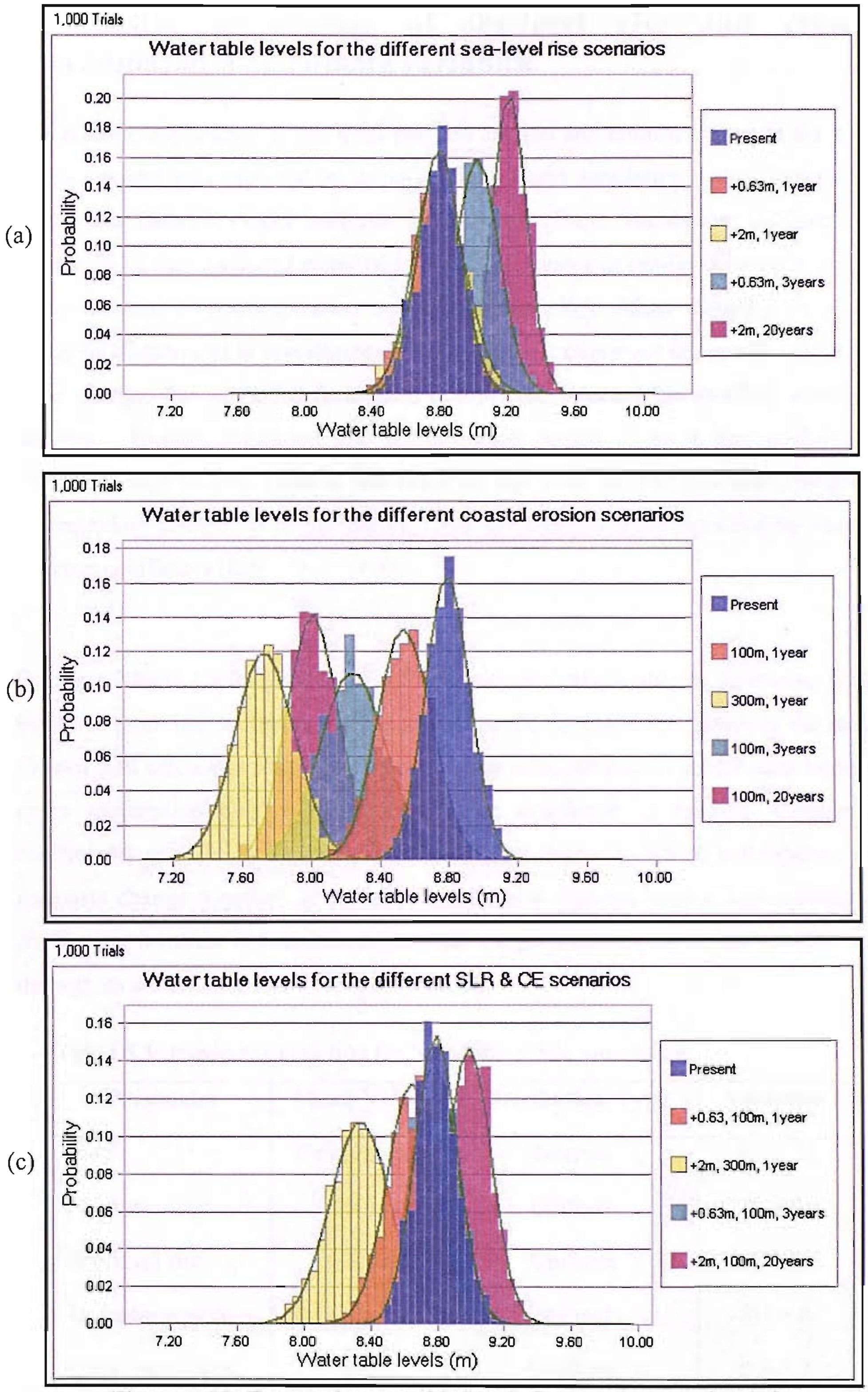


Figure 5.11: Expected water table levels from various sea-level rise and coastal erosion scenarios (Well 11)

5.4 Relative importance of sea-level rise and erosion compared with climate variables

The relative importance of sea-level rise and erosion and climate effects in the water balance model was explored by using a Monte Carlo simulation using Crystal Ball. The water balance model was run 1000 times. These simulations explored the sensitivity of the calculated water table levels to changes in sea-level, rainfall, coastal erosion, actual evapotranspiration, and crop factors (*Kc*). Many variables were used in the simulation and to investigate which is the most important factor affecting water table change, key variables from each group were selected for detailed sensitivity analysis. Evapotranspiration and rainfall were chosen to be a representative of climate change factors. Erosion and sea-level rise were used to simulate changes in the boundary conditions of the model. Land use changes were modelled by varying the crop coefficient (*Kc*)

During a Monte Carlo simulation, a Sensitivity analysis is able to determine which variables (and their assumed uncertainty) influence the calculated forecasts the most.. Crystal Ball calculates sensitivity by computing rank correlation coefficients between every assumption and every forecast while simulation is running. Correlation coefficients provide an important measure of the degree to which assumptions and forecasts change together. If an assumption and a forecast have a high correlation coefficient, it means that the assumption has a significant impact on the forecast both through its uncertainty and its model sensitivity.

Table 5.3: Parameter variation for the Monte Carlo simulation

Parameter	Mean Value	Distribution Type	Variation
Rain	73mm/month	Normal	SD = 30
Erosion	100m	Uniform	50-300m
Sea-level rise	0.63m	Uniform	0.1-2.0m
Evapotranspiration	41mm/month	Normal	SD = 6
Crop coefficient	0.9	Uniform	0.5-1.2

Table 5.3 lists the decision variables used in the Monte Carlo sensitivity analysis. Sea-level rise was varied from 0.10m to 2.0m, and coastal erosion was varied from 50m to 300m. Crop coefficients (*Kc*) was varied by using extreme values varying from 0.5 to 1.2, evolving from bare soil up to full tree cover.

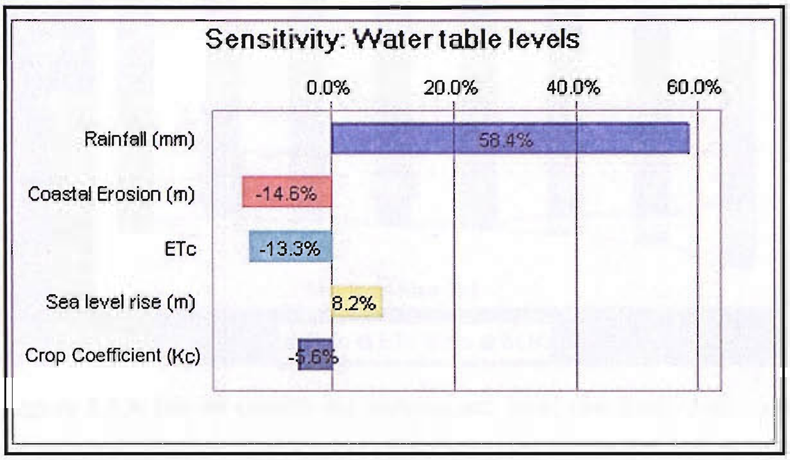


Figure 5.12: Sensitivity of simulated groundwater levels to changes in rainfall, coastal erosion, *ETc*, sea-level rise, and *Kc* (Well 11)

The results are shown in the Tornado chart (Figure 5.12). The simulation indicates that shows that rainfall has the largest effect on the modeled water table levels (accounting for to 58.4% of the model variability). The other variables had a smaller impact: *ETc*, sea-level rise and *Kc* (-14.6%, -13.3%, 8.2% and, -5.6% respectively). Positive values in Figure 5.16 indicate that an increase in the assumption is associated with an increase in the forecast; for example, an increase in rainfall and sea-level rise will raise the water table levels and water levels will drop when coastal erosion, evapotranspiration and crop coefficient increase. However, the sensitivity of the water table levels depends on the rate of change of the parameters; for example, if coastal erosion increases, erosion will become the most sensitive parameter in the modeled water table levels.

Figure 5.13 shows the sensitivity of various sea-level rises on the modeled water table levels. This indicates that sea-level rise has small effect on the water table levels compared with rainfall, and evapotranspiration. The expected sea-level rise from UKCIP climate change scenarios in 2080 is about +63cm, but this rise in sea level will not significantly affect the water table levels as much as changes in rainfall, evapotranspiration, and vegetation type.

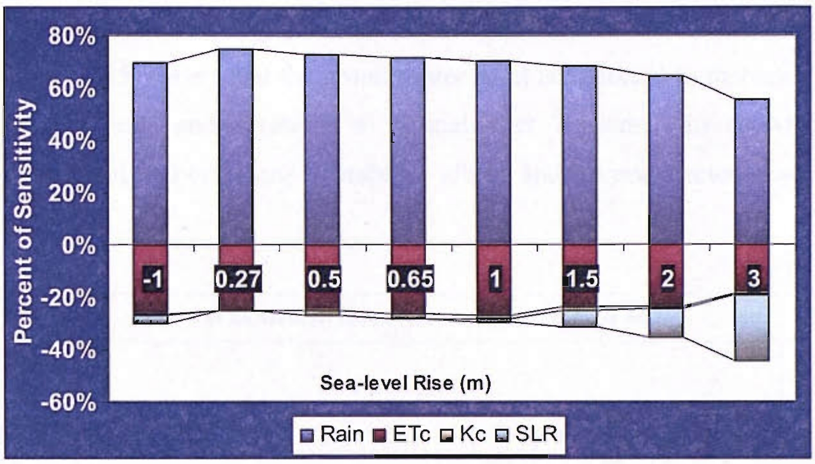


Figure 5.13: Model sensitivity: varying sea-level rise from -1 to +3m

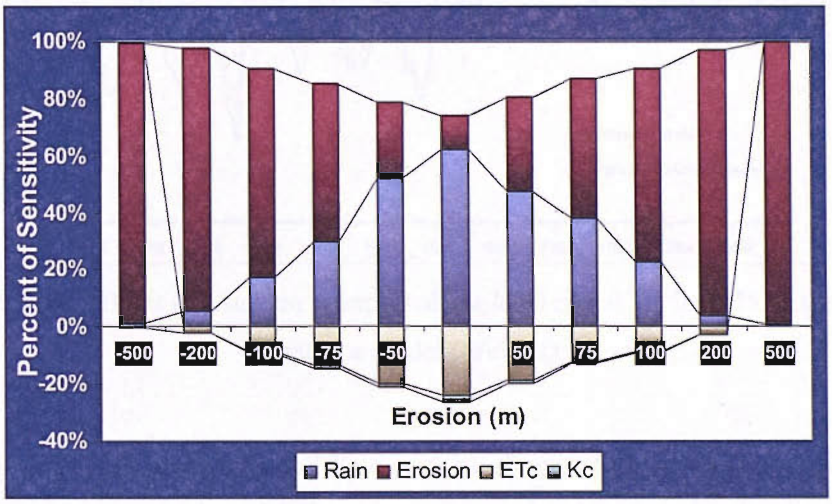


Figure 5.14: Model sensitivity: varying coastal erosion from -500m to +500m

The sensitivity of the impact of erosion on the water table levels is shown in Figure 5.14. By changing the coastline by 500m of accretion to 500m of erosion, the simulation indicates that the magnitude of the effect on modeled water table levels changes in time. Rainfall variability is more important than erosion when erosion is <75m, but after about 100m of erosion the effects becomes significant.

5.5 Response to a sudden unexpected rise in sea level

To investigate response of the water balance model to a sudden unexpected sea-level rise, the model was run using a sudden +2m sea-level rise for 1 year in 1975. The result (Figure 5.15) shows that the groundwater level is expected to increase by up to 40cm for few years and it returns to normal after 7 years. This shows that the groundwater level will take time to stabilize after a sudden unexpected sea-level rise such as tsunamis.

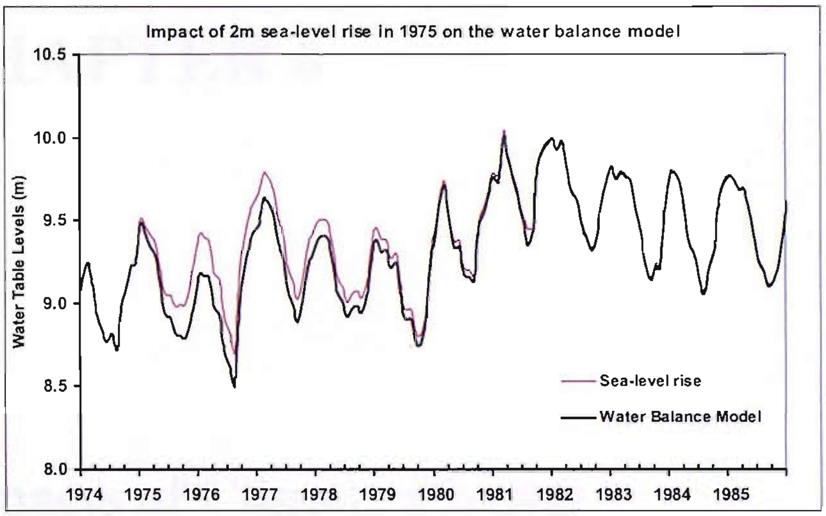


Figure 5.15: Effects of a sudden unexpected sea-level rise at 2m in 1975 on the water balance model (Well 11)

In conclusion, the magnitude and time interval of coastal erosion and sea-level rise have variable magnitudes of influence on the modeled water table levels. Coastal impacts on the water table level more than sea-level rise. However these effects are cross-linked, for example, a rise in sea level is one of the causes of coastal erosion. From the sensitivity analysis, the most important factors which affect the water table levels are rainfall and erosion depending on the magnitude of coastal erosion. The next most important factors are actual evapotranspiration, sea-level rise, and crop factors respectively.

CHAPTER 6

Impacts of Climate Change

To investigate impacts of climate change on unconfined coastal groundwater systems, the water balance model developed in Chapter 4 was run using daily weather data for the period 2011-2100. The data was synthetically generated to replicate anticipated UKCIP02 climate scenarios. This chapter will give an overview of the data characteristics and how it was used to explore multiple future weather scenarios using a Monte Carlo Simulation. The ranges of impact of climate change on the coastal aquifer at Ainsdale are described.

6.1 Assembling future weather data time series

The water balance model had been successfully calibrated by parameter estimation against observed well data for 1972-2001. Predicted climatic data were needed to simulate the water table levels for future time periods over the next century. Future climate change datasets were collected from various sources (UKCIP and BETWIXT project) as described in Chapter 2 and Chapter 3.

6.1.1 UKCIP climate change scenarios

The UK Climate Impacts Programme (UKCIP) funded by the Department for Environment, Food and Rural Affairs presents a set of four climate change scenarios for the UK based on current understanding of the science of climate change (UKCIP, 2002). The UKCIP02 scenarios are based on new global emissions scenarios published in 2000 by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emission Scenarios (SRES) and the 2001 IPCC Assessment (UKCIP, 2002). Each scenario is based on a different set of assumptions about how the world develops; therefore, no single set of scenarios can satisfy all needs, nor completely reflect all the uncertainties affecting future climate. The Medium-High Emission scenario was chosen to be a representative scenario in the research as described in Chapter 3. The Medium-High Emissions of the UKCIP02 climate change scenario relates to A2 Storyline of IPCC SRES which is described as self-reliance, preservation of local identities, continuously increasing population and economic growth on regional scales (UKCIP, 2002).

The raw data for use in climate impacts studies were accessed via the UKCIP website at *www. ukcip.org.uk/scenarios/*. Completion of a license form was needed to access the UKCIP data. Most of data available via the website are monitored climate data set at 50 km resolution for the UK. Ainsdale Sand Dunes NNR locates in the UKCIP grid square 294. The obtained UKCIP climate data file contains monthly and seasonal average climatic variables with respect to simulated 1961~90 average, simulated by HadRM3 with SRES (Medium-High) emissions scenario. Average rainfall at Ainsdale obtained from the UKCIP website for 3 future time steps is shown in Figure 6.1. Other climatic data such as temperature, humidity, wind speed and sunshine hour from the UKCIP were used to estimate evapotranspiration. The results are shown in Figure 6.2 and Figure 6.3.

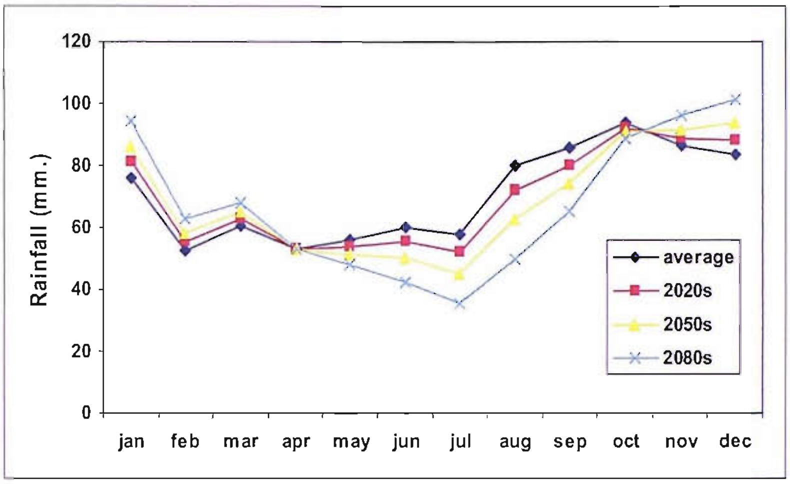


Figure 6.1: Average rainfall at Ainsdale region for 2020s, 2050s, and 2080s compared with average rainfall from 1972-2001

Figure 6.1 illustrates the predicted rainfall at Ainsdale NNR for 3 future time steps (2020s, 2050s, and 2080s) compared with average rainfall from 1972-2001. Average rainfall from May to October decreases considerably for all time steps, but rainfall increases slightly from November to March. These results correspond with the UKCIP (2002) report that states that summers will become drier and winters will become wetter.

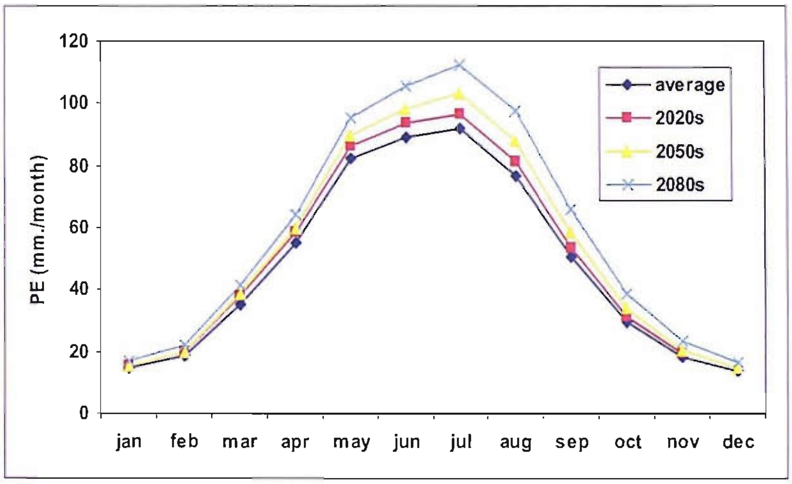


Figure 6.2: Average potential evapotranspiration at Ainsdale region for 2020s, 2050s, and 2080s compared with average *PET* in 1972-2001

Figure 6.2 shows calculate reference potential evapotranspiration rate for the 2020s, 2050s, and 2080s time steps compared to average reference potential evapotranspiration from 1972-2001. Average reference potential evapotranspiration rate rises in all time steps. The highest increase is in June, July and August. Predicted average actual evapotranspiration rates for a grass surface at Ainsdale for the 2020s, 2050s, and 2080s are presented in Figure 6.3. Rates of *AET* decline noticeably in June, July and August compared with the *PET* data. In contrast, *AET* for grass at Ainsdale increase slightly from October to April because hotter climate creates higher *ET* when the soil is still damp.

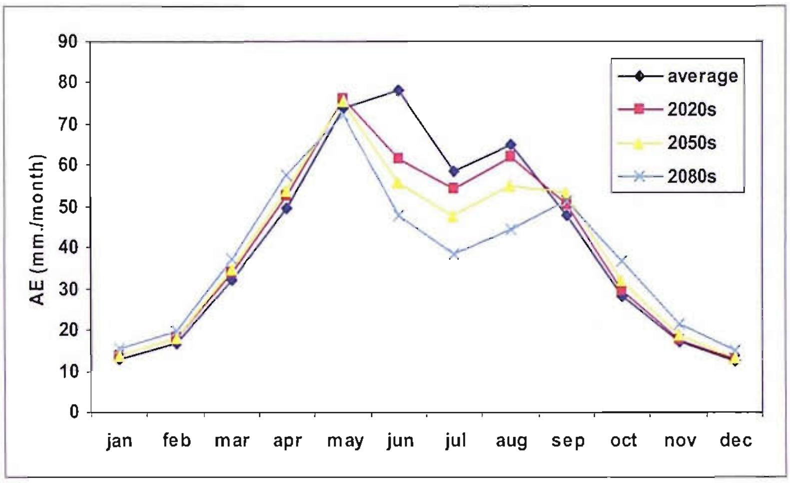


Figure 6.3: Average actual evapotranspiration rates for 2020s, 2050s, and 2080s compare with average *AET* in 1972-2001

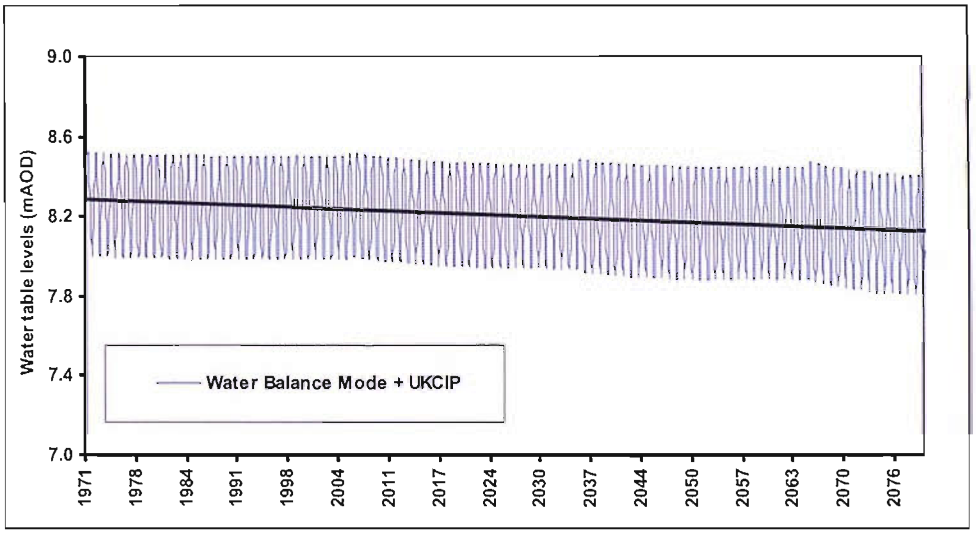


Figure 6.4: The water balance model for well 11 based on repeated years of average climate datasets from the Medium-High Emission of the UKCIP02 climate change scenarios

Future daily climatic data was derived from UKCIP monthly data by interpolation of the average climate datasets for 2020s, 2050s, and 2080s based on the UKCIP02 Medium-High Emission scenario. These data provided an "average year" for each of the three time sets. As a starting point, these were used in the water balance model by running 30 year blocks of average daily climate. Results shown in Figure 6.4 suggest that the predicted water table levels decrease continuously. The fall may possibly be caused by an increase in potential evapotranspiration and a decrease in summer rainfall. However, the simulation is based on repeated sequences of rainfall and other climatic patterns for each time step.

This model run fails to show the year to year variability shown in observed data. A more realistic approach requires a time-series of rainfall and meteorological data. Although the UKCIP02 scenario is one of the most recent, detailed and reliable climate scenarios for the UK, rainfall and climatic data are not easily available in time series format. However, the Climatic Research Unit (CRU) weather generator (part of the BETWIXT project) is a useful source of synthetically generated time-series of rainfall and climatic datasets (BETWIXT, 2005).

6.1.2 The BETWIXT project and datasets

Daily time-series output from the CRU weather generator for 11 UK sites were downloaded from the BETWIXT project website (BETWIXT, 2005). The time series are consistent with the UKCIP02 scenarios. Output is available for the '1970s' control period (i.e. 1961-1990), the '2020s' (i.e. 2011-2040), the '2050s' (i.e. 2041-2070) and the '2080s' (i.e. 2071-2100) for the Low, Medium-Low, Medium-High and High emissions scenarios. Each time-series file contains 30 years of simulated daily data for eight variables:

- RN: precipitation in mm
- TN and TX: minimum and maximum temperature in degrees Celsius
- RH: relative humidity in %
- WN: wind speed in ms^{-1}
- SS: sunshine in hours

Time-series data at Ringway site for the Medium-High emission scenario were chosen to be the representative climate change datasets for the Ainsdale region. Ringway is near Manchester, about 50km SE of Ainsdale. Scaled monthly rainfall data generated from the BETWIXT project for Ainsdale are shown in Figure 6.5. The Ringway data including rainfall, temperature, humidity, wind speed and sunshine hour were scaled to Ainsdale by evaluation of the 1961-1990 data.

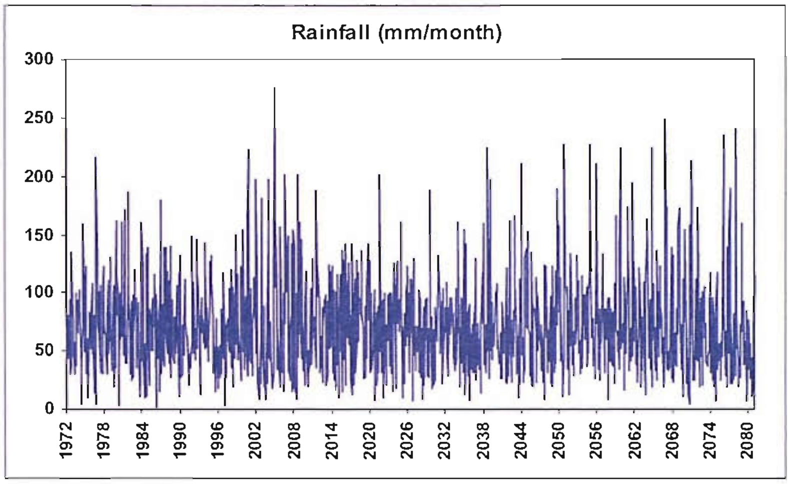


Figure 6.5: Observed rainfall at Ainsdale (1972-2007) and scaled synthetic rainfall data based on the BETWIXT Ringway dataset (2008-2085)

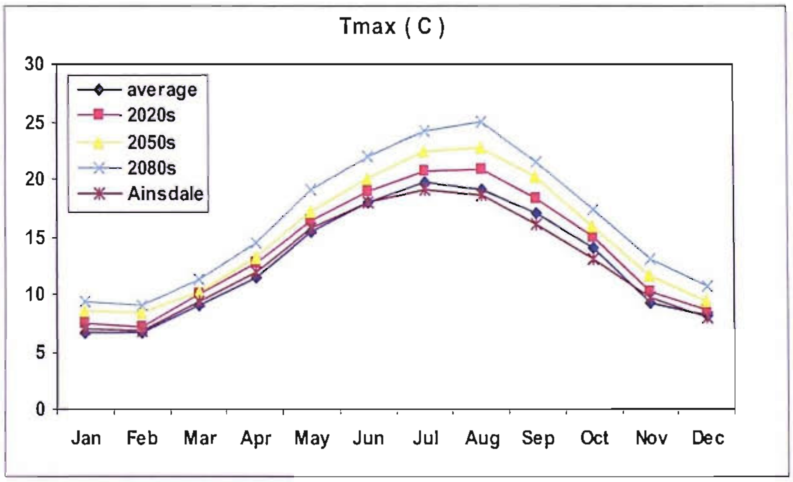


Figure 6.6: Scaled Ringway maximum temperature ("average") compared with average maximum temperature at Ainsdale 1972-2001

The synthetically generated meteorological datasets for Ringway station from the BETWIXT project were also used to estimate future evapotranspiration. The average maximum and minimum temperature for 1961-1990 were scaled against observations at Ainsdale and the scaling was applied to the synthetic data for, 2020s, 2050s, and 2080s. Figures 6.6 and 6.7s show that the scaling matched the historical data well.

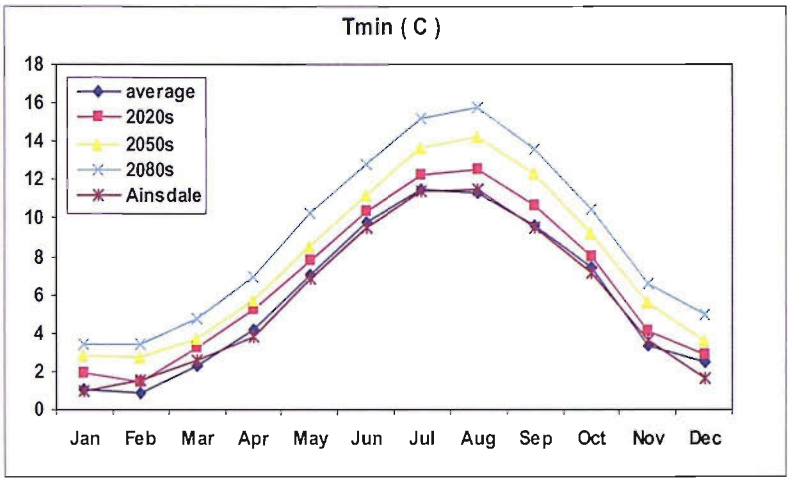


Figure 6.7: Scaled Ringway minimum temperature ("average") compared with observed minimum temperatures at Ainsdale (1972-2001)

6.1.3 Calculating *PET* and *AET* for Ainsdale based on BETWIXT data

Potential evapotranspiration and actual evapotranspiration are the major components of the water balance model. To construct the model, *PET* and *AET* were calculated based on the scaled BETWIXT climatic data.

Figure 6.8 and Figure 6.9 illustrate average *PET* and *AET* respectively for the 3 future time steps compared with the averages at Ainsdale. The graphs show that *PET* rises slightly for 2020s and 2050s, but *PET* increases considerably in the 2080s. Moreover, average *PET* based on the BETWIXT data are almost the same as average *PET* calculated using the Ainsdale data. In contrast, the patterns of predicted *AET* are nearly the same as the UKCIP *AET* patterns in Figure 6.3. Figure 6.10 shows the time series of monthly *PET* and *AET* at Ainsdale based on BETWIXT data from 1972-2080 that will be used in the water balance model.

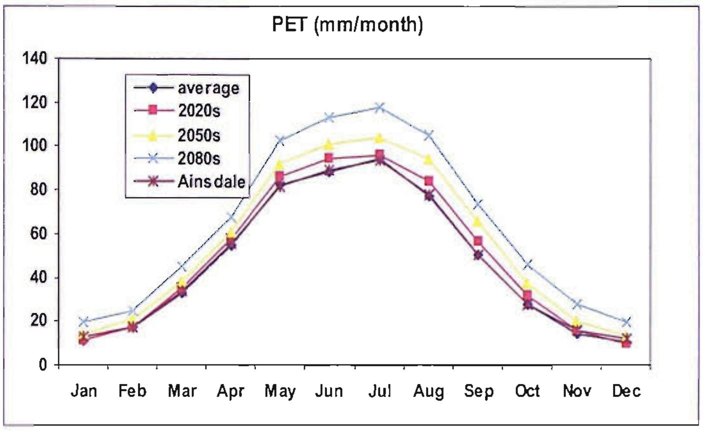


Figure 6.8: Potential evapotranspiration based on scaled BETWIXT data ("average") compared with average *PET* at Ainsdale 1972-2001

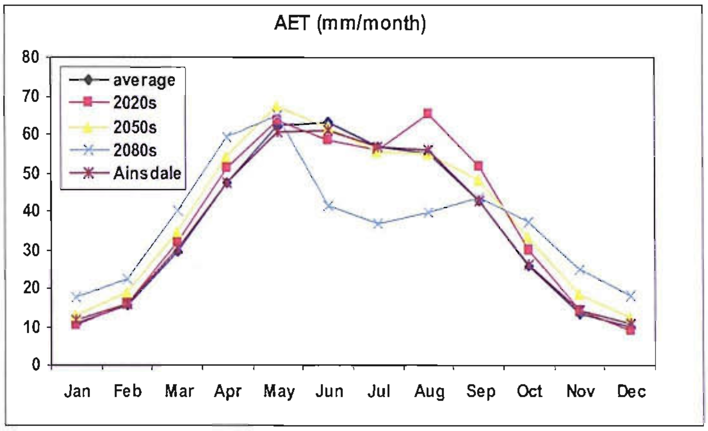


Figure 6.9: Actual evapotranspiration calculated using scaled BETWIXT data compared with average *AET* at Ainsdale 1972-2001

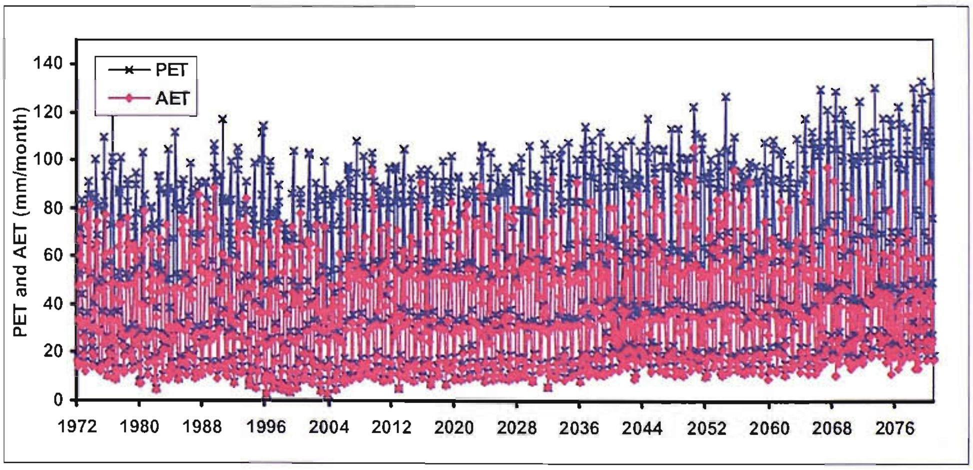


Figure 6.10: Combined sequence of Monthly *PET* and *AET* at Ainsdale 1972-2080

6.1.4 Model runs with BETWIXT data modified for Ainsdale

The predicted water balance for future time steps based on BETWIXT time series data modified for Ainsdale was constructed. The model was run with the original assembly of the BETWIXT time series data and the result is shown in Figure 6.11, which illustrates predicted water table levels for Ainsdale from 2007 to 2095.

The model was run on a daily basis between 2007 and 2095. Key findings are that on average, hot dry summers will cause a reduction in total evapotranspiration due to soil moisture deficit and that wetter winters will cause an increased range of amplitude of water table levels. Moreover, it was found that unusual wet months will recharge the aquifer quickly. It is important to note that this simulation is based on one sequence of rainfall patterns and that although the CRU weather generator provides a plausible sequence of rainfalls, the actual patterns and sequences of wet and dry days may not follow the series in the synthetically generated data set used in this simulation.

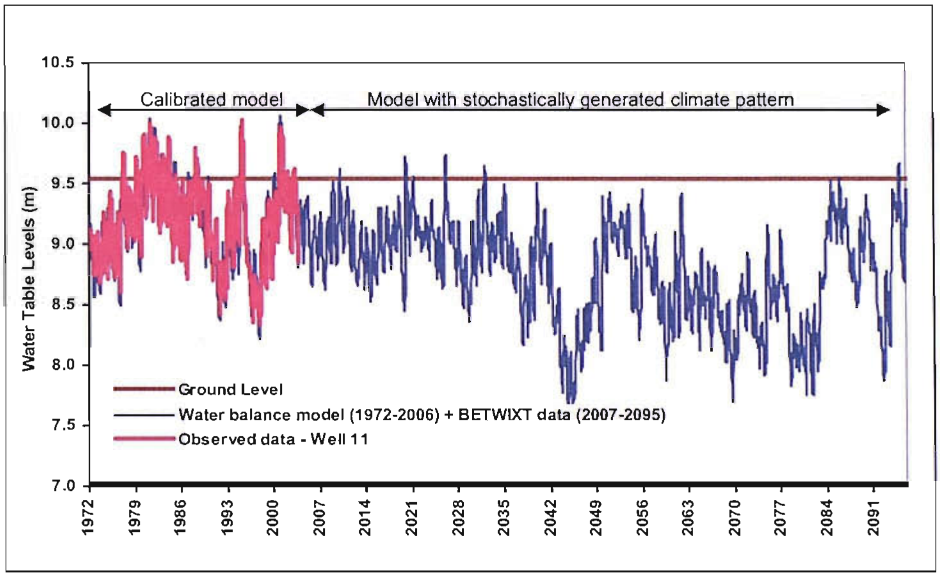


Figure 6.11: The water balance model for well 11: with BETWIXT data (2007-2095) modified for Ainsdale

In a similar manner to Figure 6.4, this simulation shows that the average water table levels in the open dunes near Well 11 are expected to fall. However, the BETWIXT simulation shows that there can be sequences of several years of much lower or higher than average water table conditions; for example, 2037-2045 shows a steep decline in predicted water levels, but this is followed by a series of wet years. This indicates that the timing of the rainfall is important in the calculated water table levels.

The simulations results shown in Figure 6.11, is only one of many possible scenarios because the pattern of rainfall, used in the simulation, was generated by a stochastic model. Testing has shown that the model and aquifer recharge is very sensitive to when the rain falls, and it is important to understand that the BETWIXT data set, provided by UKCIP, contains only one of many possible data sequences of rainfall patterns. It was decided to run the model based on BETWIXT data with varying timings of rainfall events, because the response of the water table is very sensitive to the timing of rainfall

6.2 Effects of climate data sequencing

The water balance model simulation in Figure 6.11 is based on only one sequence of future weather patterns. It was found from the historical data the inter-annual variations in *PET* were quite small (typically <5%), whereas variations in rainfall were much greater and these variations in rainfall had a significant impact on calculated values of *AET*. A better understanding of the effects of differing sequences of rainfall and actual evapotranspiration can be obtained by re-running the water balance model for the future climate conditions with different sequences of synthetically generated data.

A Monte Carlo modelling approach was chosen to create new sequences of climate data for the water balance model by re-sequencing the (scaled) BETWIXT data. This approach was chosen as it ensured that each run of the model contained exactly the same amount of rainfall and climatic data values used to estimate PET, as opposed to re-generating new synthetic data series.

The original BETWIXT data was assembled into months, and then new sequences of months of data were created by adopting a randomized sampling strategy. This ensured that the total amount of rain in each simulation was constant, but the timing was changed in each run. Figure 6.12 shows an example of the rainfall sampling algorithm used for the 2050's BETWIXT dataset. Between the years 2036-2065, there are 30 sets of rainfall data in each month; for example January. These sets were re-assembled randomly to create a new sequences of January rain and each January rain was used only once in the new sequence. Therefore, the total rain over the 30 years is the same as original data but the timing of the rainfall is changed.

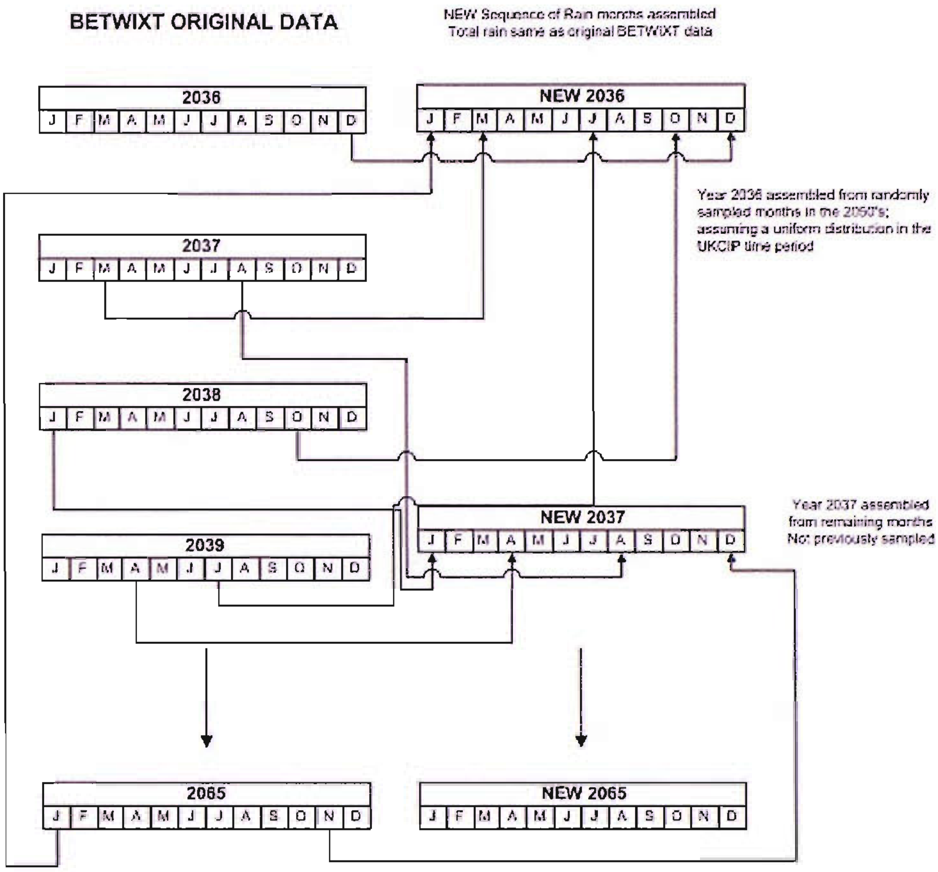


Figure 6.12: Example diagram of rainfall sampling

Typical results of the water balance model using this random sampling strategy are shown in Figure 6.13. The three examples demonstrate the impact of re-sequencing rainfall and PET data, despite the totals remaining constant. At one extreme, the predicted pattern of water table levels remains almost horizontal and at the other there is a near catastrophic fall in simulated water table levels. The central simulation (a small but continuous fall in water table levels) was the most frequent pattern found in the random sampling simulations.

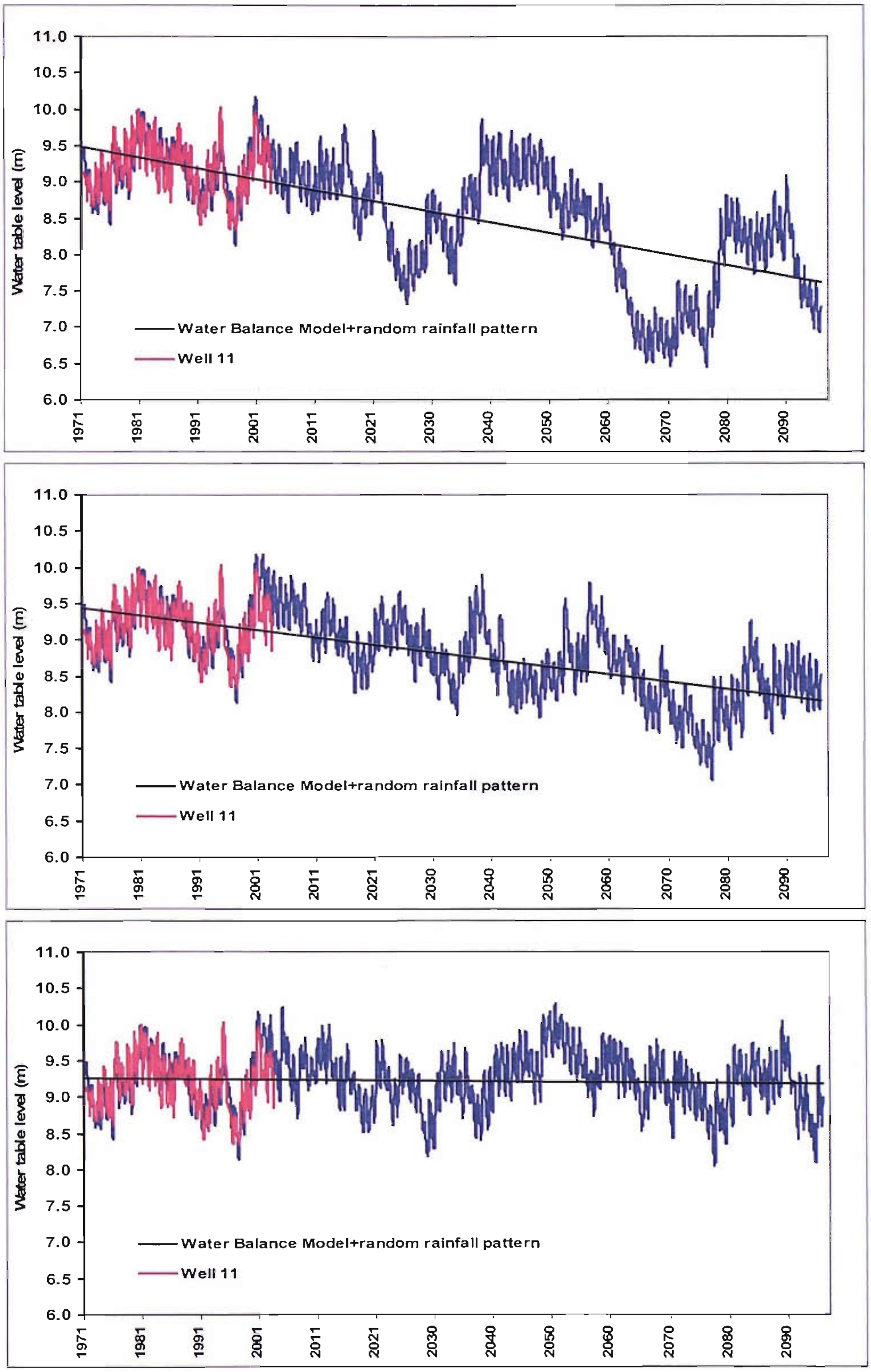


Figure 6.13: Three water balance models with random sampling runs: Based on BETWIXT datasets

The differing behaviors of the simulations can be understood in the following example; if 100mm of rain occurred in one month such as June when PET was 3mm/day and all 100m of rain the rain fell on 1st June, then 97mm of rain would recharge the soil/water table and only 3mm would evaporate on that day. This 97mm would probably reduce the SMD to zero and cause water to percolate vertically to the water table and recharge the aquifer. For the rest of the month the AET would come from the soil water store and AE would depend on the SMD, so it would be at most 29 days with 3mm/day which is about 87mm PET and quite likely it will be much less because the soil will have dried out. Conversely, if the same 100mm of rain fell in June at a constant rate, there would be 30 days with rain =3.33mm/day. If again the PET is 3mm/day, then in each day 3mm would evaporate and only 0.33mm/day would infiltrate to the soil/water table. Therefore, soil water recharge would be at most 9.9mm (30days x 0.33mm) for the whole month. If the SMD was zero then the water table would receive 9.9mm but in the month of June it is probably already partly dry so there is likely to be no recharge at all to the water table.

In reality, the likely true pattern of rainfall will be somewhere between those two extremes, but obviously the amount of rain falling in a day and the number of dry days between rain storms will affect soil water (hence SMD and *AET*) and also the water table recharge. By running the Monte Carlo simulations of differing timings of rainfall events, it was possible to evaluate the effects of different timings on the overall water balance simulation.

The water balance model simulation was run many times to investigate the range of impact of climate data sequencing. At first short sun of 50 sets of re-sampled data were investigated, but it was found that the mean predicted water table level results converged to less than 1% variability after about 150 simulations. The variability of the uncertainty around the mean predicted drawdown converged after 500 runs, but to ensure the stability of the results the simulations were eventually run 1000 times.

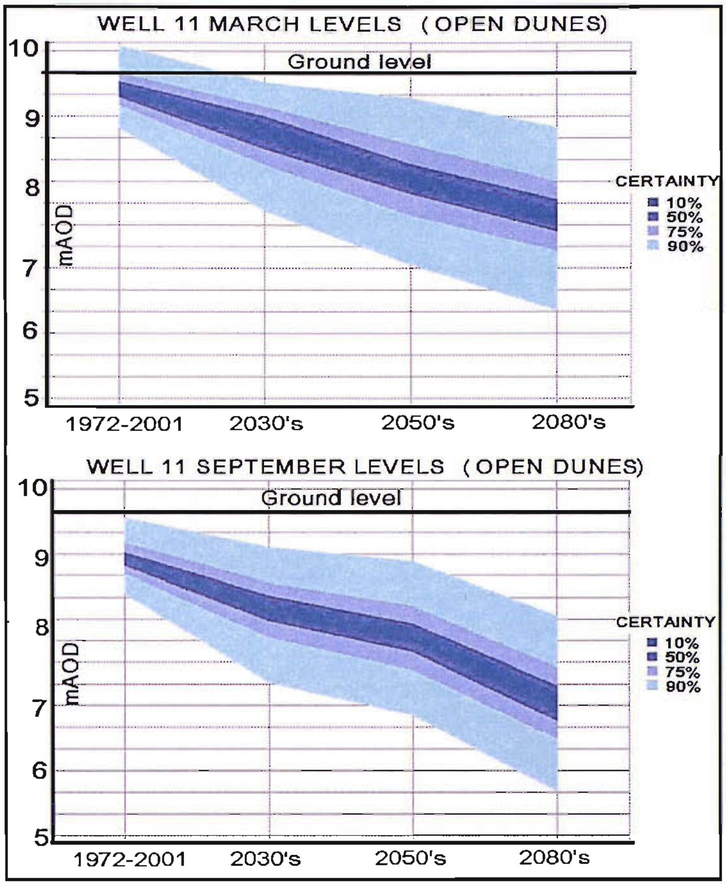


Figure 6.14: Time series plot of expected average water table levels at the end of winter and summer.

Each run of the model was equally likely to happen so a statistical analysis of the 1000 runs was carried out. The results of expected average water table levels at the end of winter and summer are presented as a time series plot in Figure 6.14. The charts show that the average water table level will fall from approximately +9.3m to +8.0m for wet conditions in March and from about +8.9m to +7.2m for dry conditions in September between now and the 2080's.

The likely ranges of change in water table levels from 1972 – 2080's for wet conditions in March and dry conditions at the end of the summer (September) for well 11 are shown in Figure 6.15. The overall pattern is a lowering of the water table levels with time, but also greater variability in these levels. The frequency plot in Figure 6.15 shows the same information as Figure 6.14 indicating that the predicted average water table level will fall more than 1m for wet conditions in March between now and the 2080's. This will affect both the vegetation and the wildlife in the sand dune system. These results suggest that there are likely to be significant changes in the eco-hydrological characteristics of the dune systems, especially in the dune slack areas which are of high bio diversity (Davy et al, 2006). As a result, it is expected that the inland slack floors at Ainsdale will gradually dry out and will be damp rarely, suggesting that species dependent on standing water for breeding (such as the Natterjack Toad) will become threatened.

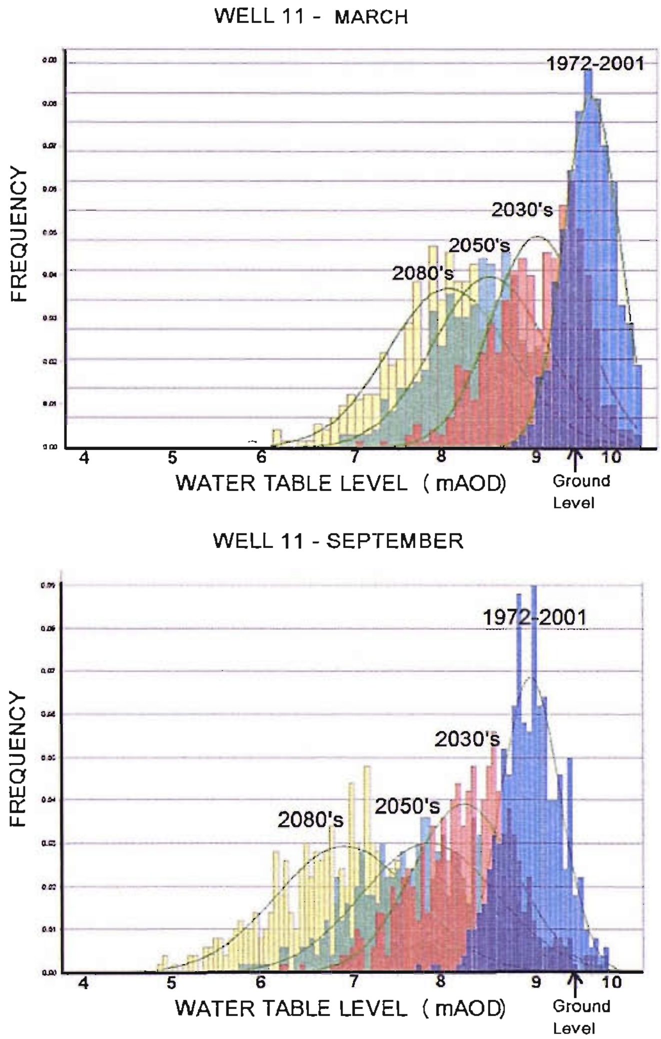


Figure 6.15: The expected frequency of occurrence of water table levels for well 11 for wet conditions in March and dry conditions in September

As discussed in Chapter 5, expected sea-level rise will raise water table levels by about 0.63m in the next 100 years in the dune system. Coastal erosion is occurring in this area up to 500m in 2100, and the impacts will therefore vary along the coastline. Further north along the coast, accretion will cause the water table levels to rise. To identify which factors will be the most important in affecting coastal aquifers in the future, a sensitivity of the water balance model to key model parameters was performed. Table 6.1 shows parameters that were set as decision variables for the Monte Carlo simulation, together with their mean value, standard deviation, range, and distribution type.

Table 6.1: Parameters used as decision variables for the Monte Carlo simulation

Parameter	Mean Value	Range	SD	Distribution Type
Rainfall	60 mm/month	-	± 20	Normal
Tree coverage	-	0.10%-50.00%	-	Uniform
Coastal erosion	-	100-500m	-	Uniform
Sand permeability	-	9-13m/day	-	Uniform
Temp. and ET	45 mm/month	-	± 10	Normal
Sea-level rise	-	0.10-1.00m	-	Uniform

These factors were programmed into the water balance model using the Crystal Ball simulation software, which enables multiple model runs to be analysed statistically. It also enabled a sensitivity analysis of the key parameters in the model to be carried out. During the 1000 model simulation runs, Crystal Ball calculated the sensitivity of the model to a given parameter by computing rank correlation coefficients between every assumption and every forecast. Correlation coefficients provide an important measure of the degree to which assumptions and forecasts change together. If an assumption and a forecast have a high correlation coefficient, it means that the assumption has a significant impact on the forecast both through its uncertainty and its model sensitivity. Positive coefficients indicate that an increase in the assumption is associated with an increase in the forecast.

The result of the sensitivity analysis of factors which impact on average water table levels over the next 100 years is shown in Figure 6.16. The most important parameters were ranked showing that rainfall is the most important (57.8%), followed by change in temperature and evapotranspiration (14.6%), tree coverage (13.5%) and coastal erosion (8.9%). Smaller impacts were found from system properties such as sand dune permeability. The impact of sea-level rise (1.2%) was relatively unimportant.

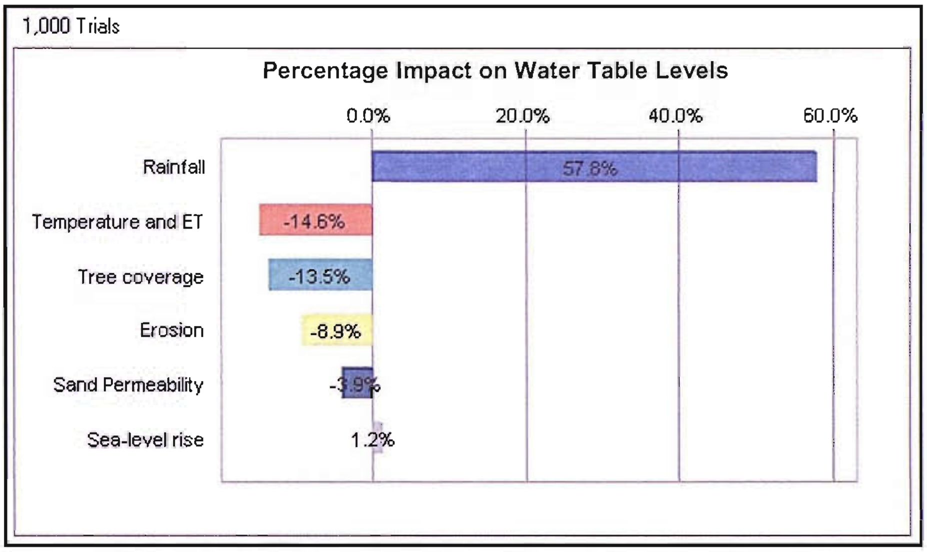


Figure 6.16: Sensitivity chart of factors which impact on average water table levels (Well 11)

The previous section shows the impacts of climate change on the water table levels in the open dunes (Well 11). The following section shows the impacts of climate change on the water table levels in the area covered by pine trees (Well 9). Figure 6.17 shows that the average water table levels in the pine tree area near Well 9 are expected to fall. This is in agreement with the results of the open dunes area shown in Figure 6.11.

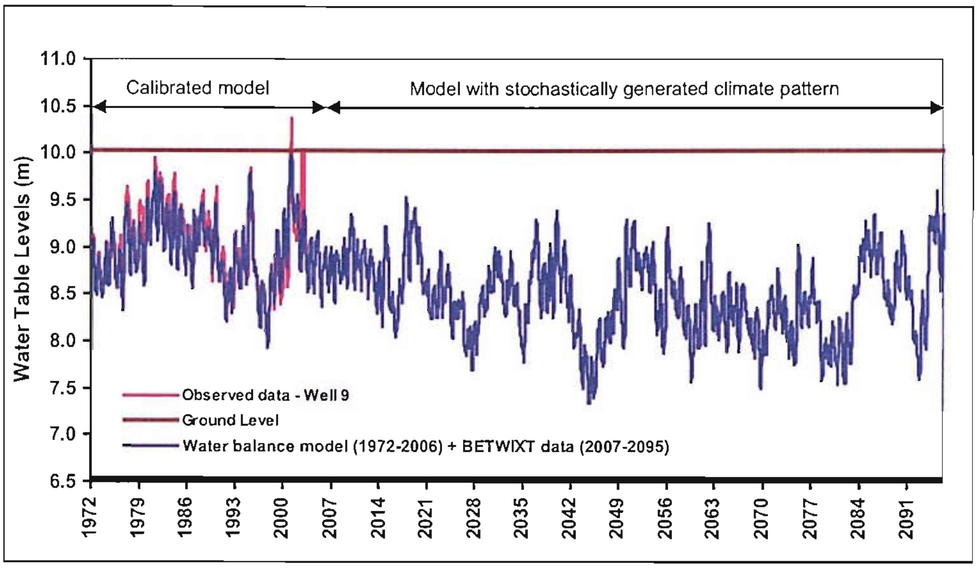


Figure 6.17: Single run of the water balance model for pine forest areas at well 9: with BETWIXT data modified for Ainsdale

In the same way as the water balance model in the open dunes, the water balance model in the pine tree area based on BETWIXT data was run with varying timings of rainfall events, because the response of the water table is very sensitive to the timing of rainfall. The result (Figure 6.18) shows the likely ranges of change in water table levels from 1972 – 2080's for wet conditions in March and dry conditions at the end of the summer (September) for well 9. The overall pattern is a lowering of the water table levels with time, but also greater variability in these levels. The average water table level will fall almost 2m for wet conditions in March and from 8.6 to 6.8m for dry conditions in September between now and the 2080's. This will affect both the vegetation and the wildlife in the Reserve. The results show the same pattern of behaviour as the results of the open dunes (Figure 6.15), but areas with pine trees are expected to become even drier.

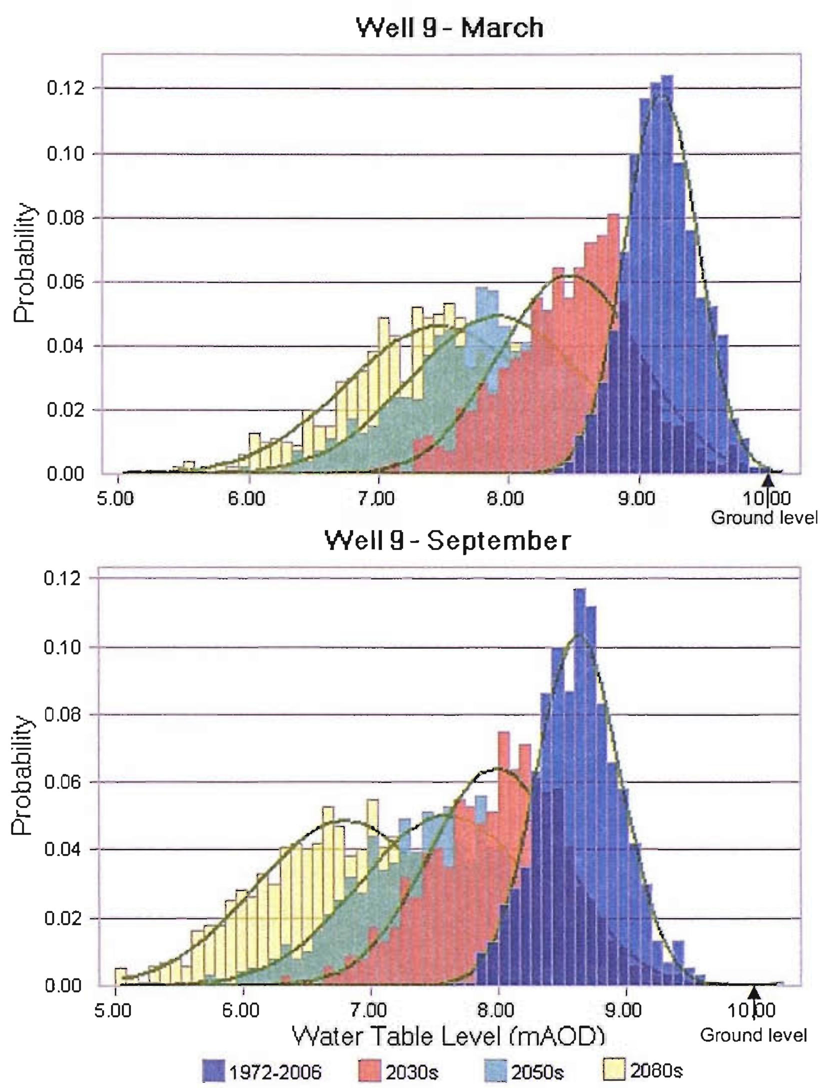


Figure 6.18: The expected frequency of occurrence of water table levels for pine forested areas (well 9) for wet conditions in March and dry conditions in September

The simulation of future water table levels, shown in Figures 6.14 and 6.15 were carried out assuming that sea level remains constant in the future, and that the coastline remains static. According to the Badon Ghyben-Herzberg principle, a water table fall of 1m will result in a rise of the depth of saltwater/freshwater interface of about 40m. This may become an important issue that influences both the plants and the animals in the sand dune system.

6.3 Impacts of climate change on groundwater system

There are many potential direct and indirect interactions between climate change and groundwater. The **direct effects** of climate change on groundwater resources depend upon the change in the volume and timing of groundwater recharge. If precipitation and evapotranspiration change, it will influence recharge. For example, UKCIP (2002) concluded that drier summers will lead to deficits in moisture content of soils extending into the autumn, and then the winter groundwater recharge season may be shortened. Next, increased rainfall intensity may lead to more runoff and less recharge. The result of these suggested changes to monthly rainfall at Ainsdale under varying climate change scenarios graphs of this research partly support the UKCIP summary.

Wetter winters might possibly cause an increase in winter recharge. It might be possible that a wet winter with many heavy rain storms will result in more recharge going in to the aquifer and will cause temporary higher water table levels. This is because runoff from the sand dunes is small, while infiltration is high. Key findings in this study are that on average, hot dry summers will cause a reduction in total evapotranspiration due to increased soil moisture deficits, and that wetter winters will cause higher recharge and an increased range of amplitude of water table levels. Higher temperatures will cause an increase in potential evapotranspiration; however, the soil moisture deficit models suggest that even with higher potential evapotranspiration, the actual evapotranspiration is limited by soil drying in summer.

Rising sea levels may lead to increased saline intrusion of coastal and island aquifers because it will change the hydraulic gradient between the fresh water in the dunes and the sea. This will initially reduce groundwater flow out of the dunes. Therefore, to investigate impacts of sea-level rise on groundwater system in coastal aquifer, the effect of relative sea-level rise will be included in the model.

The possible **indirect effects** include changes in natural vegetation and crops will influence recharge because drier summers may stress vegetation and result in change of vegetation types. Different types of vegetation including trees, grass and sand were investigated in Chapter 4.

6.4 Conclusions and Recommendations

The water balance model was successfully calibrated against a 30 year set of observed water table level data. The water table levels calculated by the model depend on many factors, but these were based on physically reasonable estimates of parameters such as porosity, permeability and root zone depletion of soil moisture deficit. The climate change scenarios published by UKCIP are in four differing categories, depending on CO_2 emission scenarios. In this study, we used the "medium-high" scenario, and a synthetically generated future climate data sequence. The modelling of future water table levels has been shown to be highly dependent not only on the amount of rainfall but when it falls and the size of each rain storm event, especially in the forested area. A randomised re-sampling strategy of the synthetic future climate data sets has enabled the construction of 1000 possible future realities for the water table system at Ainsdale. A statistical analysis of the most probable ranges of change has been calculated. Additionally, a sensitivity analysis has shown that the system is most sensitive to the amount and timing of rainfall events.

The key environmental factors that affect groundwater levels in a coastal sand dune system in Northern England have been evaluated up to the year 2095. The key result found in all simulation is that for the Ainsdale dune system, the average water table levels are expected to fall by 0.5-1.0m in the next 100 years, with prolonged periods of low water table levels. Areas with pine trees are expected to become even drier, with the water table level falling by 1.5m or more. This will have the effect of drying out the inland slack floors and reducing the biodiversity of these areas. The effects will be smaller closer to the coast. In areas of coastal accretion, new areas will be developed, and it may require proactive land management and re-zoning of areas of nature conservation.

CHAPTER 7

Thailand Case Study

7.1 Introduction

Groundwater is very important for Thailand, both for agricultural production and public and industrial water supply. Most of the cultivated areas are irrigated by surface water such as sprinkle and drip irrigation. However, irrigation in some regions relies on pumping groundwater (IGES, 2007). Thailand's groundwater use had increased due to city growth since the late 1960s. Economic growth has brought dramatic increases in water demands for industrial, commercial, and domestic purposes, particularly in the Bangkok Metropolitan and its vicinity.

The regional topography of the country varies from the mountainous terrain with dense forests of the North, the relatively dry and high land plateau which borders the Mekong River of the Northeast, to the flat and low land subject to flooding of the Central plains and the peninsula of the South (Figure 7.1). Thailand can be divided into 7 major river basins, and it is generally divided into 25 sub-basins (FAO, 1997). The most important river is the Chao Phraya River which flows from the northern valleys through the central plain and into the Gulf of Thailand. The Chao Phraya watershed is the largest watershed in Thailand, covering approximately 35% of Thailand, and drainage area is about 157,924 km^2 (JICA, 1995). The country has about 2600 km of coastline, which is an important economic area in terms of recreation, tourism, and commerce (MSTE, 2000).

Figure 7.1: Map of Thailand
(Source: *http://www.stageproperty.com/_assets/Image/map_thailand.gif*)

Thailand is an agricultural country which is one of the top rice exporters of the world. In 1995, the cultivated area was estimated at about 40 per cent of the total area, and 84 per cent of the cultivated area were under annual crops with mainly paddy rice (Figure 7.2). The remaining 16 per cent were used for permanent crops (FAO, 1997). Therefore, water management is very important for the country. The backbone of Thailand's agricultural economy is supported by the two main river systems including the Chao Phraya and the Mekong. Total amount of water used for irrigation in the

Lower Chao Phraya Basin in 1996 was more than 70% of the total water demand in the basin at that time (IGES, 2007). However, domestic and industrial water uses are increasing continuously every year due to increasing population and growing city.

Figure 7.2: Cultivated area in the study area
(Source: *http://www.ldd.go.th/*)

Thailand is located in a tropical monsoon region. Therefore, the climate is mainly controlled by the alternation between the southwest monsoon, and the northeast monsoon (JICA, 1995). The southwest monsoon carries heavy rainfalls from May to October, but the northeast monsoon is relatively dry and cool from November to February. The climate is predominantly monsoonal with three main seasons: rainy season (May-October), cool season (November-January) and hot season (February-April). The climate is humid and tropical with average rainfall amounts varying from 1100 mm in the central plain to 4000 mm in the southern peninsula near the Andaman Sea (FAO, 1997).

Large amounts of water are diverted from the rivers for irrigation support in the northern and central regions for dry season. As a result, a water level cannot be maintained for navigation purposes, and to prevent saltwater intrusion. Therefore, Bhumiphol Dam and Sirikitt Dam in northern and Chao Phraya Dam in the central area are used to release water to maintain the water level in the river (Vongvisessomjai, 2007).

The lower central plain, especially Bangkok and vicinity, faces problems both of too much and too little water. Bangkok receives water from three primary sources including rain, river water and backwater from the sea. These sources contribute to the flooding problems which occur almost every year. In the wet season, flooding occurs frequently due to lower than average ground level, inadequate drainage and high tides in the Gulf of Thailand. The problem of flooding is becoming a more and more serious problem. In the dry season, water demand for irrigation has to compete with demand from other sectors such as navigation, to prevent salt water intrusion, and to supply water for domestic and industrial purposes. Moreover, groundwater abstraction for private and industrial purposes exceeds the safe yield of aquifer for the reason that the Metropolitan Water Works Authority is unable to supply water to meet all domestic and industrial demand. This accelerated the rate of land subsidence. Piezometric levels of the main aquifers dropped to a maximum of 40-50m below the ground surface (IGES, 2007). The monitoring of annual subsidence rate based on more than 220 subsidence benchmarks installed throughout the city showed that the areas characterized by high subsidence rates also experienced declines in groundwater levels (IGES, 2007; Phien-wej et al., 2006).

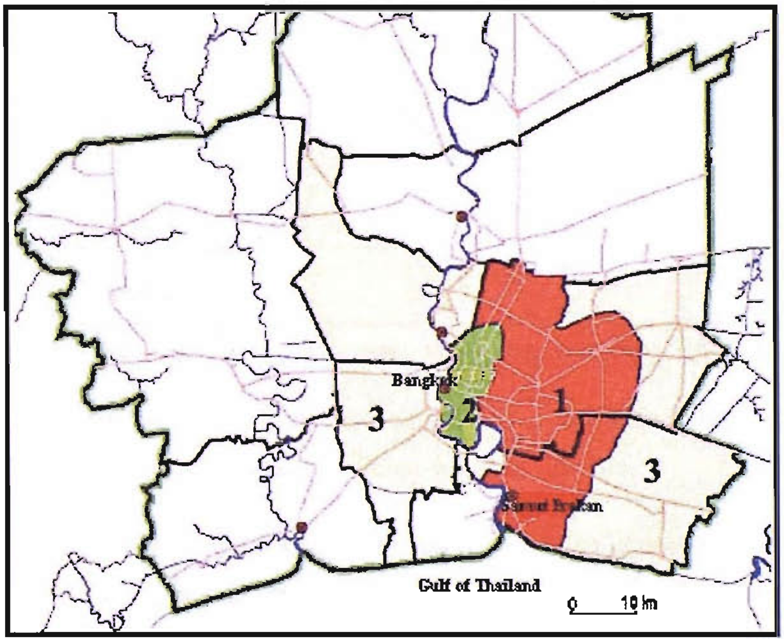


Figure 7.3: Groundwater control zones in 1987 (zone 1 > 10 cm/year of land subsidence, zone2 between 5-10 cm/year, and zone 3 <5cm/year) (Modified after: http://www.dgr.go.th/hilight/file/report50.pdf)

In Bangkok, groundwater abstraction control was introduced in 1977; however, the control was ineffective and groundwater use increased. The Groundwater Act was enforced in 1987 and then amended twice until 2003 (IGES, 2007). Groundwater control zones were designated for critical areas where more intensive control (Figure 7.3).

Under the Act, permissions for drilling groundwater use are only allowed for groundwater users in an area where a public water supply is unavailable. The trend of groundwater abstraction increased until 2000 in the Bangkok vicinity (Figure 7.4), and then it decreased because of expansion of piped-water supply services and rising charges for groundwater pumping. At present, enforcement of the Act has begun to strengthen due to the extension of the public water supply scheme (IGES, 2007).

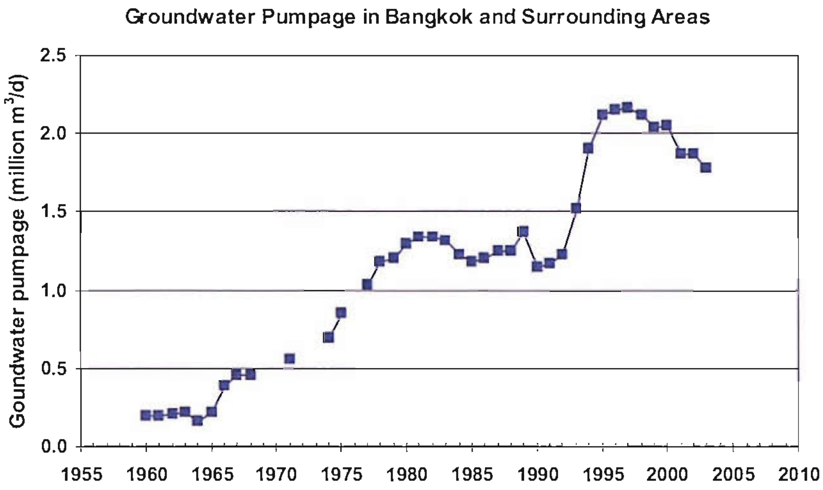
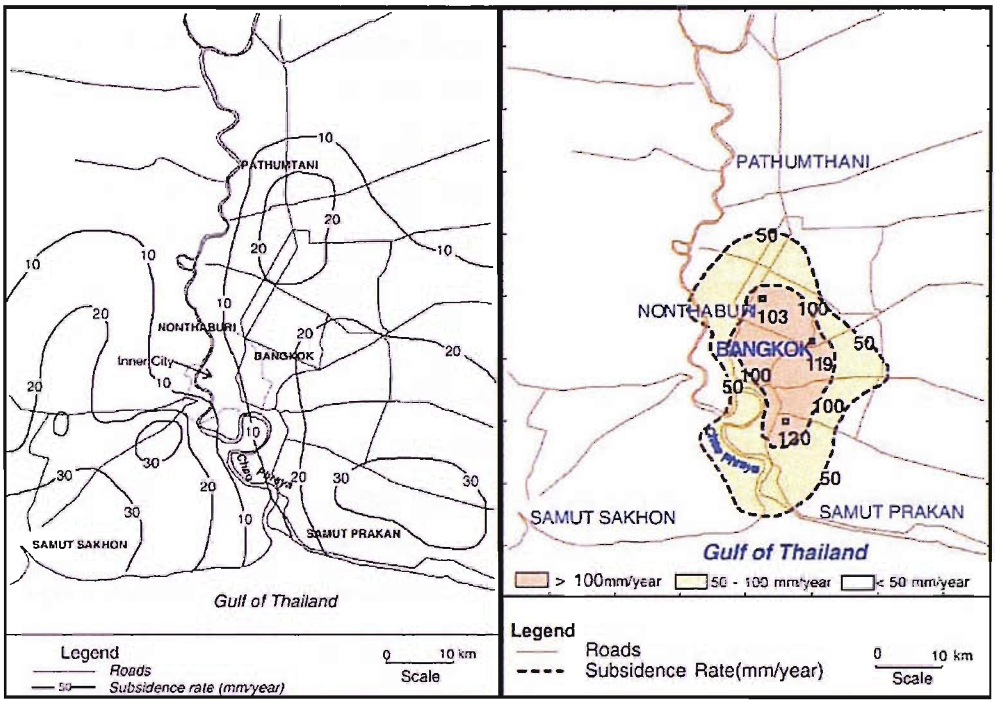


Figure 7.4: Groundwater abstraction in Bangkok and vicinity
(Modified after: Phien-wej et al., 2006)

As a result of increased groundwater pumping from the aquifer system of the Bangkok (from 1.2million m^3/day in the early 1980s to about 2.0million m^3/day during 1996-2003), land subsidence still continues (Phien-wej et al. 2006). The most critical zone in 1981 (Figure 7.5 b) was in the eastern part of Bangkok which experienced a subsidence rate of 120mm/year. At present, this area still continues to subside at 20mm/year (Figure 7.5 a). The location of the most affected areas has changed; the largest subsidence rate in 2002 was in the southeast and southwest of Bangkok (30mm/year) (Phien-wej et al. 2006). At present, subsidence rates of around

10mm/year exist in most parts of Bangkok Metropolitan Region including the central, east, and south-eastern parts of Bangkok City, where land subsidence was from 0.5m to more than 1.0m between 1978 and 1999 (IGES, 2007). In the industrial area of Samut Prakan, land subsidence rate at 20-50mm/year was observed in 2003 (IGES, 2007).



(a) (b)

Figure 7.5: Land subsidence in Bangkok and vicinity in 2002 (a) and in 1981 (b)
(Modified after: Phien-wej et al., 2006)

Over-pumping of groundwater in Bangkok not only causes land subsidence and flooding problems, but also leads to saline intrusion into both the top aquifer and deep aquifers. The elevation of the tidal plain is around 1-2 m a.s.l., and its surface is very flat and low (Umitsu, 2000). The sediments of this area consist of very soft silt or clay. In addition, this elevation is almost the same as the high tide level of the Gulf of Thailand. Salinity pollution occurs in the Chao Phraya River because sea water intrudes into the lower reach of the river during low-flow periods. Saltwater intrusion would occur through small waterways connecting the sea to inland areas where land is very low lying. A river discharge for the purpose of salinity control and navigation is maintained at $75m^3/s$ (MSTE, 2000).

The salinity problem of the Chao Phraya River depends on the discharge rates of fresh water from upstream, the ocean tide, the difference in density between the river water and the sea water, and mixing processes (Vongvisessomjai, 1989). The river shows a well-mixed condition when the discharge is less than $150m^3/s$. At discharges between $150\text{-}300m^3/s$, the river shows a partly mixed condition near the river mouth, and there is no problem of salinity in the river when the discharge exceeds $1{,}000m^3/s$. The discharge in the Chao Phraya River during the low-flow period from January to April is about 50 to $200m^3/s$, so the inundation is more serious in this season (Vongvisessomjai and Rojanakamthorn, 1989). As a result of high demand and low supply of freshwater, saltwater intrusion is severe during the dry season. Without sea-level rise, saltwater intrusion would increase by 2km if the discharges were constant at current rates (MSTE, 2000).Due to sea-level rise, thus saltwater intrusion will be exacerbated.

Relative sea-level rise is a significant problem in this area, as it is a low and deltaic region. Many processes already on-going will be accelerated, and areas previously unthreatened will become vulnerable to impacts such as increased risk of inundation, seawater intrusion, erosion and recession. If sea-level rise continues in the future, severe coastal erosion will probably occur.

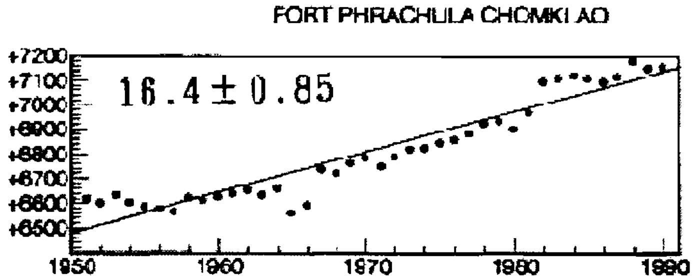


Figure 7.6: Variations of yearly mean relative sea level at Fort Phrachula Chomklao in Bangkok in mm/year (Source: Yanagi and Akaki, 1994)

Yanagi and Akaki (1994) studied mean sea-level variation in the East Asian region between 1950 and 1991. Figure 7.6 shows the variation of yearly mean sea level at Fort Phrachula Chomklao in Bangkok. The mean relative sea-level rise rate is 16.4± 0.85mm/year. The rapid rise of mean sea levels between 1965 and 1982 were caused by the large extraction of groundwater; however, the rapid increase of sea level has stopped after 1982 because of the groundwater abstraction control (Yanagi and Akaki, 1994).

Although the relative sea-level rise is currently less than 1m, a horizontal retreat of the coastline will cause a movement inland of the present coast. The soft silt and clay deposits of this area also eroded. Therefore, the case study area was chosen in this region to investigate the impacts of climate change and sea-level rise on groundwater levels in the coastal aquifer in order to understand the importance of groundwater recharge in this area.

7.2 Case study site and boundary conditions

7.2.1 Case study area

The case study area is bounded on the west by the Chao Phraya River, on the east by Bangpakong River, on the north by Khlong Samrong (big canal), and on the south by the Gulf of Thailand (Figure 7.7).

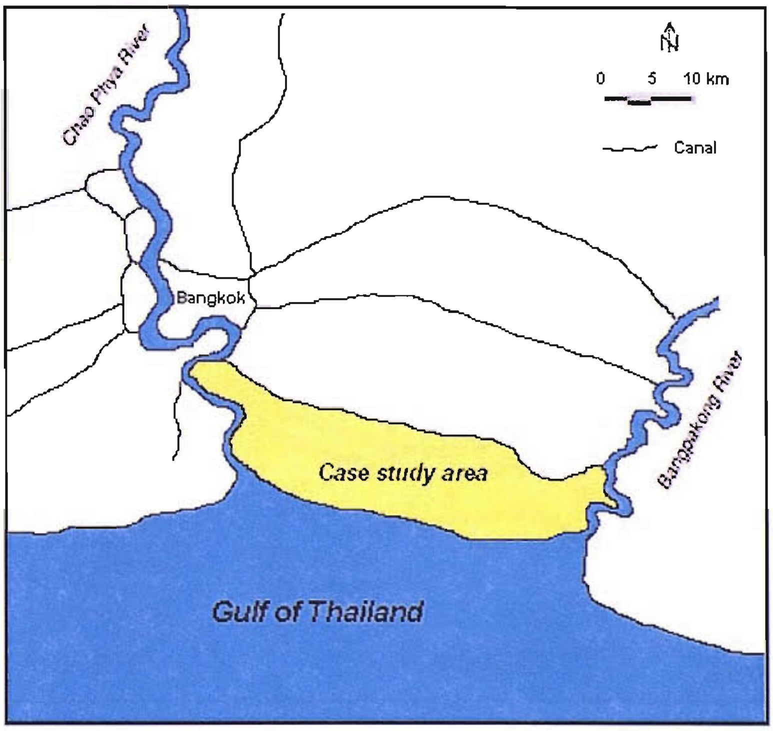


Figure 7.7: Case study area in Thailand

The study area comprises about 600 km^2 half in Samut Prakan province and a small part of southern Bangkok on the lower central plain. The elevation of the study area is between 0.5 - 2 m msl. (Figure 7.8), and the land surface is very flat.

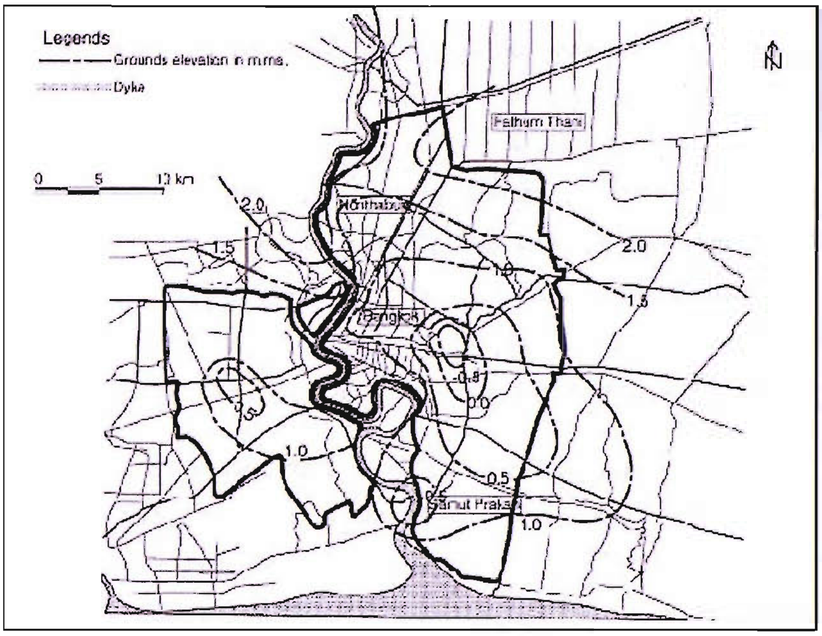


Figure 7.8: Grounds elevation in m.msl. (Source: Phien-wej et al., 2006)

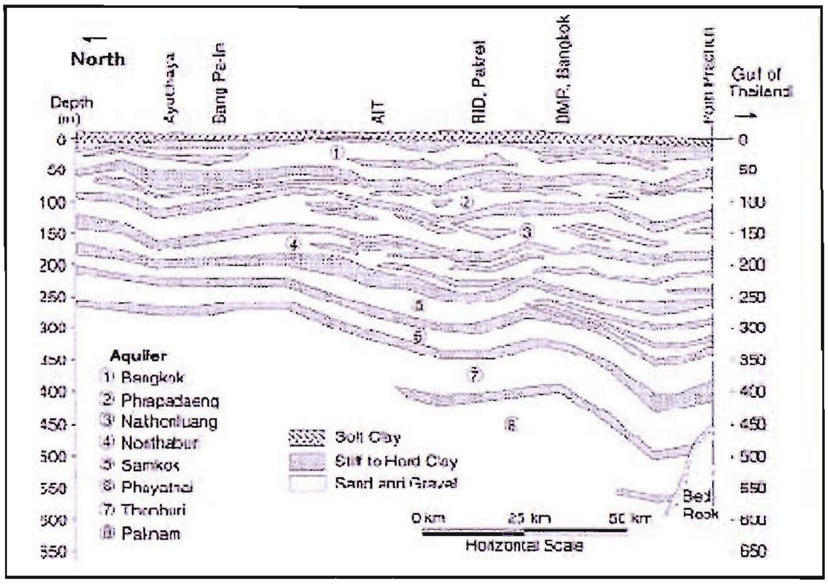


Figure 7.9: Schematic section of the lower central plain's aquifer system in the north-south direction (Source: Phien-wej et al., 2006)

The aquifer system in the lower central plain consists of 8 main confined aquifers composed of sandy and gravely sediments with stiff to hard clay bases (Figure 7.9). Each confined aquifer is separated by layers of clay aquitards. In an area where the separating aquitards discontinue or thin out, leakages between aquifer layers are expected (Phein-wej et al., 2006). Therefore, over-pumping in one aquifer may induce drawdown in the adjacent aquifers. The groundwater of the top aquifer layer (named Bangkok aquifer) is currently unusable due to the high salinity, and it is partly contaminated. The main productive aquifers are the second (Phrapadaeng), third (Nakhonluang), and fourth aquifer (Nonthaburi). The Nonthaburi aquifer is the most pumped aquifer, supplying approximate 50% of the total groundwater extraction (Phein-wej et al., 2006). However, groundwater pumping from deeper aquifers has recently become necessary in some areas where salt water intrusion has occurred.

Soft to stiff dark grey to black clays, called Bangkok Clay, make up the topsoil layer of the Lower Chao Phraya basin with thickness about 20-30 m. As a result, groundwater recharge to the aquifers mostly occurs along the peripheral of the basin (Phein-wej et al., 2006) with the age of the potable groundwater being about 10,000 – 30,000 years BC (JICA, 1995). However, some groundwater recharge is obtained by rainfall. FAO (1997) summarized that aquifer recharge from rainfall in Thailand is estimated at 41.9 km^3/year or approximately 5 to 6 per cent of the total precipitation. JICA (1995) summarized that natural groundwater recharge to the aquifer system is a very slow process.

7.2.2 Available data

Available data

Rainfall data are obtained from the Thai Meteorological Department (Figures 7.10 and 7.11), together with data needed to calculate evapotranspiration (temperature, wind speed, humidity, and sunshine) (Figures 7.12 to 7.15). Figure 7.10 shows that December to April are the driest months, whereas May to November are the wettest months. Figure 7.11 shows that between 1981 and 2005, the highest rainfall recorded is 1988, whereas the driest periods occurred between 1991-1992 and 1994-1995.

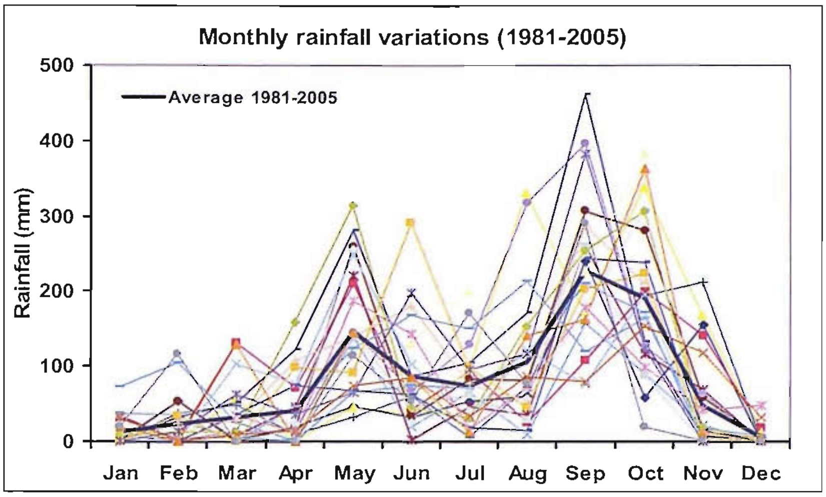


Figure 7.10: Monthly rainfall variations in Samut Prakan 1981-2005

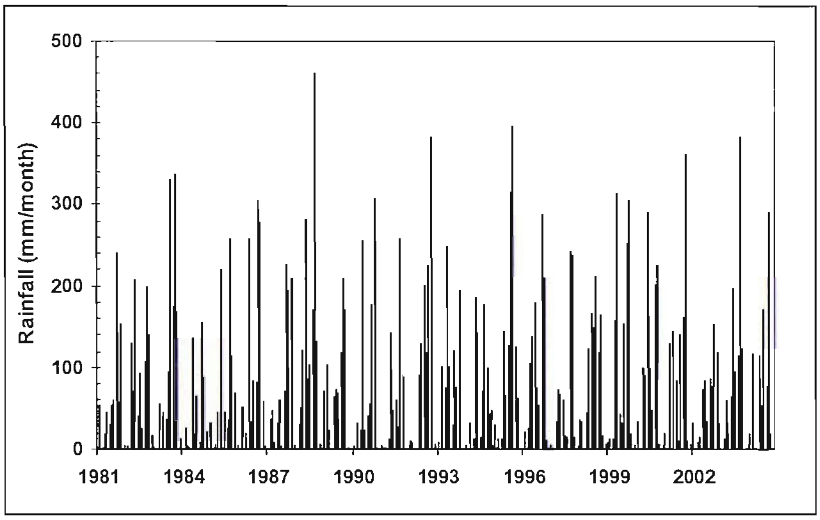


Figure 7.11: Monthly rainfall in Samut Prakan 1981-2005

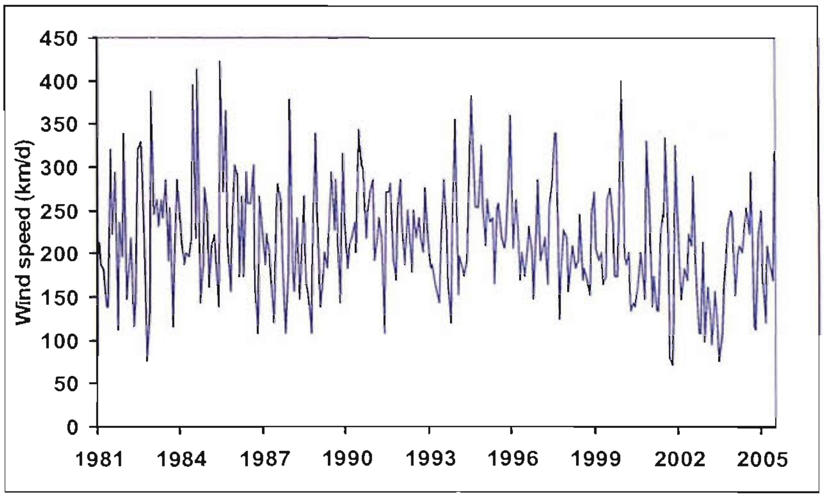


Figure 7.12: Monthly wind speed 1981-2005 at Samut Prakan

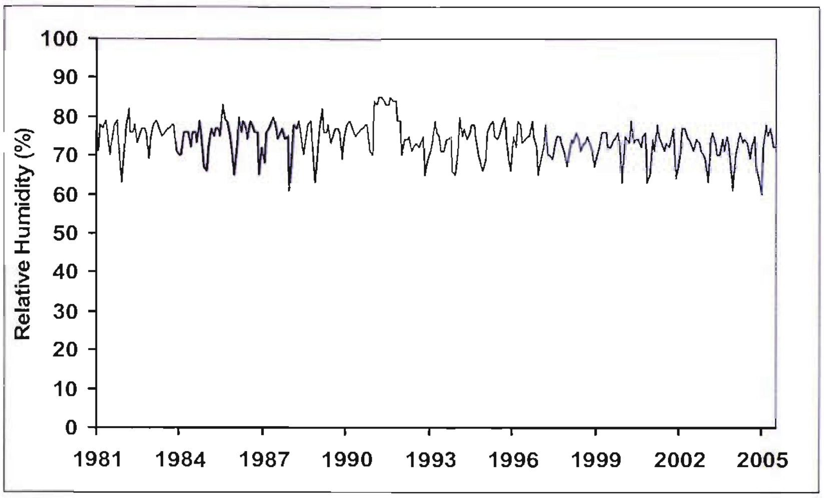


Figure 7.13: Monthly relative humidity 1981-2005 at Samut Prakan

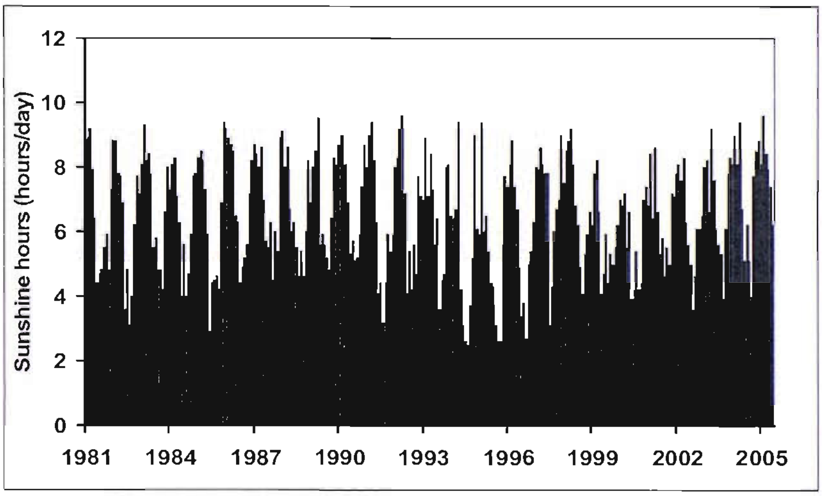


Figure 7.14: Monthly sunshine hours 1981-2005 at Samut Prakan

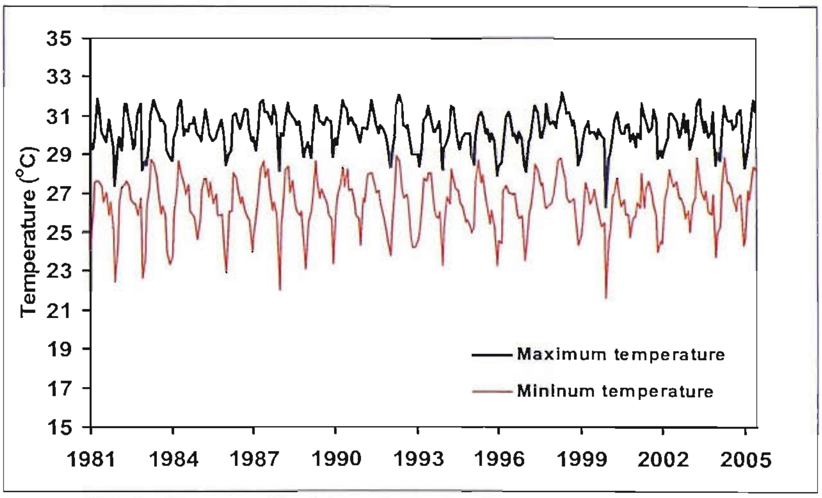


Figure 7.15: Maximum and minimum temperature 1981-2005 at Samut Prakan

The meteorological data were used to estimate potential evapotranspiration using the Penman-Monteith equation (Figure 7.16). The graph shows that potential evapotranspiration in Samut Prakan is between 120-170mm/month throughout the year, which are relatively constant compared to those rates in the UK. Actual Evapotranspiration, which is one of the main components needed to construct the water balance model, was calculated using soil moisture deficit model for a standard grass surface (Figure 7.17)

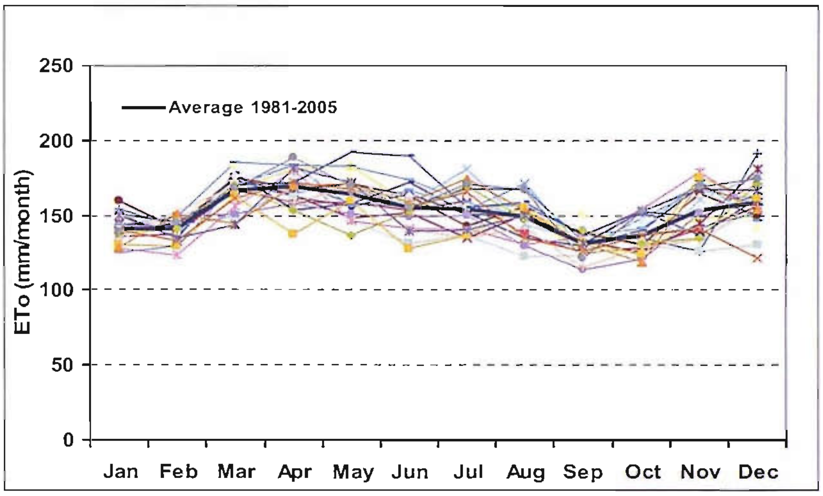


Figure 7.16: Monthly *ETo* 1981-2005 at Samut Prakan

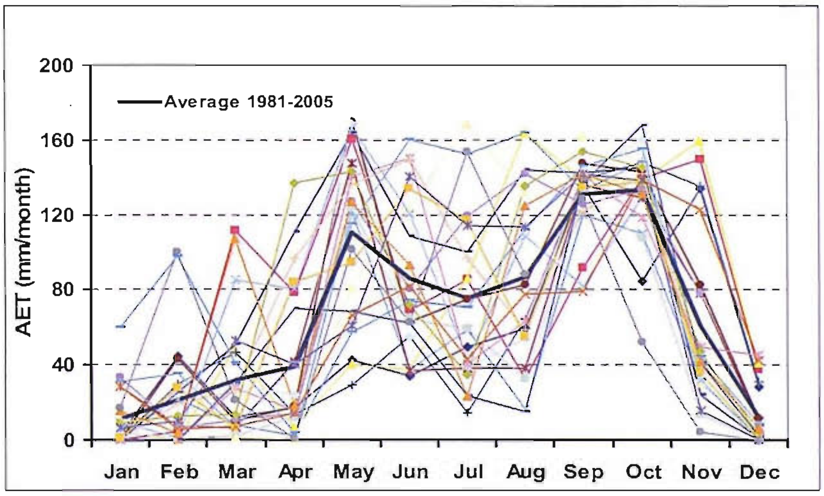


Figure 7.17: Seasonal *AET* 1981-2005 at Samut Prakan

Groundwater data were available at Department of Groundwater Resources of Thailand. Nevertheless, the groundwater level data in the study area were collected only from deep confined aquifers starting from the second aquifer (Phrapadaeng aquifer) to the deeper aquifer layers (Figure 7.18).

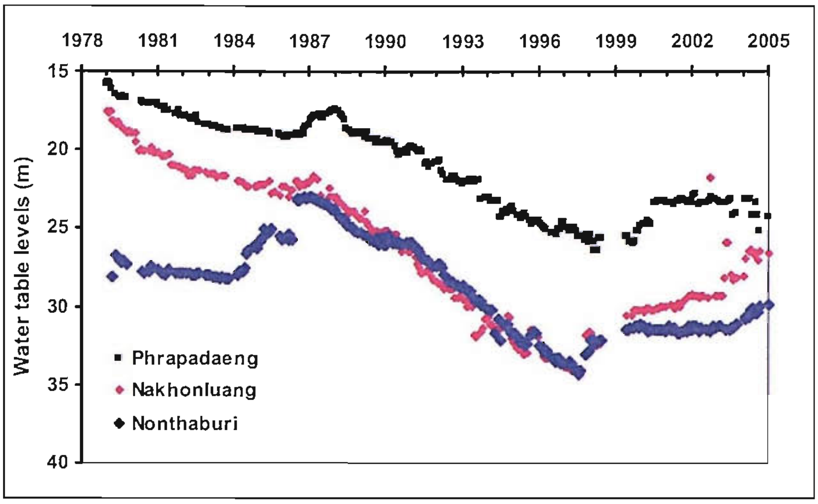


Figure 7.18: Measured groundwater levels of the second (Phrapadaeng), third (Nakhonluang) and forth (Nonthaburi) aquifers in Samut Phrakan

The graph shows that the groundwater levels dropped considerably from 1979-2005, but there were two periods shown that the groundwater levels were restored in 1984 and in 1998 when the groundwater abstraction was controlled (Figure 7.4). This shows that the groundwater pumping has directly affected the measured groundwater levels, because Nakhonluang and Nonthaburi are the most heavily used aquifers.

Boundary conditions and parameters used

To investigate impacts of climate change on coastal groundwater, the top soil layer was chosen to calculate the water balance model; this is strongly linked to climate inputs (rain, ET) which are expected to change in the future, and this may have an important impact on coastal defense, deep water recharge and salinity in the region. The thickness of this layer is about 20-30 m with hydraulic conductivity 4.06×10^{-5} m/day (Giao et al., 1999). The effective porosity is 0.05% (JICA, 1995). The shallow groundwater in this area varies typically 1.0-2.0m below the ground level with an annual variation of $\pm$ 0.5m (JICA, 1995).

The boundary of the study area is defined by two rivers and one canal in the north, east and west of the area; therefore, groundwater and surface water are allowed to flow into the study area from these three directions. Water input to the top soil layer of the study area consists of rainfall, groundwater flow from the surrounding rivers, and surface water flow from the canals and rivers. In this region, water levels are commonly controlled through a series of tidal water gates as shown in Figure 7.19.

Depending on the top soil layer conditions, water balance outputs are evapotranspiration, infiltration or vertical groundwater flow to the deeper aquifers (Bangkok aquifer), groundwater flow out to the sea (Gulf of Thailand), and drainage water controlled by canals and water gates.

Figure 7.19: Water gate separating a city canal from the Chao Phraya River (Source: http://depts.washington.edu/agaligo/agaligo/naga/pdf/3.pdf)

7.3 Applying the water balance approach

The simple water balance model equation (7.1) was used to describe the water balance model components for the study area; however, the water balance model components are based on data availability.

$$R - ET - GW - D = \Delta S \qquad (7.1)$$

Where R = rainfall

ET = actual evapotranspiration

GW = groundwater flow in/out of the system

D = drainage controlled water

ΔS = change in groundwater storage (water table level)

The available sources of data used in the water balance model in Thailand are shown in Table 7.1. Rainfall is easier to measure compared with evapotranspiration; furthermore, it is available in the site specific and long records. Actual evapotranspiration was estimated using the Penman-Montieth equation and the crop coefficient with soil moisture balance model. Groundwater flow both vertical and horizontal direction will be estimated by using Darcy's Law.

Table 7.1: The available sources of data used in the water balance model in Thailand

Data	Source	Details
1. Rainfall	Thai Meteorological Department	1981-2005
2. Climatic data for ET calculation	Thai Meteorological Department	1981-2005
3. Groundwater levels in confined aquifer	Department of Groundwater Resources of Thailand	1979-2005, confined aquifers from the second aquifer (Phrapadaeng) to the deeper aquifers.
4. Groundwater levels in unconfined aquifer	JICA(1995)	The shallow groundwater in this area are managed by drainage to keep the water table at about 1.0-2.0m below the ground level with an annual variation of ± 0.5m level to allow crops to grow in some areas and in other places the canals and fish farms have water levels at or close to ground level
5. Hydraulic conductivity	Giao et al. (1999)	4.06×10^{-5} m/day
6. Effective porosity	JICA(1995)	0.05%
7. Thickness of aquifer layer	Giao et al. (1999)	20-30 m
8. Ground elevation	JICA (1995)	1-2 m msl.

Model calibration at Samut Prakan was constrained by the lack of data on the surface layers of the aquifers. At Ainsdale, the near surface water table data were available, but groundwater levels in Thailand were available only in the deep confined aquifer (Figure 7.18). Additionally, the canal system near Bangkok regulates the irrigation water supply and drainage water. This means that the shallow groundwater water levels in the area depend on the controlled surface water. The aim is to maintain water levels at about 1.0-2.0m below ground level while controlling irrigation water supply, flood control, navigation, and salinity control. The available sources of data used in the water balance model in Thailand are shown in Table 7.1.

The model development for the case study in Thailand was set up so as to achieve a working water balance with the water table set to between 1.0 and 2.0m below ground level, the current target operational level used in the drainage system. By tuning the model to achieve these conditions it will become possible to explore the effects of anticipated future climate change in the area.

7.3.1. First run of the model – no surface drainage water outputs

The first run of the model was done using the three major water balance components; rainfall, actual evapotranspiration, and groundwater flow. The result (Figure 7.20) shows that the predicted water table level continuously rises. This means that there is too much water left in the system, because drainage is not included in the water balance model.

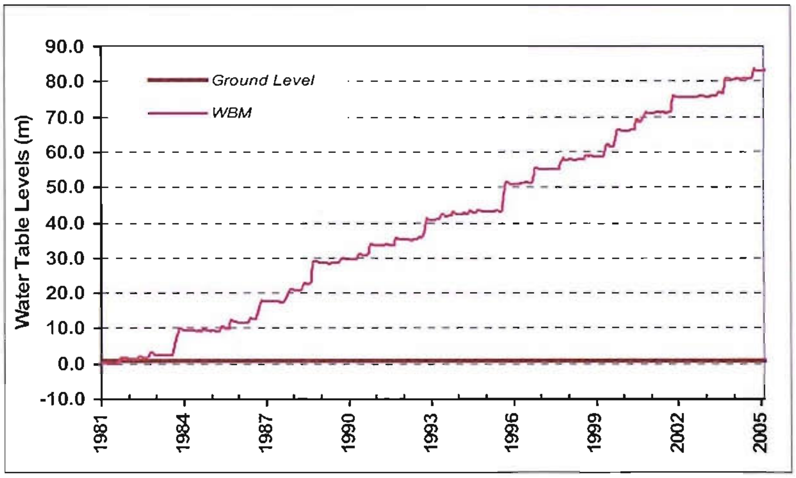


Figure 7.20: First run of the water balance model – no drainage water

7.3.2. Second run of the model – fixed drainage water

The next stage was to introduce the effects of surface water drainage. A constant output of 15 mm/month was introduced to the model and it brought the water balance calculation into a long term equilibrium over the period 1981-2005. Figure 7.21 shows the results, with mean water table levels around 3-4m below ground level, however the amplitude of water table variation is unrealistically high as the observed variation is usually only ± 0.5m.

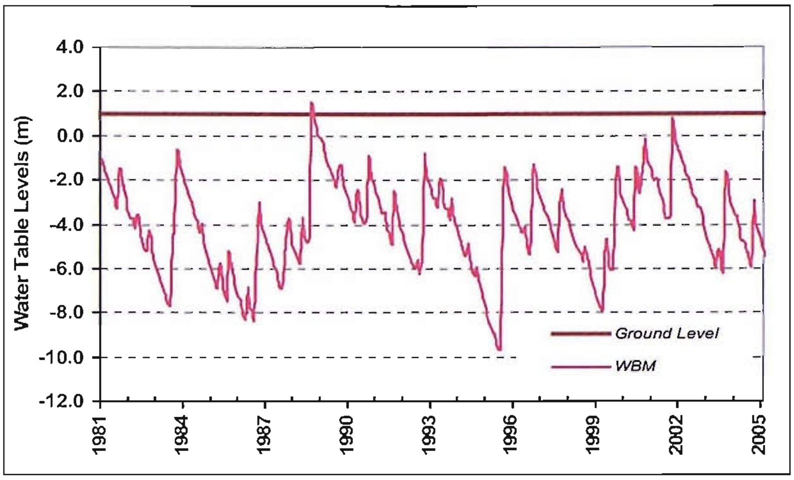


Figure 7.21: Second run of the water balance model – constant drainage rate set to 15mm/month

7.3.3. Third run of the model – constant drainage and peak surface runoff

Figure 7.22 shows the water balance model by assuming drainage removing 15 mm/month and also gate operations which would open to remove excess water when the water level reaches 0 m. This caps the upper limit of the simulated water tackle levels but again the amplitude of water table levels is too high.

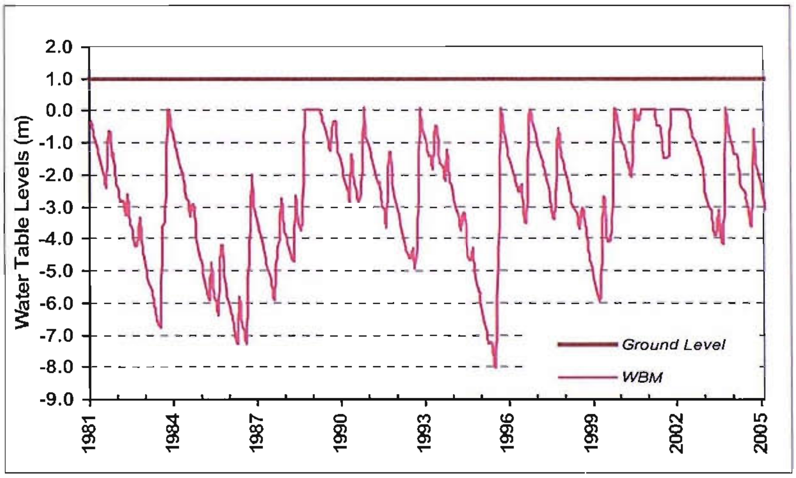


Figure 7.22: Third run of the model –drainage 15mm/month and gate opening when level reaches 0m

7.3.4. Forth run of the model –drainage when heavy rain occurs

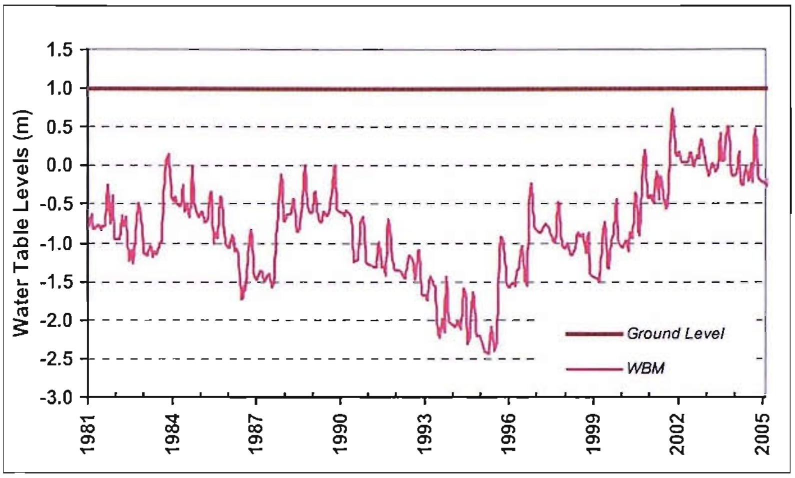


Figure 7.23: Forth run of the model –drainage when rainfall exceeds 160 mm/month

The assumption that drainage removed a constant amount of 15 mm/month was not a realistic solution. The water balance model was revise so as to generate drainage outputs water when rainfall was more than 160 mm/month. The result shown in Figure 7.23 provides a more temporal variation in calculated groundwater levels but the amplitude of variation (3m) is still higher that that observed in the field.

7.3.5. Final run of the model – drainage triggered when water levels exceed an operational level

The model was re-run by assuming drainage occurs when the water in the system exceeds a fixed level. After rainfall occurs, some water becomes overland flow (especially in residential areas), some water infiltrates into the ground and becomes groundwater flow, some water flows through the soil as subsurface flow, and some water discharges into streams as surface runoff to be outflow of the system. The water left in the system was estimated as surplus of rainfall, minus evapotranspiration, and groundwater flow. When the remaining water in the system is more than a fixed level (typically -1.0m), then water is assumed to flow out through the controlled gates. This is a more realistic scenario which matched observed water management in the region. The result is shown in Figure 7.24.

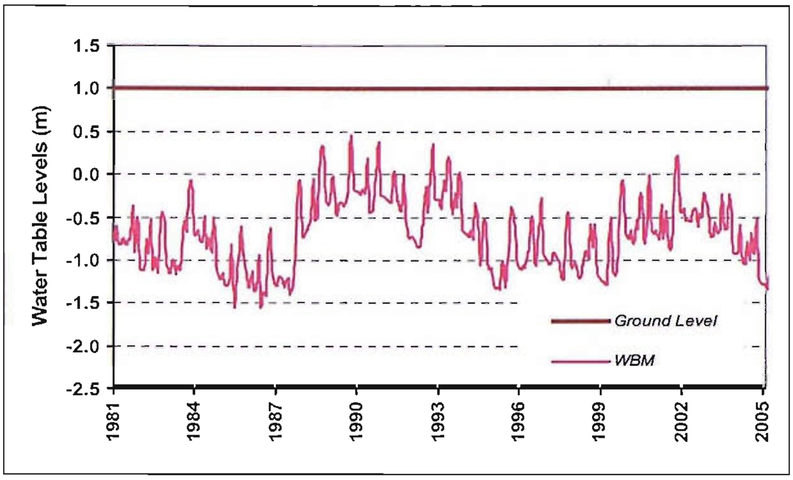


Figure 7.24: Final run of the model – drainage at 21mm/month trigger when water tables rise above a trigger level of -1.0m

Unfortunately, there is no long term record of observed data available to calibrate this model in the study area. However the simulation results in Figure 7.24 do follow the observed pattern of water table levels i.e. approximately 1.0-2.0m below ground level (JICA, 1995). Figure 7.24 shows that the water table level increases considerably in 1988 and drops in 1992 and 1995; these results correspond with recorded rainfall (Figure 7.11) which indicates the wettest year in 1988, and drier periods between 1991-1992 and 1994-1995. Although the results are not fully verified, they will be used to explore the impact of possible future climate change in the region.

7.4 Applying climate change to the model

MSTE (2000) summarized that a doubling of CO_2 potentially could reduce annual rainfall and increase temperature in the Chao Phraya basin. As a result of the doubling of CO_2 emissions in the control case, annual rainfall could decrease by about 20-30%, while temperatures could increase by 2 to 4°C. Annual runoff could reduce by more than 50% in some areas of the lower central plain.

Investigating climate change impacts of the case study in Thailand was considerably different from the UK case study, because there is no climate change scenario dataset readily available. Therefore, climatic datasets for future conditions were constructed covering a range of possible scenarios based on the available dataset from 1981-2005, perturbed by the overall expected change sin climate reported by MSTE (2000). These were used with the water balance model from the previous section. Figure 7.25

shows water balance model outputs using repeated 3x30 year sequences of historical rain and AET data.

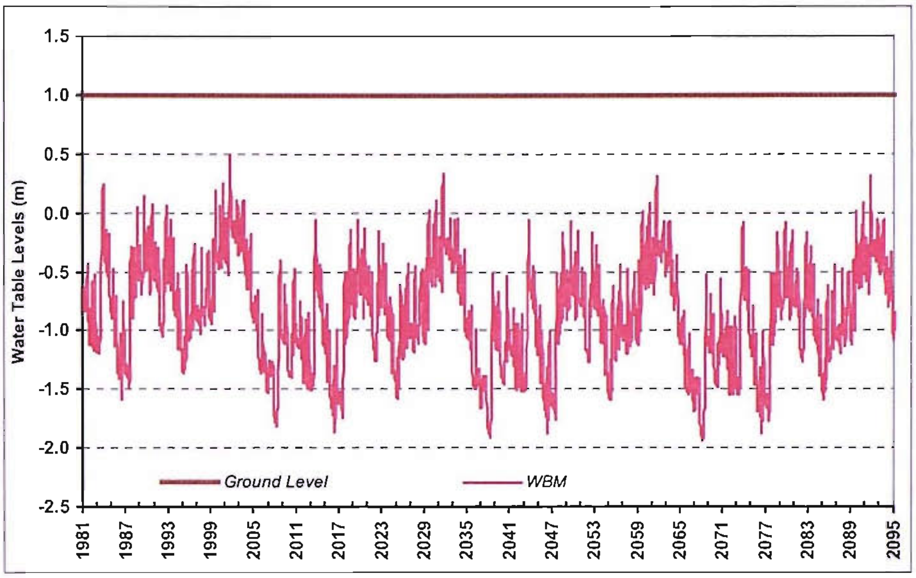


Figure 7.25: Water balance model with repeated sequences of historical rainfall and AET in 30 years sequences

Stochastic weather scenarios were generated by applying the projected climate change scenarios from Table 7.2 to the historical climatic data. The model was run by creating different scenarios of varying rainfall and evapotranspiration. Four time steps were used: 1981-2005, 2006-2035, 2036-2065 and 2066-2095.

Table 7.2: Climate change scenarios rainfall and evapotranspiration

Scenarios	Rainfall			ETo		
	2030s	2050s	2080s	2030s	2050s	2080s
A	+5%	+10%	+15%	-	-	-
B	-5%	-10%	-15%	-	-	-
C	-	-	-	-5%	-10%	-15%
D	-10%	-20%	-30%	-	-	-
E*	**-7%**	**-14%**	**-20%**	**+3.5%**	**+7%**	**+10%**
F	+7%	+14%	+20%	+3.5%	+7%	+10%
G*	**-10%**	**-20%**	**-30%**	**+5%**	**+10%**	**+15%**

*E and G are most likely to occur

MSTE (2000) concluded that annual rainfall could decrease by about 20-30% depending on area and annual runoff could reduce by more than 50% in some areas of the lower central plain.

The scenarios simulated in this work are described in Table 7.2 and were run assuming that drainage water network system is operated as at present. Random sequences of rainfall were generated using the same approach described in Chapter 6 ie by re-sampling the same data set randomly to create several hundred future rainfall sequences. This kept the total amount of rainfall in each simulation the same.

Figure 7.26 shows that the modelled water level is sensitive to both rainfall and evapotranspiration change. An increase in rainfall and a decrease in evapotranspiration (Scenario A and Scenario C) result in a big increase in groundwater levels; this shows that most of area will flood unless drainage is used. In contrast (Scenarios B, D, E, F and G), as a result of rainfall reduction and increases in evapotranspiration, water table levels will fall significantly in the future. This will result in saltwater intrusion if the freshwater in the rivers, released by Bhumiphol, Sirikitt and Chao Phraya Dams is less than $75m^3$/day.

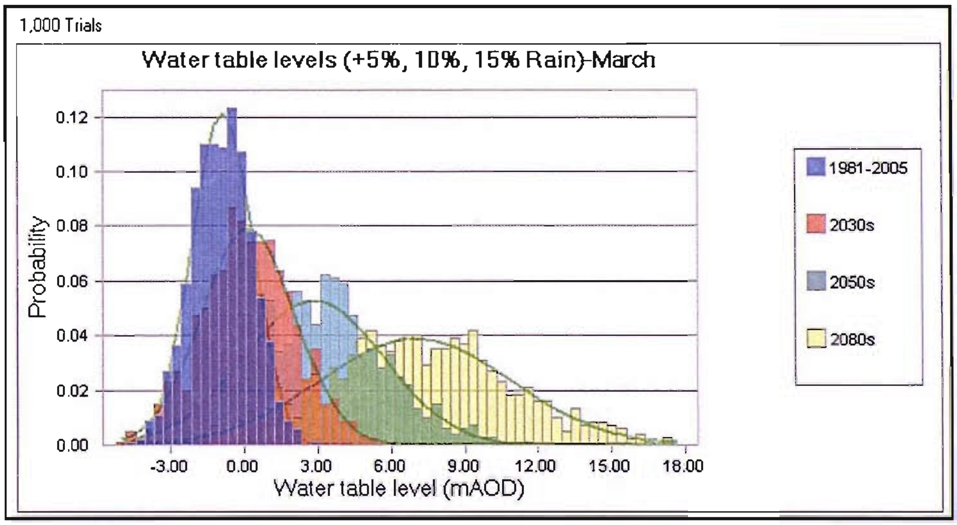
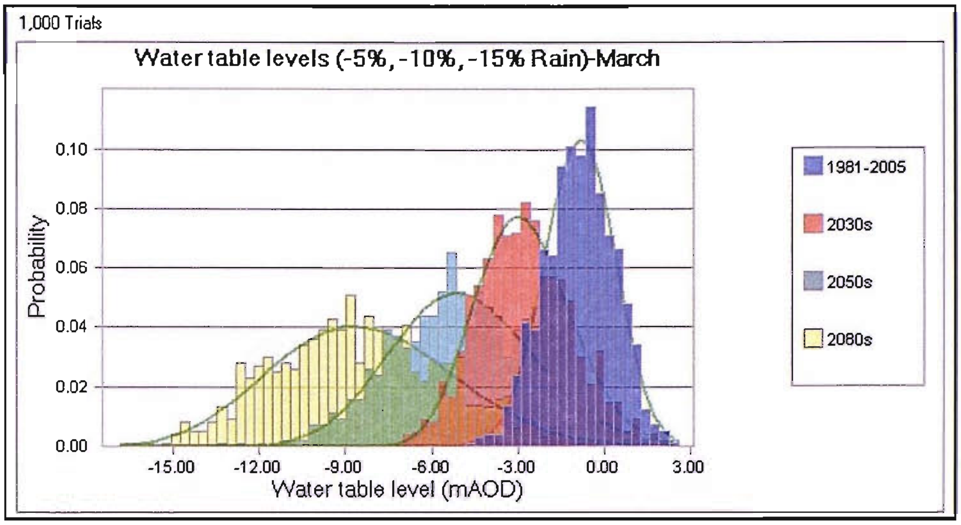
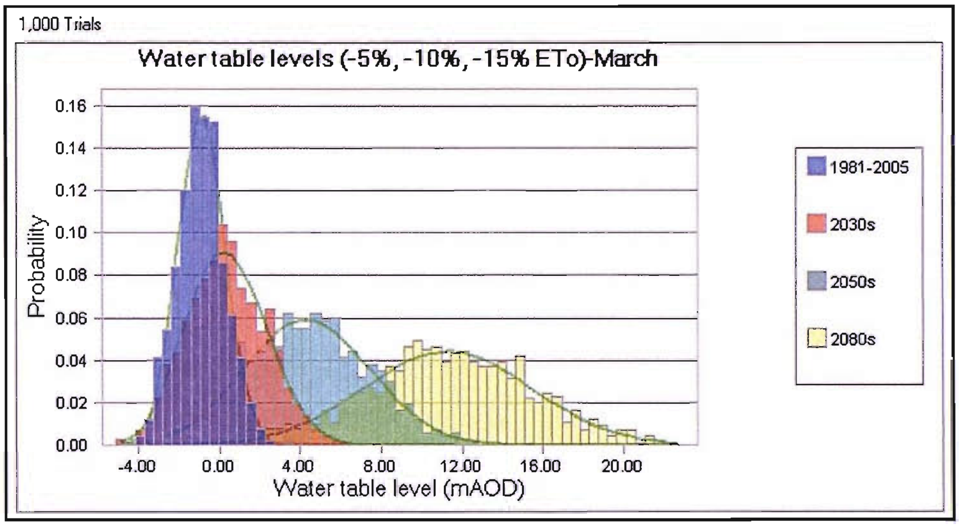


Figure 7.26: Water table levels in March for scenario A





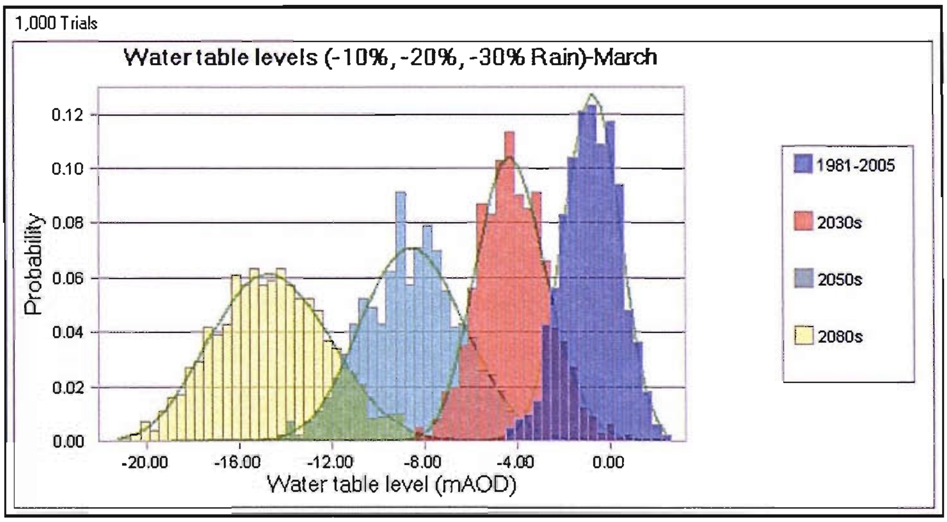


Figure 7.26 (cont.): Water table levels in March for scenario B, C and D

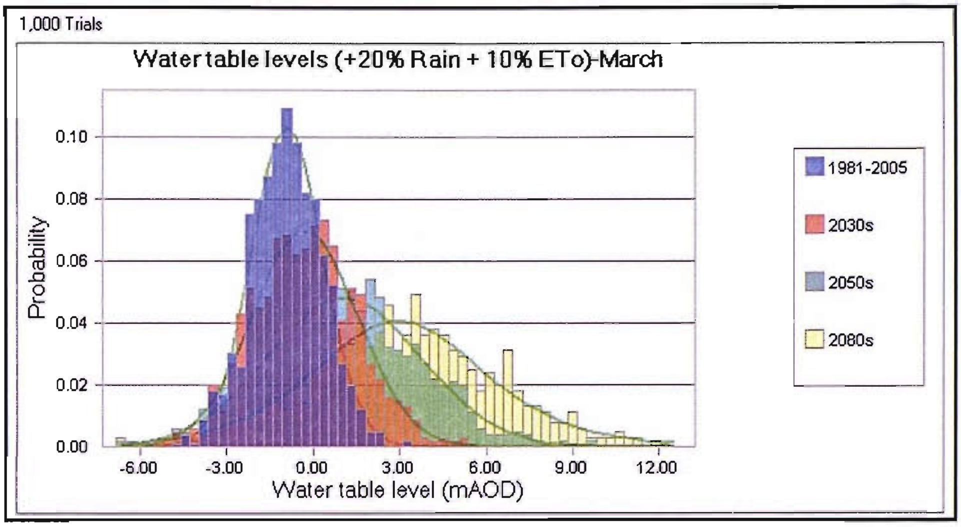


Figure 7.26 (cont.): Water table levels in March for scenario F

MSTE (2000) suggests that the scenarios which are most likely to occur are **E** and **G** in Table 7.2. The following graphs show only the result from Scenarios E and G. Other graphs are shown in Appendix A.

Scenario E and Scenario G model result (Figure 7.27) suggest that water table levels will drop dramatically from -1m at present to about -15m in 2080s for scenario E and from -1m to -18m in 2080s for scenario G. There is no difference between water levels in dry and wet seasons. Figure 7.27 shows that predicted runoff would decrease from more than 13 mm/month at present to less than 5 mm/month for scenario E and to less than 3 mm/month for Scenario G in 2080s.

Figure 7.28 shows the same data as a time series plot for scenarios E and G. The overall pattern is a lowering of the water table levels with time. With the surface layer water table falling below sea level it is highly likely that saline intrusion will become a significant problem and this suggest that there are likely to be significant changes in the eco-hydrological characteristics of the coastal area in Samut Prakan. Additionally agricultural areas will be short of irrigation water especially in the dry season. This may in part counterbalance the saline intrusion if water is released from northern area dams and is maintained for irrigation needs and other purposes such as salinity control and navigation.

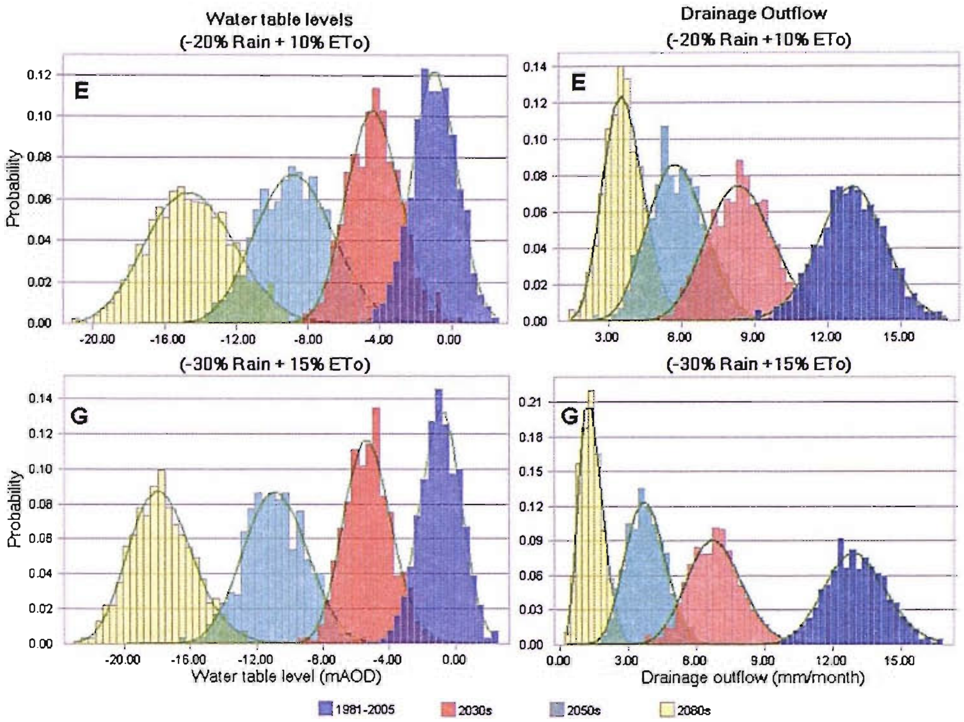


Figure 7.27: Modelled water levels and runoff for scenarios E and G (Dry season)

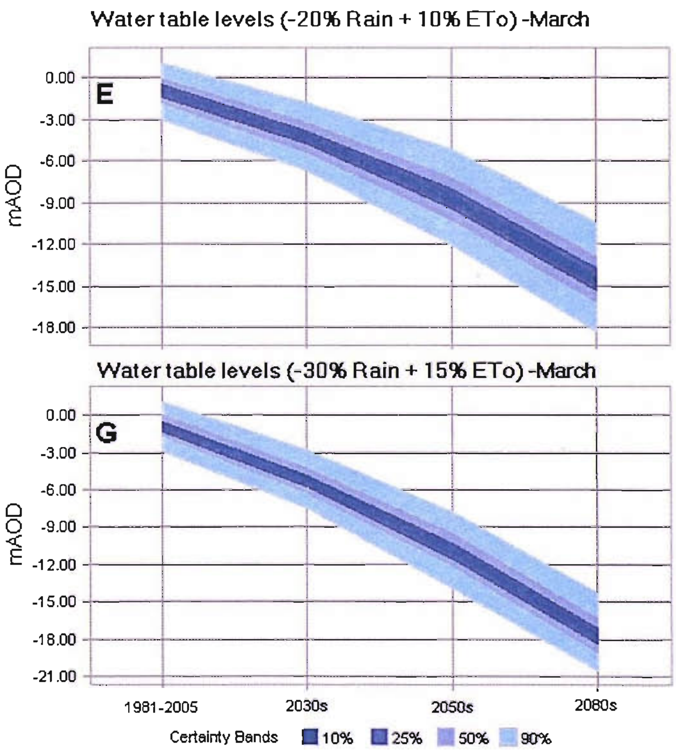


Figure 7.28: Trend of water table levels for scenarios E and G

A sensitivity analysis of the water balance model to model parameters was performed to identify which factors will be the most important in affecting groundwater levels in coastal aquifers over the next 100 years. The model was run 1,000 times by varying climate change scenarios to scenarios E and G. Rainfall, evapotranspiration and sea-level rise were set as the decision variables for the simulation (Table 7.3).

Table 7.3: Parameters used as decision variables for the simulation

Scenario	Expected change	Rainfall Normal Distribution	ET Normal Distribution	SLR Uniform Distribution
Present	-	32.5 ± 38 mm/month	31.5 ± 30 mm/month	± 0.50m
Scenario E	-20% Rain +10% ET	26 ± 34 mm/month	34.5 ± 28 mm/month	± 0.75m
Scenario G	-30% Rain +15% ET	22.5 ± 30 mm/month	36.25 ± 26 mm/month	± 1.00m

The results shown in Figure 7.29 shows that at present the most important parameters were rainfall (50.0%), followed by evapotranspiration (45.7%). Surprisingly, the impact of sea-level rise at ± 0.5m was relatively unimportant (4.2%). The relative magnitude of these impacts also changes in time. In the 2080's, the most important parameters are evapotranspiration (56.9% for Scenario **E** and 66.7% for Scenario **G**), followed by rainfall (41.3% for Scenario **E** and 32.7% for Scenario **G**). The impact of sea-level rise of ± 0.75m and ± 1.00m (for scenarios E and G respectively) was again relatively unimportant compared with changes in rainfall and evapotranspiration. The probable reason for this is that sea-level rise is linked to the water balance model by lowering *dh* in the groundwater flow calculation. In Thailand, the hydraulic conductivity of the top aquifer layer is very small (4.06 x 10^{-5} m/day, Giao et al., 1999); therefore, groundwater flow is small compared to other components in the water balance model.

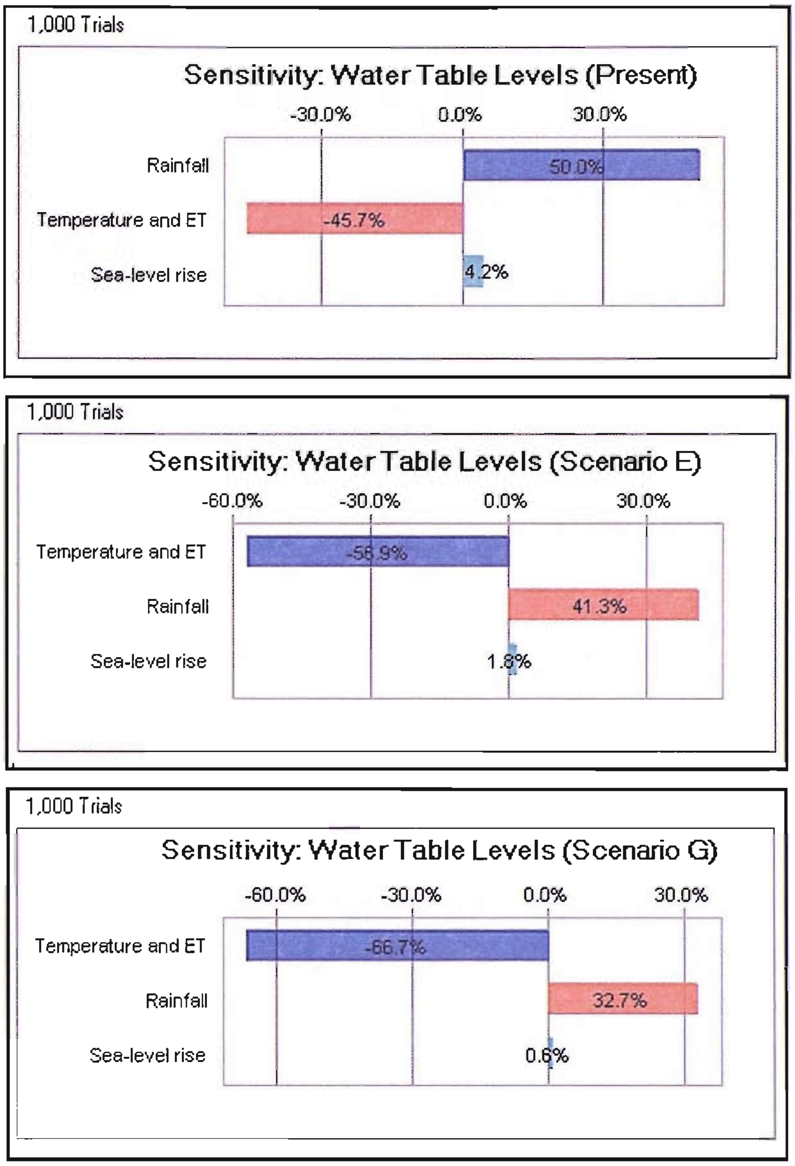


Figure 7.29: Sensitivity chart of factors which impact on average water table levels at present, and scenarios E and G

7.5 Summary

The key environmental factors that affect shallow groundwater levels in a coastal system at Samut Prakan in Thailand have been evaluated up to the year 2095.

Average rainfall is expected to decrease in the study area. This reduces surface runoff, which is essential for water storage in the river. Moreover, a decrease in precipitation will also cause a decrease in the groundwater recharge. Increasing temperature, which leads to an increase in evapotranspiration, is also a cause of water storage reduction in the rivers.

Results from the model simulations over the next 100 years indicate that the runoff could decrease more than 50 per cent in certain areas of the lower basin. This is in agreement with results published by MSTE (2000) and may lead to a water shortage in the central plain, especially during the dry season. Water scarcity will increase, and this will significantly impact on agriculture. This will contribute to saline intrusion in the coastal area, particular areas where sea-level rise is already an important issue. Although sea-level rise was found to be relatively insignificant, it exacerbates the seawater intrusion problem. At present, saline intrusion in the Chao Phraya River is already critical due to the over-pumping of groundwater and land subsidence, especially during the dry season.

Groundwater levels have been declining continuously, and land subsidence is continuing in the study area. To avoid irrevocable damage to aquifer, an effective implementation of the groundwater basin management is needed; for example, construction of subsidence and salinity monitoring stations and also extension of the monitoring to the surrounding areas. Improved discharge and water gate controls, limitation of the total pumpage and water permits in the critical zone together with designation a new critical zone of groundwater should also be enacted. Moreover, artificial recharge of groundwater should be seriously considered for the recovery of water levels and reduction of land subsidence. JICA (1995) stated that direct injection by using recharge wells is expected to recover groundwater levels and reduce the land subsidence rate. Recharge water may possibly be taken from the Chao Phraya River or from surplus water in the rainy season; however, this study has shown that climate change may restrict the availability of recharge water outside the rainy (monsoon) season.

CHAPTER 8

Discussion

8.1 Introduction

Groundwater recharge in coastal aquifers is affected by many environmental factors including rainfall, evapotranspiration, sea level, coastal erosion, aquifer recharge and land use. These are all variables which change in space and time and cannot always be accurately quantified. Additionally, climatic change predictions are inherently uncertain, so the magnitude of predicted impacts of climate change will also be difficult to quantify. This uncertainty, and how to deal with it, is a key aspect of the research presented in this thesis.

The following discussion will cover issues of uncertainties in factors that can be quantified, assumptions made in the model construction and development (both explicit and implicit), limitations created by of data availability and issues relating to uncertainty in climate change and sea level rise predictions.

8.2 Spatial and temporal variation of recharge estimation

Recharge into shallow unconfined aquifers has been shown to be highly dependent on rainfall amount, but also on timing and seasonality. The interaction between rainfall, soil moisture and soil moisture deficit is an important factor for estimating actual evapotranspiration losses from a shallow groundwater system. The calibration work done at the Ainsdale site has shown that with careful selection of physically based realistic parameters that describe rooting depth, surface zone porosity and surface runoff, it is possible to model the behaviour of a shallow water table system over medium term (30+ years). The modelling work has also been extended to include the effects of differing land use types, including open water surfaces, lightly vegetated sand dunes and coniferous forest.

The water balance model used in this research is based on the relatively simplistic model described by Clarke (1980). This original model was not able to consider actual evapotranspiration or other effects such as tree cover. The model developed in this work uses with physically-based representations of ET, interception, soil moisture stress, groundwater flow aquifer porosity and other variables such as seasonal variations in hydraulic gradients. This approach had the advantage that it is strongly rooted in the physical domain using well known sub models such as the Penman Montieth equation combined with the CROPWAT approach to estimating actual evapotranspiration from short vegetation, the Calder model for pine tree interception and the Darcy/Dupuit approach for estimating groundwater flow out of a prismatic aquifer system. These sub models have been proven to work in many other applications so have been accepted as the best available appropriate technology for achieving the aims of this research.

The water balance approach was chosen in preference to more complex 2 or 3-D simulations of the groundwater system because groundwater flow was found to be only one component of a much larger hydrological budget. A benefit of the choice of using a spreadsheet based rather than finite difference simulation was that it was possible to run the model in a stochastic mode. The sensitivity analysis showed that uncertainties in porosity and permeability had a much smaller impact on model outputs than other variables such as rainfall amount, rainfall timing and land use cover.

8.2.1 Spatial variability

The choice of the Ainsdale site for model development was made in part to the availability of a long term series of observed water table levels. This was aided by the fact that the area is relatively homogenous in that the aquifer properties (material, thickness, porosity) are relatively uniform within the study site. The area was also zoned into areas of differing land use which enables the testing and calibration of the recharge model under to extremes of land use cover – open water/vegetated dunes and dry ridges covered with pine forest. This provided a relatively constant spatial distribution of and environment that could be explored using the model. Where land use changes did occur, e.g. as a result of planned tree felling, it was possible to investigate the impact of land use change on the water balance. Other forms of spatial variability were also investigated, including the impacts of costal erosion and accretion which served to modify the hydraulic gradient in the aquifer system.

8.2.2 Temporal variability

Temporal changes in aquifer recharge are also important. Many studies tend to assume an annual value of excess rainfall that contributes to groundwater recharge. The daily water balance modelling approach adopted here enabled the calculation of soil moisture recharge and percolation to the water table. This was dependent on rainfall and a soil water balance which enabled the estimation of actual evapotranspiration and hence a more realistic value for aquifer recharge. Year to year variations in daily rainfall patterns were shown to significantly influence soil water status, and hence aquifer recharge. It was possible to predict with some accuracy, the month by month changes in water table levels in the dune system, and this included the impacts of extreme years such as the droughts of 1975-76 and very wet periods in 2000-01.

By demonstrating that the water balance model was able to replicate observed behaviour over such as wide range of climatic conditions, confidence was gained in its ability to explore the impacts of climate change such as changes in air temperature (which impacts in actual evapotranspiration) and rainfall amount and seasonality. The technique of simulating daily SMD's and recharge using stochastic models has not been done before in studies of climate effects on groundwater. This approach is an important step forward to contributing to a wider understanding of the climatic impacts on groundwater recharge in coastal aquifers.

8.3 Uncertainty

The recharge model was successfully calibrated against about 30 years of observed groundwater levels from the Ainsdale National Nature Reserve. The model worked well in both sand dune area and area covered by pine trees. After calibration, the model has been used to investigate the significance of sea level rise, coastal erosion and climate change (changes in precipitation and temperature) on shallow groundwater levels. However the results of the calculations are build on many modelling and data assumptions which will produce uncertainty in the calculated results. The followings section discusses the issue of uncertainty and goes on to describe how the use of the Monte Carlo modelling approach used in the thesis was able to capture and quantify the magnitude of these uncertainties

8.3.1 Uncertainties in input data

The water balance modelling approach depends on the availability of suitable climatic and system data. This part describes uncertainties in the historical data rather than the synthetically generated climate data, which will be discussed later. Rainfall is usually assumed to be one of the more accurately measured climatic variables and the published data are usually taken at face value. However this does ignore issues such as rain gauge location. In an extremely windy site an old fashioned 5 inch cylindrical gauge 300mm above ground level might under record rainfall by up to 6%. In this work the published data were taken as accurate records. At the opposite extreme, the met site at Ainsdale is slightly under exposed and might be affected by a small rain shadow effect from nearby trees. To create a long run of coherent climate data it was necessary to correlate rainfalls from various sites such as Ainsdale, Bidston, Blackpool and Ringway. Uncertainties and potential errors in the Ainsdale data sets were evaluated by comparison with these standard meteorological sites.

Potential Evapotranspiration was estimated using the Penman Montieth equation. This is widely recognised as a standardized method for estimating PE based on climatic data. Again the climatic data sets used were based in records at Ainsdale but were cross correlated with Met Office weather data sets to check for consistency.

Groundwater level observations were made at the same sites by trained staff at Ainsdale, so the measured values were accepted. However there is a possible issue of datum drift as the measurements were made relative to concrete datum slabs placed nest to the observation wells.

Aquifer property data were obtained from field and laboratory work done by Clarke (1980) and these were evaluated in the model testing and calibration work.

Similar issues existed with the Thai case study data. In this case it was necessary to reply on official published data sets as no others were available.

8.3.2 Uncertainties in the sub models

The main water balance model used sub models to compute aquifer recharge. These models consisted of evaluations of potential evapotranspiration, actual evapotranspiration, soil moisture deficit, tree interception, groundwater flow and surface flow.

Potential ET was computed using the well known Penman Montieth equation and this has been adopted as the standard methodology for estimating PE in many countries and in the UK it underpins the Met office MORECS system. However the Penman Montieth equation has inherent assumptions and the theoretical surface defined in the equation is rarely achieved in the natural environment, so it is difficult to evaluate the uncertainty in the estimate of PE. Smith (1992) produced an unpublished report "FAO expert consultation on equations for estimating evapotranspiration" that was the fore-runner for the FAO Penman Montieth equation. This indicated that the equation could estimate PE within +/-10% of a well run lysimeters experiment. Clarke (1980) carried out a sensitivity analysis of the Penman equation, which shows its sensitivity to variations in climatic data. A similar analysis was carried out by Xu et al (2006) (Figure 8.1) This showed that the equation is most sensitive to variations in relative humidity and net radiation and is less sensitive to changes in wind speed.

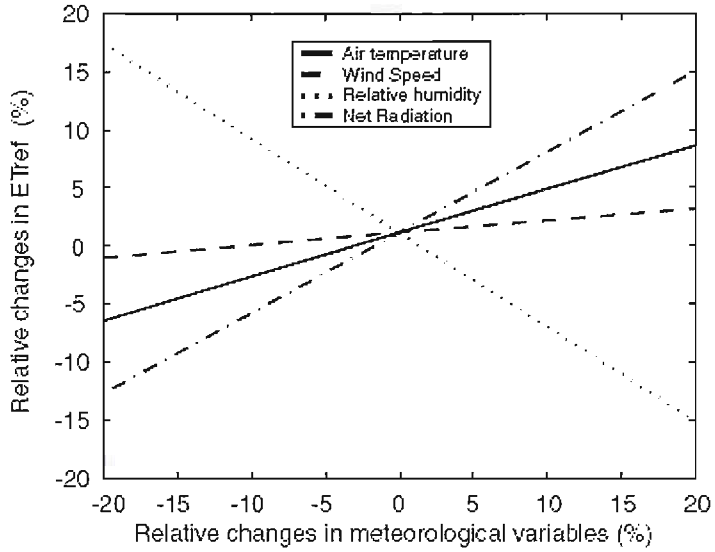


Figure 8.1: Sensitivity of the Penman Montieth equation to meteorological component errors (From Xu et al, 2006).

Figure 8.1 illustrates how sensitive the Penman Montieth equation is to changes in vapour pressure. Using historical data it was necessary to depend on observations made and the correlations between metrological sites showed that the data used was consistent. However this does raise a key issue relating to future climate data sets and how they are generated.

Actual Evapotranspiration is a key model parameter which is derived from both the PE estimate, rainfall and a sub model used to estimate soil moisture deficit. In this work the well known CROPWAT methodology was used to estimate AE. However the calculations depend on the soil moisture deficit sub model which is a function of assumed crop rooting depth, and soil water availability. The CROPWAT model as chosen for this work because it includes an SMD and AE model which ahs been proven to work well over a wide range of soil types and vegetation covers around the world. It is not possible to fully quantify the uncertainty in the models used to estimate of AE, especially as a large rainfall event in summer will reduce the SMD rapidly and hence raise AE to PE in a few hours. The model calibration at Ainsdale was used to identify the most appropriate values for variable such as rooting depth and moisture holding capacity.

Tree evapotranspiration and interception loss calculations were based on a work published by Calder and Gash. Much of these results depend on locally derived parameters such as beta and gamma and the fact that transpiration is often assumed to be similar to that of a grass surface and surprisingly this does not seem to vary much across Europe. This is an area which deserves more attention. In the calibration at Ainsdale, the models were able to support Calder's and Gash's findings that ET from pine trees is typically 10-20% higher than from a grass surface.

Groundwater flow from the model was found to be a relatively constant component of the water balance model. It was computed initially using geological information gathered by Clarke (1980) and estimated of permeability. The groundwater flow estimates were then tuned by varying Transmissivity in the waterbalance model to produce a satisfactory fit with long term water table level measurements. There was little difference between groundwater flow estimates made using the Darcy or Dupuit assumptions.

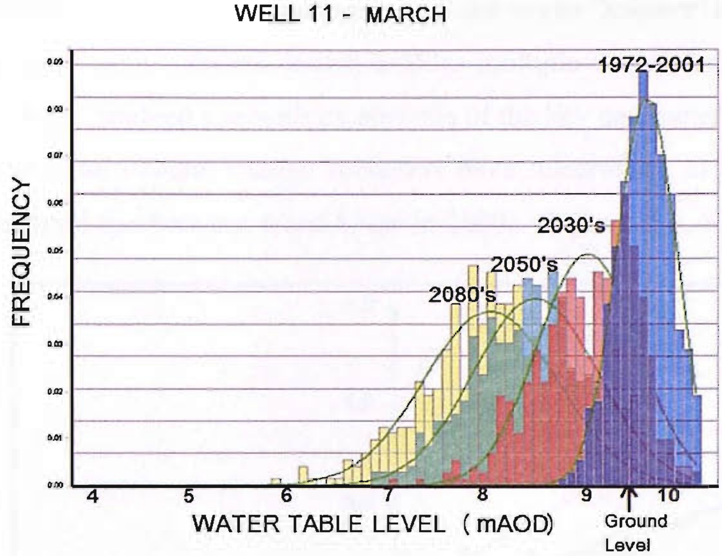
8.3.3 Uncertainties in the future climate scenarios

Future climatic conditions are difficult to predict and the large number of global and regional climatic models that exist today reflect that fact. This work is beyond the scope of this thesis and the result shown here much be read with these uncertainties remembered. A further problem is the down scaling of regional climatic change models to a local level and the generation of seasonal data sets into daily time series such as those generated by the BETWIXT project. Again this work is outside the range of this PhD. However to model uncertainties in these data, the Monte Carlo method used were able to show how changes in the time series of data sets can have big effect on the predicted results of the ground water levels. This is a new approach and has not been done before. It could be improved by running the models using "Low" and "High" emissions scenarios BETWXT data sets, but for the reasons of time this was not yet done.

8.4 An approach to dealing with future climate data uncertainty

Change to precipitation sequencing under climate change was investigated by stochastically re-sampling from previously generated precipitation data sequences produced by the BETWIXT project. The Monte Carlo modelling approach was chosen to create new sequences of climate data for the water balance model by re-sequencing the (scaled) BETWIXT data. The original BETWIXT data was assembled into months, and then new sequences of months of data were created by adopting a randomized sampling strategy. This approach was chosen as it ensured that the total amount of rain in each simulation was constant, but the timing was changed in each run. A randomised re-sampling strategy of the synthetic future climate data sets has enabled the construction of 1000 possible future realities for the water table system at Ainsdale. The 1972-2001 values in figure 8.2 show the effects of the natural variation of the measured historical climate and rainfall data on water table levels.

The re-sampling process used for the future climate data produces more and more spread further into the future, The usefulness of using the stochastic approach compared with running the model with fixed sequences of the same (average) data against is that it provided the additional understanding and knowledge such as ability to analyse the future frequency of occurrence of high and low water table levels as well as the overall trends. As a result the understanding of climate change impacts on groundwater systems has been improved.



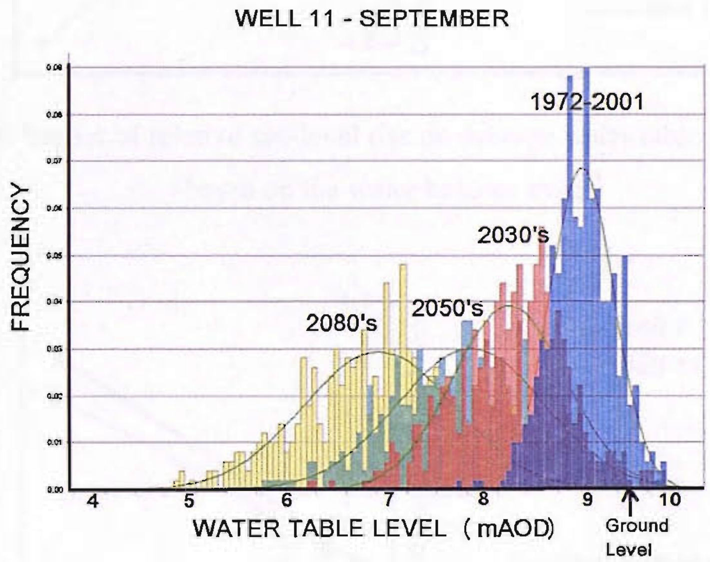


Figure 8.2: The expected frequency of occurrence of water table levels for well 11 for wet conditions in March and dry conditions in September

8.5 Sensitivity of predicted water table levels to other factors

A sensitivity analysis of the water balance model was performed to identify which factors will be the most important controlling coastal groundwater change in the future. These factors were programmed into the water balance model using the Crystal Ball simulation software, which enables multiple model runs to be analysed statistically. It also enabled a sensitivity analysis of the key parameters in the model to be carried out. The climate change scenarios have uncertainty in their values e.g. projected sea-level rise between 6 and 63cm in 2080s. (Figures 8.3, 8.4)

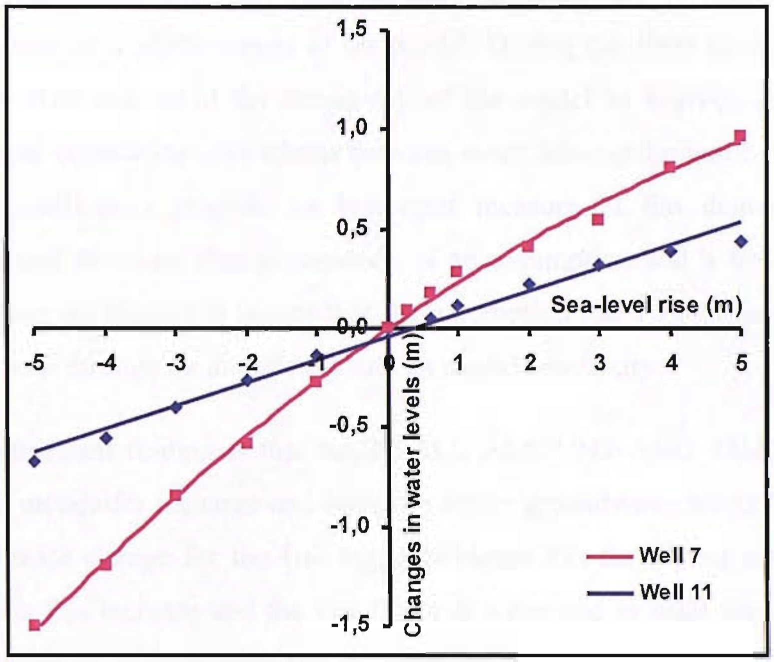


Figure 8.3: Impact of relative sea-level rise on average water table for well 7 and 11 based on the water balance model

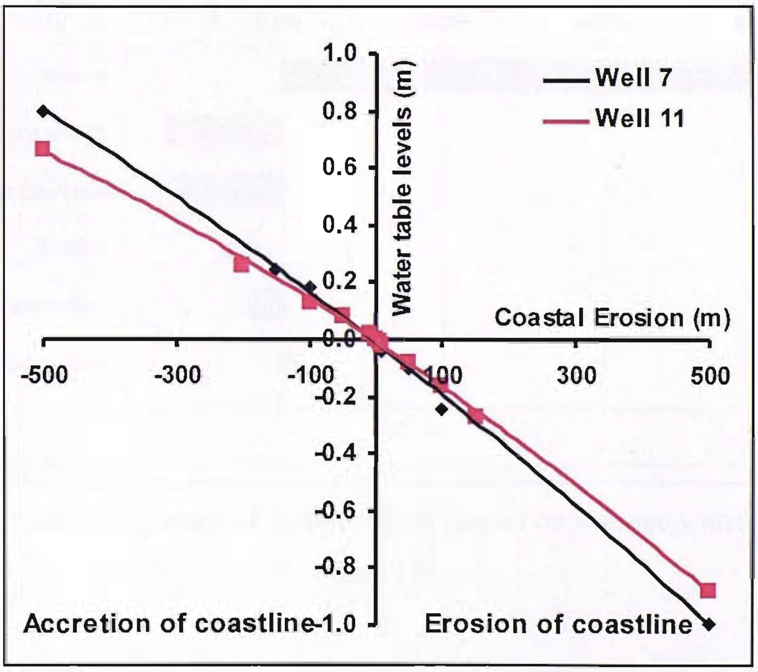


Figure 8.4: Impacts of coastal erosion on average water table levels for Well 7 and Well 11 based on the water balance model

To deal with uncertainties, these uncertainties were analysed by running a Monte Carlo simulation of 1,000 instances of the model. During the 1000 model simulation runs, Crystal Ball calculated the sensitivity of the model to a given parameter by computing rank correlation coefficients between every assumption and every forecast. Correlation coefficients provide an important measure of the degree to which assumptions and forecasts change together. If an assumption and a forecast have a high correlation coefficient, it means that the assumption has a significant impact on the forecast both through its uncertainty and its model sensitivity.

The most significant finding is that RAINFALL AMOUNT AND TIMING has the largest effect on aquifer recharge and therefore future groundwater levels (Figure 8.5). Although climate change for the UK suggests higher PE, the drying out of soils in summer limits this increase and the key factor is when and at what time of year the rain falls, in relation to the current soil moisture deficit.

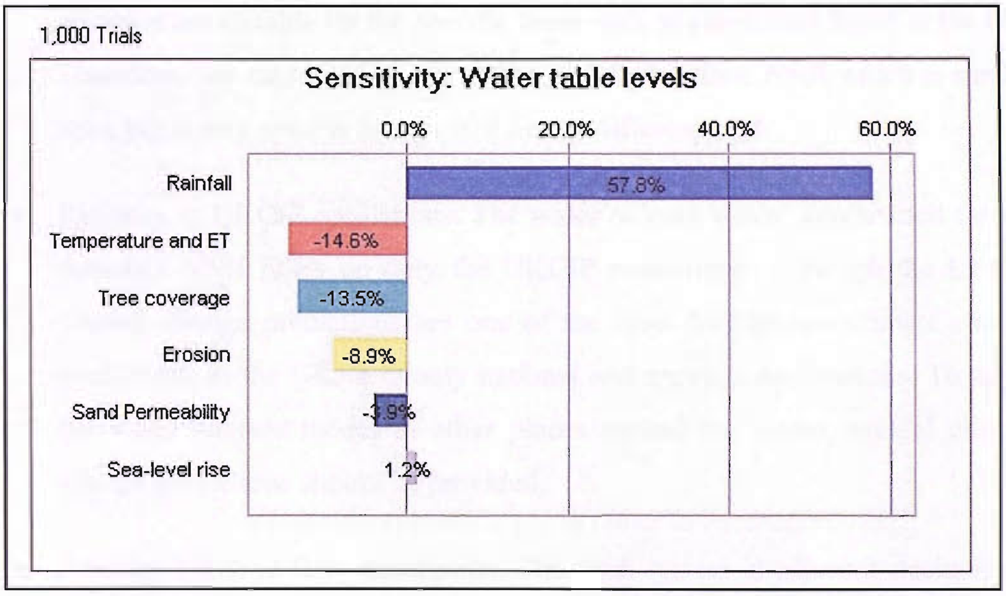


Figure 8.5: Sensitivity chart of factors which impact on average water table levels (Well 11)

8.6 Weaknesses in the approaches used

Weaknesses in the approach created by assumptions in the water balance model are described as follows:

- Constant vegetation assumption. The water balance model estimates evapotranspiration by assuming constant vegetation for whole case study area which is unrealistic. In general, the vegetation grown in coastal areas is normally combined with various types of vegetation inconsistently. The water balance model would be more accurate if calculations of evapotranspiration and interception are based on actual land use and vegetation types.

- Interception parameters in Calder model. Interception estimation using Calder model consists of several parameters. Some parameters can be used in general, but some parameters such as interception parameters β and γ in Calder model equation are suitable for the specific areas such as coniferous forest in the UK. Therefore, the calibrated model works well in Ainsdale NNR which is similar area, but it may need to be adjusted for the different area.

- Reliance in UKCIP predictions. The water balance model constructed for the Ainsdale NNR relies on only the UKCIP predictions. Although the UKCIP climate change predictions are one of the most well-known climate change predictions in the UK, it is only national and regional applications. To apply the water balance model in other places around the world, several climate change predictions should be provided.

- Average overland flow assumption. The ditch system in adjacent slacks is the only possible mechanism for the removal of surface water in the central part of the NNR. It was unfortunate that there was no direct method of quantifying overland flow. Therefore, the amount of water the ditch carried out of the

Reserve was approximated by assuming the average flow rate to be about 10-30 litres/second based on Clarke (1980). This assumption is appropriate for Ainsdale, but overland flow estimation would need to be improved to be applied to other places around the world.

8.7 Possible future improvements

Additional research that could be done to improve the models and the accuracy of the result are proposed as follows.

- The model could be improved for using in both confined and unconfined aquifers. The groundwater flow calculation and aquifer property parameters such as hydraulic conductivity, aquifer thickness and effective porosity need to be available for chosen by the user.

- Different climate change scenarios produced by various projects or organizations around the world could be selected for using with the model. The water balance model is currently relies on only the UKCIP02 predictions and the BETWIXT stochastic generators. Other new generators are becoming available (e.g. EARWIG). The accuracy of the result from the water balance model will be more effective if climate change prediction scenarios for other places around the world are provided and can be selected by the user.

- The model could be refined for tree interception and also changes in vegetation types as it was set to be constant in this research. Evapotranspiration was estimated by assuming constant vegetation for whole case study area which is unrealistic. Coastal vegetation is normally combined with various types of vegetation inconsistently such as coniferous trees, scrubs, and grasses. The water balance model would be more accurate if calculations of evapotranspiration and interception are based on actual land use and vegetation types. Therefore, the model would be used in the various types of land use.

- Monthly effective rainfall and PET would be interpolated into a daily format directly in the water balance model to run the daily soil moisture deficit model. In this research, monthly effective rainfall and PET was interpolated using the CROPWAT model. Therefore, the model would be more convenient and easier for the user if these data could be imported directly in the water balance model.

- Groundwater pumping from the aquifer could be built into the modelling if adequate data were available to estimate the water table levels.

- Saline intrusion calculations could also be developed. Then, the model would be more effective to investigate impacts of sea-level rise on the groundwater recharge together with how far the distance of saline intrusion is further inland.

- The water balance model can be easily applied to places where aquifer properties and land use are similar to Ainsdale. The model can also be applied to other places around the world, but parameters in the model such as interception factors and overland flows may need to be adjusted.

- **At Ainsdale**, improvement of the observed groundwater level data is required; for example; more monitoring wells (perhaps with data loggers) especially under tree areas. This will improve the result of the impacts of climate change on groundwater in pine tree areas.

- **In Thailand**, it is necessary to have more information that could be collected in Bangkok to test and calibrate the Thai model such as water table level data. Furthermore, regional climate change scenarios are needed complete with estimates of their uncertainty. It will be useful to generate expected climatic data such as rainfall, temperature, humidity, sunshine, and wind speed for this region. Moreover, the model could further be developed by improving the understanding of the water inputs and water outputs in each aquifer due to a multiple confined aquifer system in Thailand. However, groundwater pumping data in each aquifer is necessary.

CHAPTER 9

Conclusion

Groundwater in coastal aquifers is affected by many environmental factors including rainfall, evapotranspiration, sea level, coastal erosion, aquifer recharge and land use. The key factors that affect groundwater levels in a coastal sand dune system in North West England have been evaluated up to the year 2095 using the stochastic water balance model developed in this work. The water balance model contains physically-based representations of ET (Penman-Monteith), Interception (Calder), soil moisture stress, groundwater flow (Darcy/Dupuit), was used to investigate the most important factor affecting groundwater quantity in coastal aquifers. The model was successfully calibrated against 30 years of observed groundwater levels from Ainsdale National Nature Reserve.

After calibration, the model has been used to investigate the relative importance of sea level rise, coastal erosion and climate change (changes in precipitation and climatically driven evapotranspiration) on shallow groundwater levels using a dynamic model rather than steady state solutions used in previous studies. In particular, changes to precipitation amounts and sequencing were investigated, by stochastically sampling from generated precipitation time series whilst keeping the overall precipitation amount constant.

As a result, the understanding of climate change impacts on groundwater systems has been improved. Previous work acknowledged that fact that climate change will affect aquifers but used a deterministic approach by making a step shift in the average climate conditions. The simulation work in this thesis has shown that the timing of rainfall has a very significant effect on recharge. By using sequences of daily rainfall events and by repeated re-sampling of the data series of daily rainfalls, simulations of future aquifer response were shown to exhibit the natural variability seen in historical data. A statistical analysis of the likely effects of climate change over the next 80 years on aquifer recharge was possible by statistically analyzing 1000 runs of the re-sampled data sets, providing much more insight into the range of possible outcomes and behaviour of shallow groundwater systems. This is a valuable contribution to the understanding of the future pattern of behaviour of unconfined aquifer systems and could be applied to other aquifers such as the UK's Chalk groundwater resource.

English case study – specific outcomes

The model was successfully calibrated against a 30 year set of observed water table level data at Ainsdale. The modelling of future water table levels, simulated using UKCIP climate change scenarios, showed that water table response was highly dependent not only on the amount of rainfall but when it falls and the size of each rain storm event, especially in forested areas. The work found that for this dune system the average water table levels are expected to fall by 0.5-1.0m in the next 100 years, with prolonged periods of low water table levels. Areas with pine trees are expected to become even drier, with the water table level falling up to 1.5m. This will have the effect of drying out the inland slack floors and reducing the biodiversity of these areas. The effects will be smaller closer to the coast. This will impact on both the vegetation and the wildlife in the sand dune system. These results suggest that there are likely to be significant changes in the eco-hydrological characteristics of the dune systems, especially in the dune slack areas which are of high biodiversity (Davy et al, 2006). It is expected that species dependent on standing water for breeding (such as the Natterjack Toad) will become threatened.

The model also showed that pine trees intercept about 150mm of rain each year, lowering the water table levels under the pine trees by 0.5-0.6m. This is in agreement with water table levels observed by Clarke (1980) and CEH (2006), and supports other work that suggests that pine trees have a significant effect in reducing aquifer recharge in temperate climates (Calder et al, 2002; Atkins, 2004)

Sea level is expected to rise in NW England by +63cm under High Emission scenario and +3cm under Low Emission scenario in 2080s (UKCIP 2005, Lymbery et al. 2007). Erosion and accretion will vary along the coastline but the model results suggest that the effect will be to raise water table levels by +0.14m by every 100 meters of accretion and decrease it by 0.18m for every 100m of erosion. Furthermore, wells nearer to the sea show larger impacts from erosion and sea level rise than those further inland. Erosion will impact on the water table level more than sea-level rise. However, a rise in sea level is one of the causes of coastal erosion. Furthermore, together with decline in water table levels, sea-level rise will exacerbate saline intrusion. As a result of 1m reduction in groundwater level, the depth of saltwater/freshwater interface will rise about 40m. This may influence both the plants and the animals in the sand dune system.

The sensitivity analysis of the water balance model identified the most important environmental change factors that affect coastal aquifer groundwater. This included evaluating a range of land uses, climatic change, sea-level rise and coastal erosion. The effects of uncertainties in expected change in these input parameters were explored using a Monte Carlo simulation of 1,000 instances of the model. It would not be practical or effective to build and run the complex models such as MODFLOW so many times. The sensitivity analysis shows that the most important parameters were rainfall, followed by change in temperature and evapotranspiration, tree coverage and coastal erosion. Smaller impacts were found from uncertainties in system properties such as sand dune permeability. Sea-level rise and vegetation were the least important factors affecting coastal groundwater compared with the environmental factors. The impact of sea-level rise was relatively unimportant over a short time period of 50 years, but the relative importance of these factors will probably change further into the future depending on the magnitude of each factor.

A Thailand case study – specific outcomes

The expected changes of groundwater levels in the Thailand Case study were calculated using the water balance model which was partly constrained by lack of shallow groundwater level data. However the conceptual model was applied to surface recharge by perturbing the current climate data with two expected climate change scenarios and generating multiple instances of future rain/climate events. Climate change potentially increases temperature and alters rainfall patterns (the rainfall variability and rainfall intensity) in Central Thailand. Average rainfall is expected to decrease in the study area and this is expected to decrease the groundwater recharge. An increase in temperature that leads to an increase evapotranspiration is also a cause of water reduction in the rivers.

Although the model was effectively an exploratory model based on limited observed data, results suggest that recharge will decrease, causing a fall in water table levels and surface runoff. Runoff could decrease more than 50 per cent in certain areas of the lower basin, agreeing with MSTE (2000). This will lead to water shortages in the central plain, especially during the dry season. Water scarcity will impact on the irrigated areas, and will cause significant effects on agriculture such as stresses on cropping pattern, and crop grown. Additionally, a decrease in surface runoff and groundwater flow out to the sea will contribute to increased saline intrusion in coastal areas.

Although the effects of sea-level rise were relatively small on the simulated groundwater levels in the water balance model, it will exacerbate the seawater intrusion problem because it will change the hydraulic gradient between fresh groundwater and the sea. At present, saline intrusion in the Chao Phraya River is already a critical problem due to over-pumping of groundwater and land subsidence, especially during the dry season. Recent analysis of monitoring data from the

Department of Groundwater Resources has shown an increase in salinity of the three most heavily used aquifers especially in Samut Prakan and areas along the Chao Phraya River.

Since management of water resources has become increasingly critical for sustainable development, Thailand will need to expand the understanding of potential impacts of climate change on water resources. Improving groundwater resource management is urgently needed together with surface water management. An effective implementation of the groundwater basin management is recommended to avoid irrevocable damage to aquifers; for example, construction of subsidence and salinity monitoring stations and also extension of monitoring to the surrounding areas, improved discharges and water gate control, limitation of groundwater use and water permits in the critical zone in cooperation with redefinition of the new critical zone of groundwater. Moreover, artificial recharge of groundwater should be considered for the recovery of water levels and reduction of land subsidence and saline intrusion. Recharge water may possibly be taken from the Chao Phraya River or from surplus water in the rainy season, but the availability of water to do this in the future will be reduced, especially outside the monsoon season.

APPENDIX A

Thailand case study results

The following section shows the results from Thailand case study (Chapter 7) including the charts of water table levels and drainage outflow for each scenario.

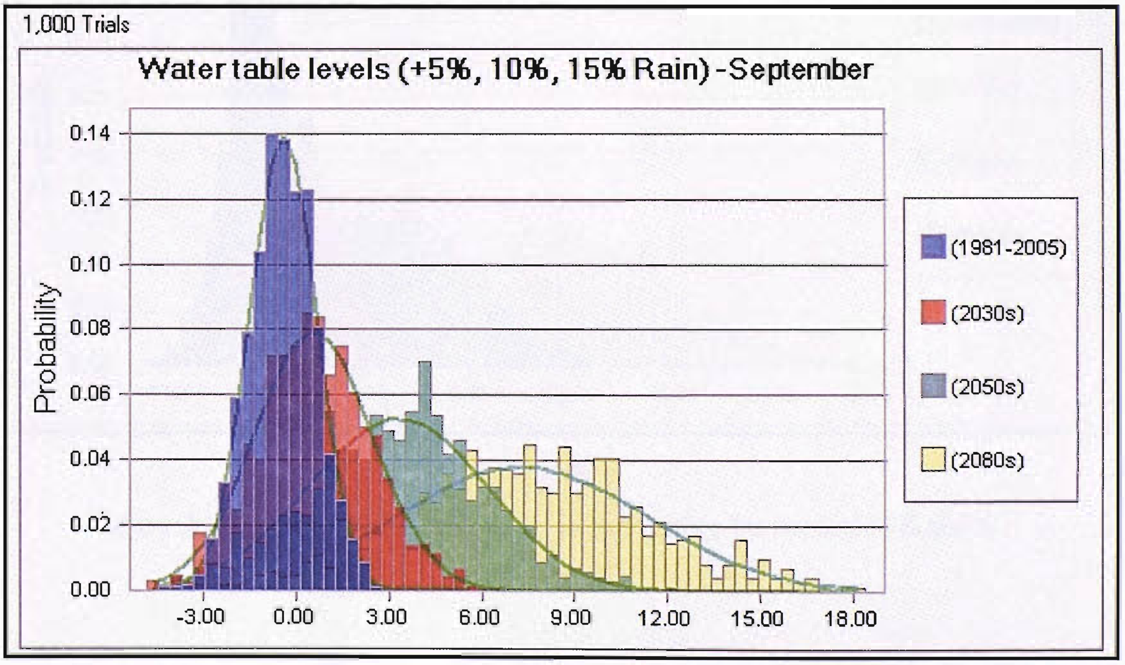
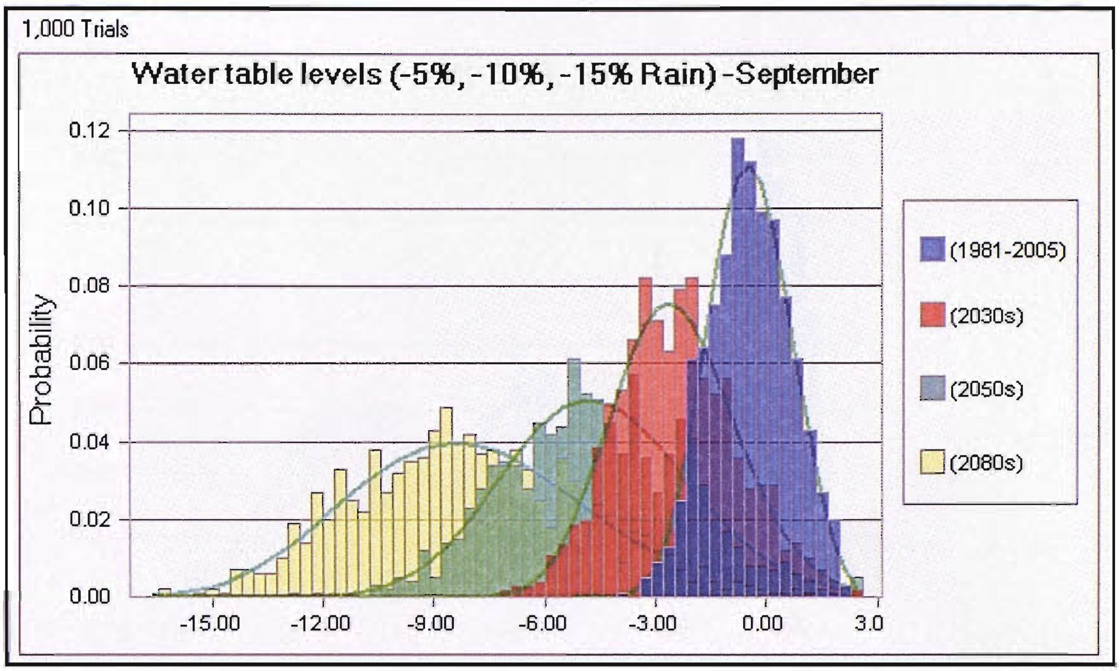


Figure A.1: Water table level in September for scenario A



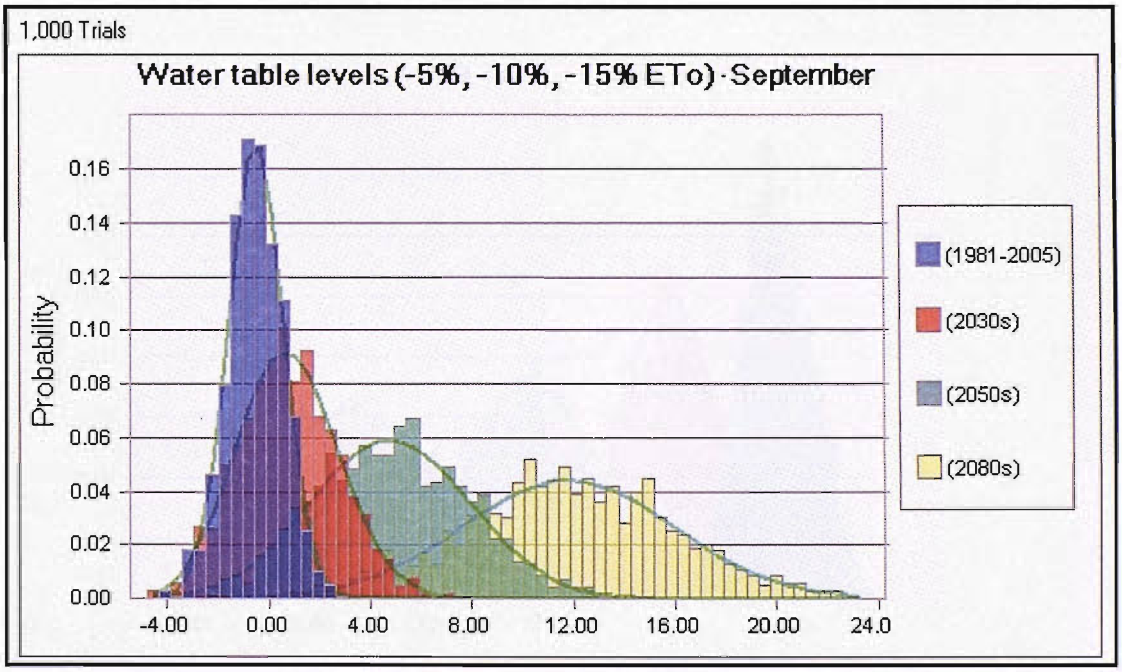
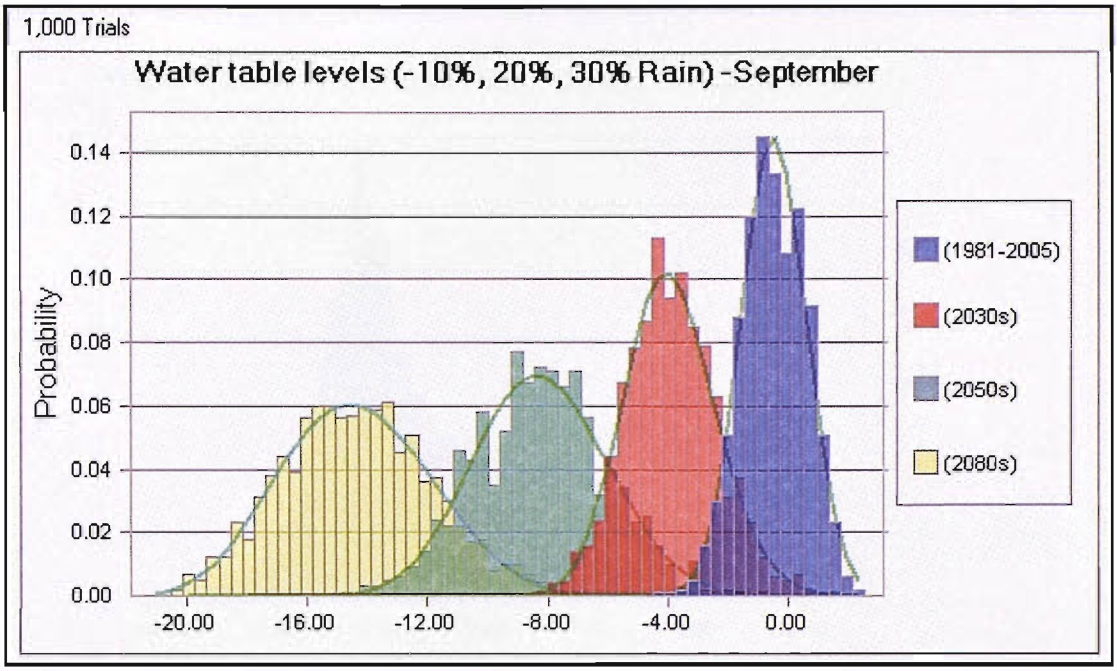


Figure A.1 (cont.): Water table level in September for scenarios B and C



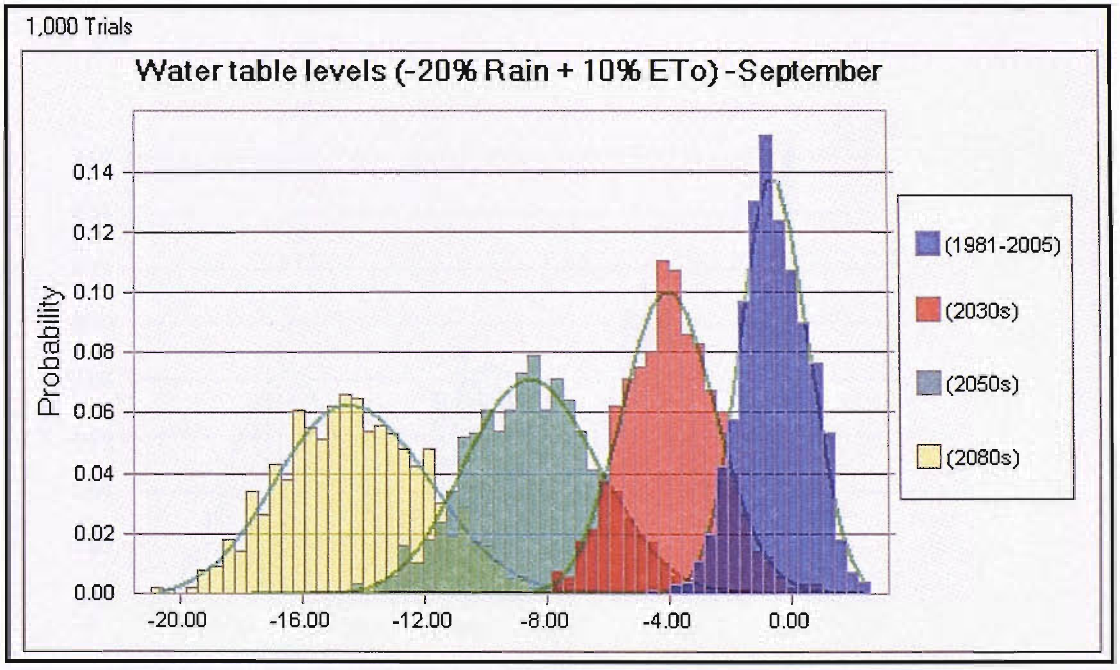
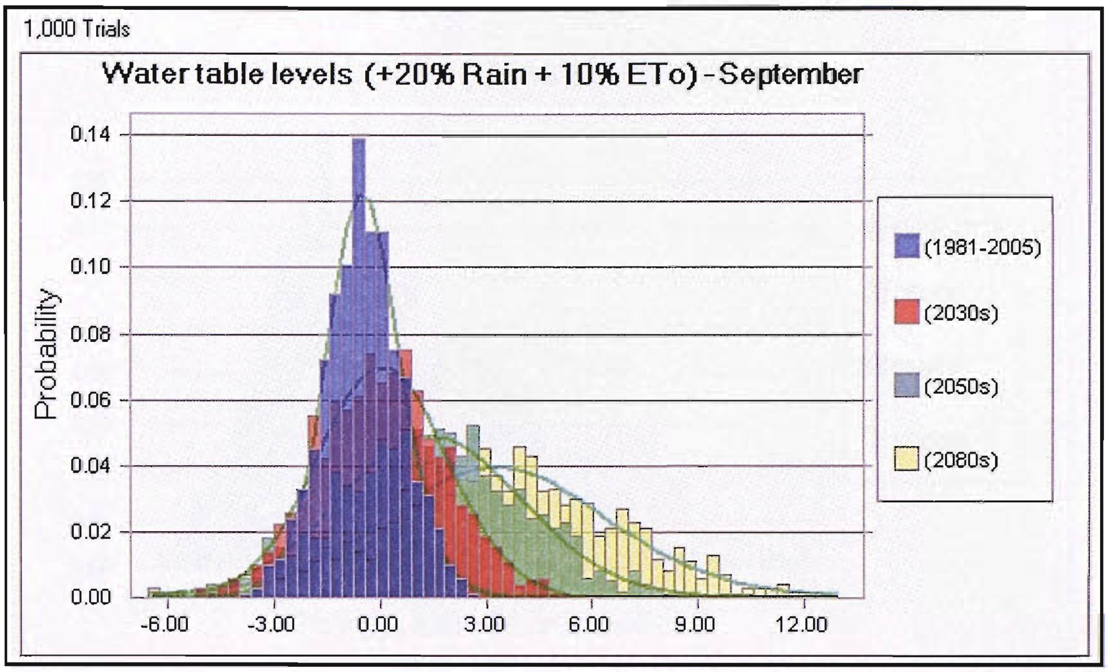


Figure A.1 (cont.): Water table level in September for scenarios D and E



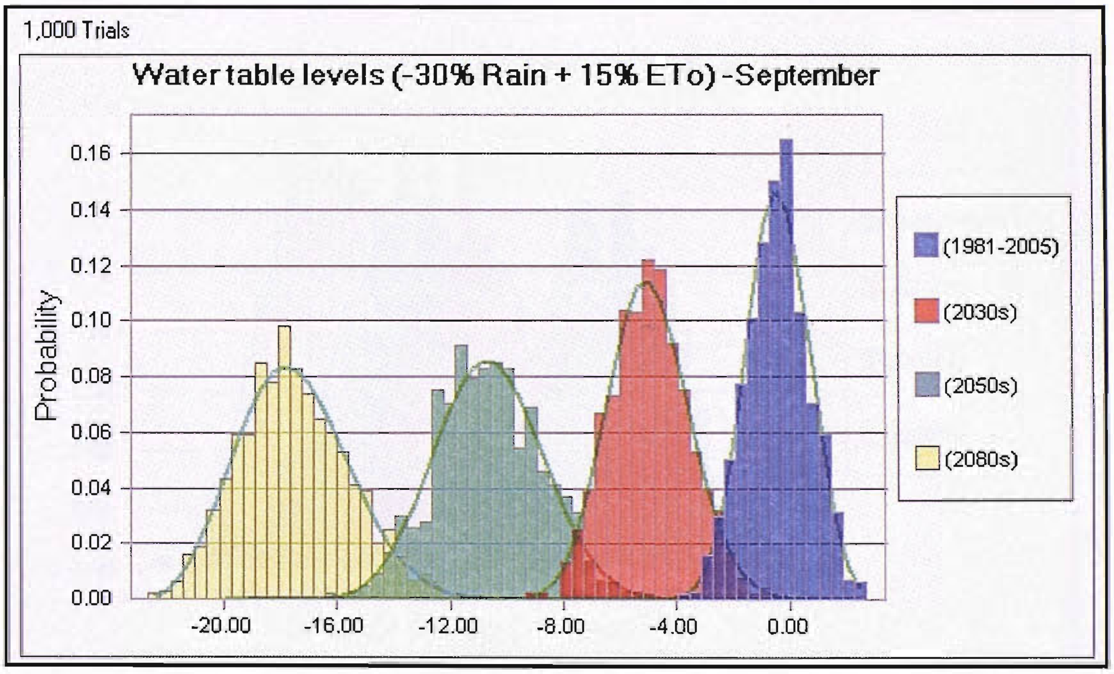
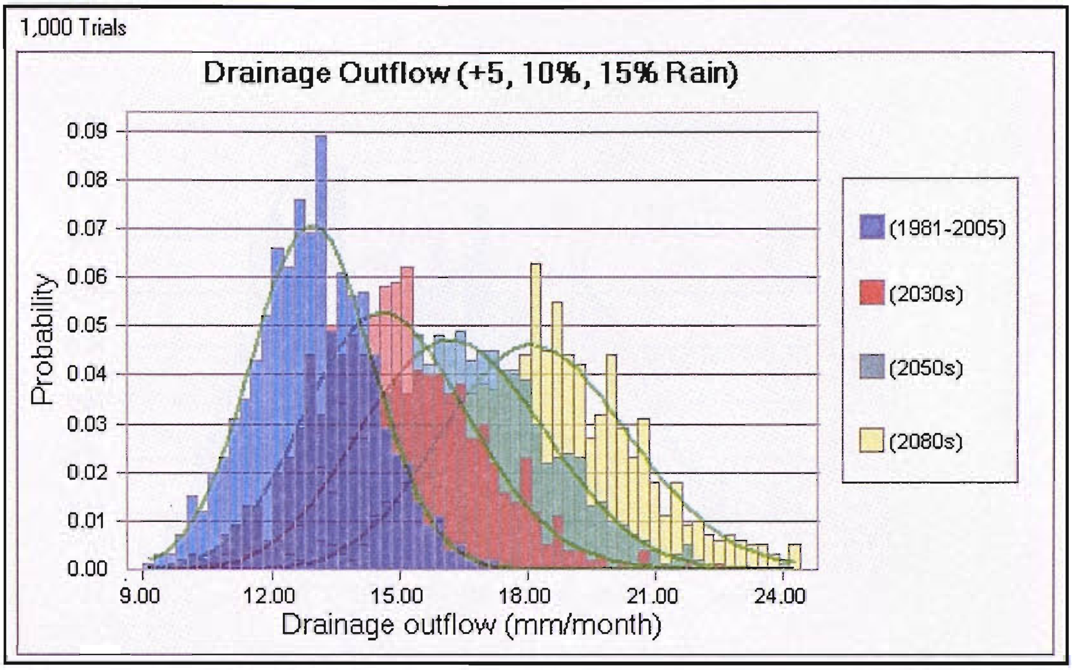


Figure A.1 (cont.): Water table level in September for scenarios F and G



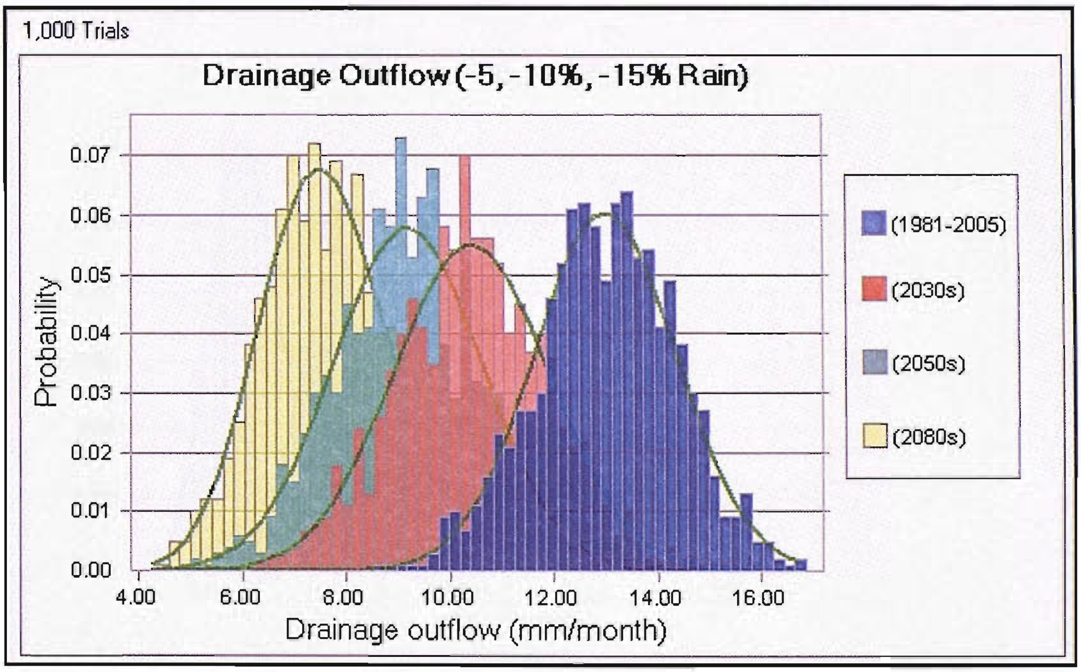
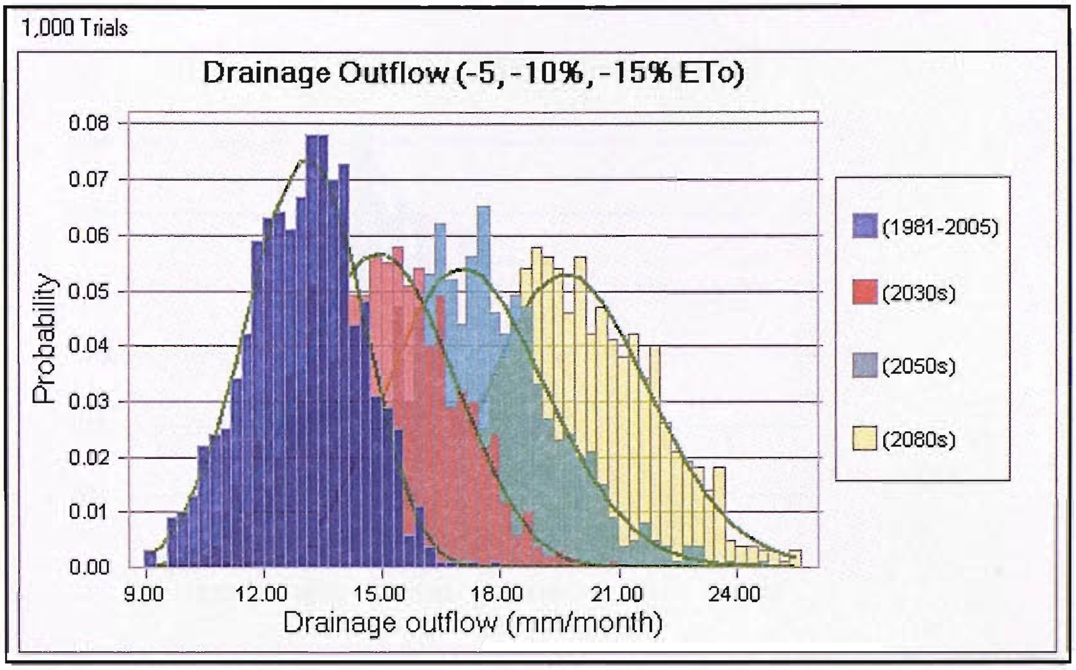


Figure A.2: Drainage outflow for scenarios A and B



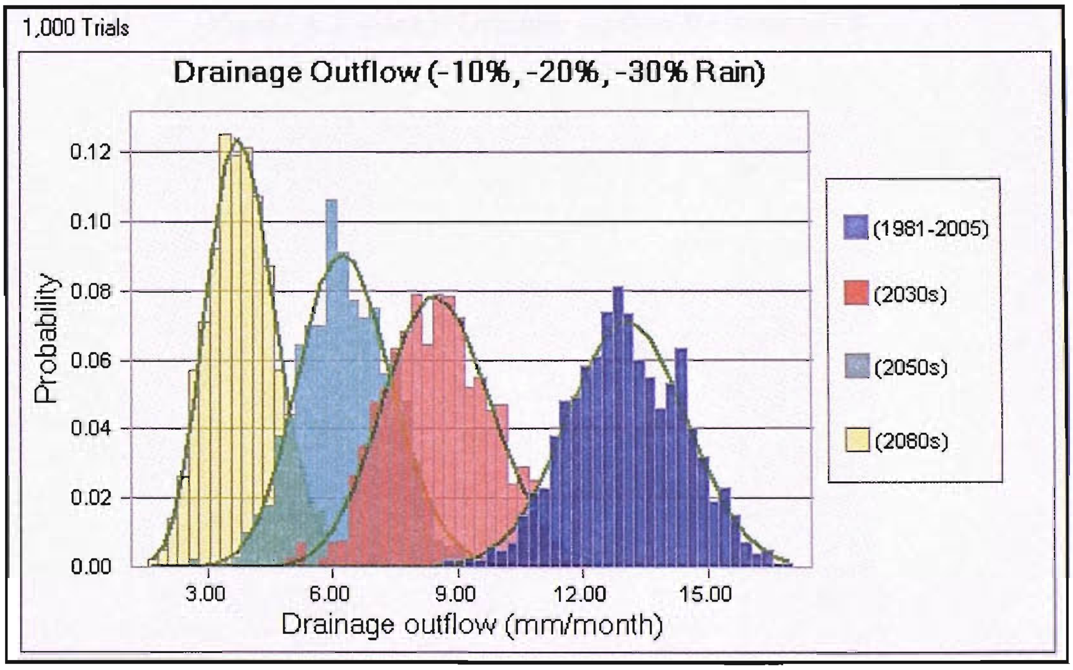


Figure A.2: Drainage outflow for scenarios C and D

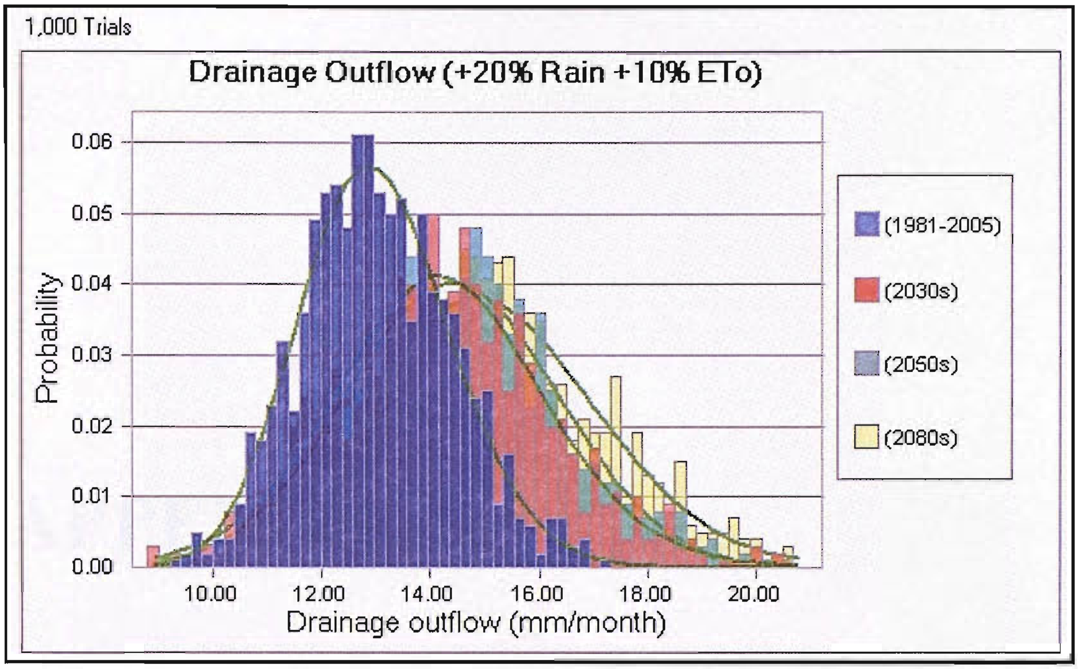


Figure A.2 (cont.): Drainage outflow for scenarios F

APPENDIX B

Example of conference presentations

- **Poster presented at YCSEC in 2006 at the University of Southampton**
- **Poster presented at IWA UK Young Researchers Conference in 2004 at the University of Southampton**
- **International conference publication at ICCD in 2007 at Santander, Spain**
- **Clarke D., and S. Sanitwong_Na_Ayutthaya, 2007,** A Probabilistic Assessment of Future Coastal Groundwater Levels in a Dune System in England, Proceedings of the International Conference on Coastal Dunes 2007, October, Santander, Spain

Poster presented at YCSEC in 2006 at the University of Southampton

Impacts of climate change and sea-level rise on groundwater systems in coastal aquifers

Sarinya Sanitwong-Na-Ayutthaya and Dr Derek Clarke
School of Civil Engineering and the Environment, University of Southampton

Aims of research: To identify which factors will be the most important in affecting coastal aquifers over the next 100 years in the light of predicted climate change and sea level rise.

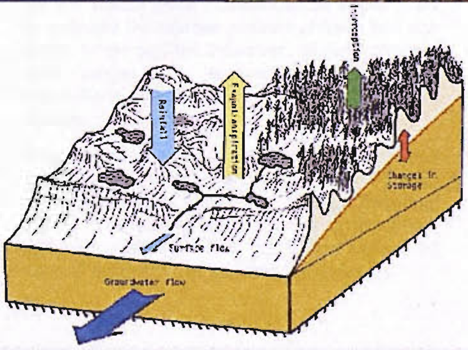
Climate change has many potential impacts on the environment. Possible problems that would affect coastal aquifers are :-

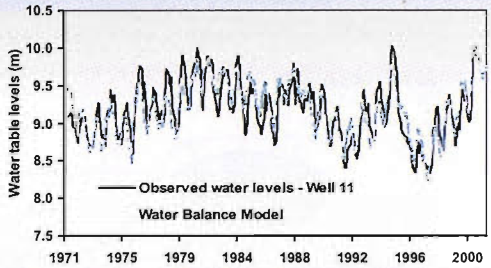
Temperature rise - increased evapotranspiration
Precipitation change - decreased recharge in summer

These will cause groundwater levels to fall, but higher rainfall in winter may counteract their effects.

Sea level rise will cause saline intrusion and more extreme events such as storms will cause coastal erosion steepening the water table path

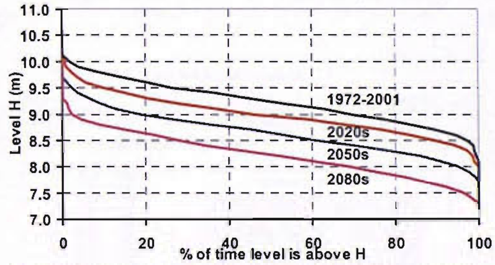
Study site: work is being carried out on a coastal sand dune system at Ainsdale, 25km north of Liverpool where a 30 year set of groundwater level data is available.





A Water Balance Model has been constructed and tested against the observed well levels for 1972-2002. The model comprises a daily simulation of rainfall, soil moisture deficit and recharge based on an AET sub model using the Penman-Montieth equation and crop/soil descriptors. The model had been successfully calibrated by parameter estimation.

Future climate change scenarios have been developed based on UKCIP'02 scenarios. A Monte Carlo modelling approach has enabled the model to run with thousands of sequences of rain patterns. The overall trend shows that groundwater levels will fall by about 1 metre in the next 100 years, causing the fragile ecosystems in the dune floors to dry out completely.



Key findings are that on average, hot dry summers will cause a reduction in total evapotranspiration due to soil moisture deficit and these will be modest overall decrease in groundwater recharge. Decrease in groundwater flow out of the dunes will affect uplift interface between salt and fresh water. Moreover, wetter winters will cause an increased range of amplitude of water table levels.

Further work is continuing with assessment of the impacts of sea-level rise and vegetation change on groundwater flow conditions. Then, the model will be applied to other sites around the world.

SUPERVISOR : DR. DEREK CLARKE
SPONSOR : GOVERNMENT OF THAILAND
START DATE : 2 FEBRUARY 2004

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT
UNIVERSITY OF SOUTHAMPTON

Poster presented at IWA UK Young Researchers Conference 2004

Impacts of climate change and sea level rise on groundwater systems in coastal aquifers

Sarinya Sanitwong-Na-Ayutthaya and Dr Derek Clarke
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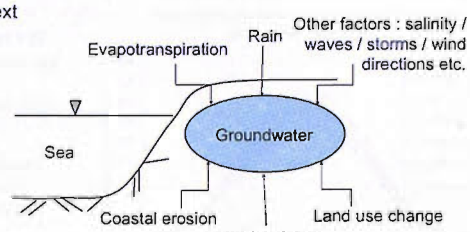
Aims of research: To identify which factors are the most important in affecting coastal aquifers over the next 100 years in the light of predicted climate change and sea level rise.



Conceptual model of factors which may affect coastal groundwater systems

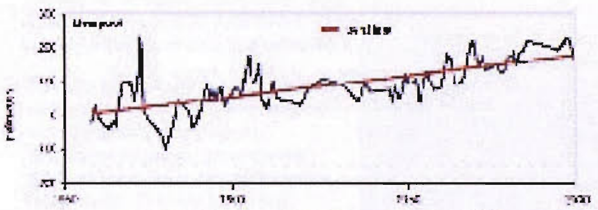
The term "climate change" usually refers to recent changes in climate that have been observed since the early 1900s. Climate change has many potential impacts on the environment. Possible problems that would affect coastal aquifers are :-

Temperature rise - increased evapotranspiration

Precipitation change - decreased recharge

More extreme events - storms / coastal erosion

Sea level rise - saline intrusion



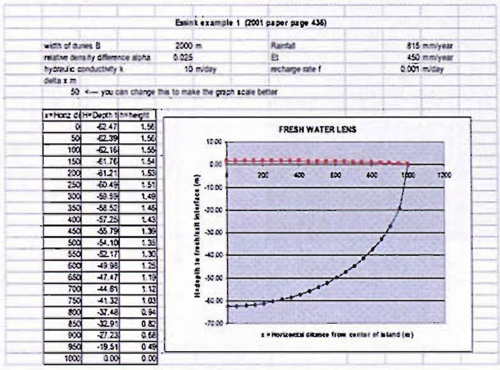
Trend of changes in sea level at Liverpool from 1860 - 2000

Sea level rise would increase the risk of flooding and coastal erosion. In addition, it may have a significant effect on the boundary between fresh water and sea water in coastal zones. Coastal aquifers are recharged by the surplus of rainfall over evapotranspiration, allowing for any net inputs or losses due to man made or natural groundwater flow.

The impact of sea level rise on groundwater systems is being investigated. Essink (2001) illustrated that two important factors are the aquifer recharge rate and hydraulic gradient.

Simple steady state models can be constructed to estimate the relative position of fresh and salt water in an aquifer; however, climate change, tidal range and sea level rise produce interactions which complicate such simple models.

This research aims to build a prototype groundwater model, calibrated against known groundwater level observations over a long time period. The model will be used to determine which factors will have the largest effect on coastal aquifers over the next 100 years



Essink example 1 (2001 paper page 436)

width of dunes B	2000 m	Rainfall	815 mm/year
relative density difference alpha	0.025	Et	450 mm/year
hydraulic conductivity k	10 m/day	recharge rate f	0.001 m/day
delta x m			
50 <— you can change this to make the graph scale better			

x=Horiz d	H=Depth	h=height
0	-62.47	1.56
50	-62.39	1.56
100	-62.16	1.55
150	-61.76	1.54
200	-61.21	1.53
250	-60.49	1.51
300	-59.59	1.49
350	-58.52	1.45
400	-57.25	1.43
450	-55.79	1.39
500	-54.10	1.35
550	-52.17	1.30
600	-49.98	1.25
650	-47.47	1.19
700	-44.61	1.12
750	-41.32	1.03
800	-37.48	0.94
850	-32.91	0.82
900	-27.23	0.68
950	-19.51	0.49
1000	0.00	0.00

Example calculation of steady state flow balance between fresh water and sea water in an unconfined coastal aquifer with a fixed recharge rate. The upper line is the water table and the lower line is the theoretical interface between the fresh water on the left and the salt water on the right

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Poster presented at IWA UK Young Researchers Conference 2004

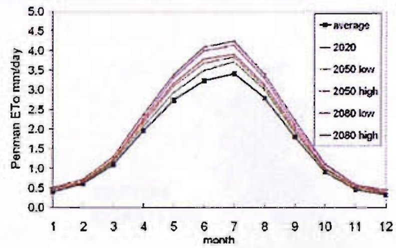
Impacts of climate change and sea level rise on groundwater systems in coastal aquifers

Sarinya Sanitwong-Na-Ayutthaya & Derek Clarke
School of Civil Engineering and the Environment, University of Southampton

Climate Change predictions made by UKCIP suggest temperatures in the UK will rise by up to 4°C in the next 100 years. Rainfall totals are unlikely to change but summers are predicted to become drier. These effects will result in increased evapotranspiration and higher soil moisture deficits in summer.

These changes will affect the timing and rate of recharge of water into the aquifer system. Additionally vegetation may change in response to the modified climate , also affecting interception and evaporation.

Predicted changes in Potential Evapotranspiration at Southampton 1963-2080

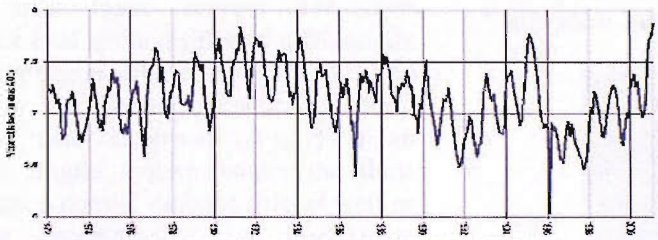


Preliminary study site :

A preliminary scoping study is being carried out on a coastal sand dune system at Ainsdale, 25km north of Liverpool where a 30 year set of groundwater level data is available.

The aim of the work is to construct a water balance model describing the inputs (rainfall) and outputs (evapotranspiration, groundwater flow) and use these to predict water table levels. This will be tested against a groundwater model, probably developed using MODFLOW.

Study Site : Ainsdale Sand Dunes National Nature Reserve and Formby Point



30 years of groundwater level data are available at Ainsdale

Model Development :
The calibrated groundwater model will then be used to explore the effects of climate change on recharge rate and effect of sea level rise on hydraulic gradient. Once the key variables that have the largest influence on the groundwater system have been identified a more comprehensive 2D groundwater model will be developed and a range of scenarios will be investigated. It is intended to use this model to explore climate change and sea level impacts on coastal aquifers in other parts of the world, including Thailand.

SUPERVISOR : DR. DEREK CLARKE
SPONSOR : GOVERNMENT OF THAILAND
START DATE : 2 FEBRUARY 2004

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT
UNIVERSITY OF SOUTHAMPTON

A PROBABILISTIC ASSESSMENT OF FUTURE COASTAL GROUNDWATER LEVELS IN A DUNE SYSTEM IN ENGLAND

Derek Clarke and Sarinya Sanitwong_Na_Ayutthaya

School of Civil Engineering and the Environment, University of Southampton

Southampton, United Kingdom.

ABSTRACT

Groundwater in coastal dune systems is affected by many factors including rainfall, sea level, erosion, aquifer recharge and land use. Observed groundwater conditions in an unconfined aquifer in North West England were used to create a water balance model which simulates those changes in water table levels in the sand dune system. The calibrated model was then used to simulate the impacts of climate change, tree coverage, relative sea level rise and coastal erosion on the groundwater storage in an unconfined coastal aquifer.

KEY WORDS: Groundwater, coastal aquifer, climate change, sea-level rise, water balance model, water table levels.

INTRODUCTION

Groundwater systems are vulnerable to impacts such as change in recharge, contamination from natural and man made sources and over exploitation. Coastal groundwater is additionally susceptible to contamination from sea water. The dune system of the Sefton Coastline in North West England near Liverpool (Fig.1) is an example of a fragile system where the dune system performs a coastal defence role as well as supporting an exceptionally rich bio-habitat. (Sefton Coastal Partnership web site, 2007) The coastline is dynamic and is undergoing erosion of up to 4.5m/year at the southern and (Fig 2 "A") and accretion at the northern end (Fig 2 "B").

In the 1960's when a National Nature Reserve was established at Ainsdale, the water table in the dunes was relatively high and many of the dune slacks were flooded in winter. Several remained flooded throughout the year. In the early 1970's, the water table fell and many dune slacks dried up (Clarke and Pegg, 1992). Although these changes correlated with periods of relatively high rainfall and low rainfall, little was known of the impact of other factors such as the development of the pumped agricultural drainage system inland of the Reserve and also the expansion of nearby areas of urbanisation with associated road drainage system, which intercepts water which would naturally drain to the water table.

Figure 1. Location map of Sefton Coastline

A well tube monitoring network was set up in 1972 and water table levels have been measured every month since. Figure 2 shows the network and some key wells mentioned in the paper.

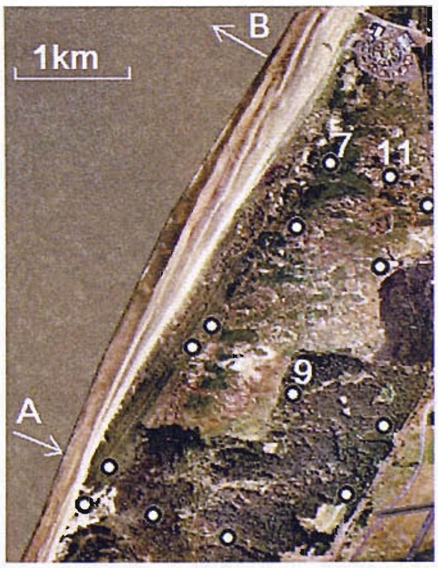


Figure 2. Site map showing well tube network and coastal erosion(A) and accretion(B).

Average water table levels above mean sea level are shown in Figure 3. These are based on the measurements at 13 wells. The water table rises from sea level (+0.2m) to a maximum +10.5m at the east side (Figure 4) and then slopes downward gently inland. This indicates that groundwater flows through the dunes towards the sea in the study area. Water table contour lines run parallel with the coast except in the southern end where groundwater levels are approximately 50cm lower. This is closely correlated with the presence of the pine trees. This relationship was confirmed in the 1990's when selective tree removal took place in the central part of the Reserve and water table levels rose by approximately 40cm in the following years. (Atkins, 2004)

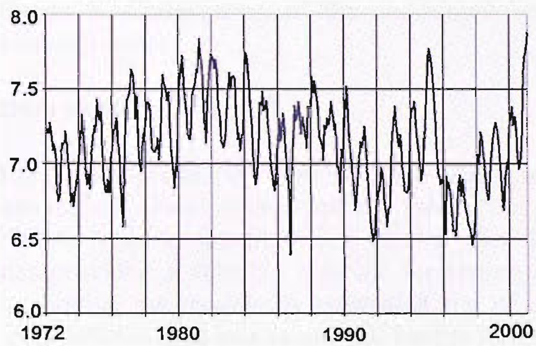


Figure 3. Average groundwater levels (mAOD) at Ainsdale 1972-2002

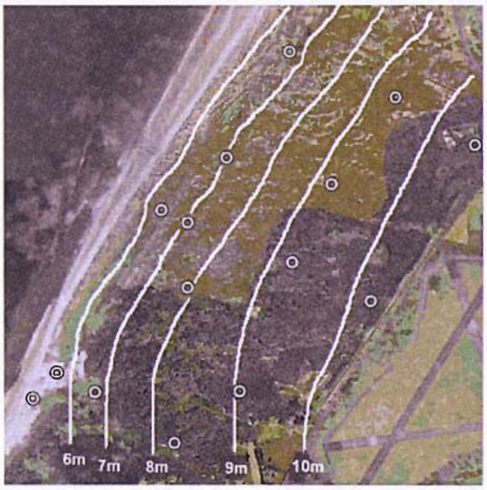


Figure 4. Typical pattern of water table contours

The long term monitoring of the wells over the last 35 years has provided a useful data set to understand the influences of seasonality, changes in climate, coastal erosion and land use management changes.

A primary concern is that although water table levels rose from the low in the 1970's, there are still sequences of years with low water levels, causing difficulty in managing the ecology in the dune floors (Davy et al 2006). What is needed is a model that will describe the behaviour of the water table levels, which if correctly calibrated, will enable managers to simulate the effects of climate change on the dune system. It will also enable the simulation of other environmental impacts such as sea level rise and coastal erosion.

FACTORS AFFECTING GROUNDWATER AT AINSDALE

Clarke (1980) described a conceptual water balance model for the dune system, based on the principles of catchment hydrology. The model is initially simple:

Water inputs – Water outputs = Storage change

Inputs include rainfall, and groundwater flow from inland or watering such as irrigation of golf greens. Outputs are the losses of water out of the system by groundwater flow out to the sea, evaporation from water areas, evapotranspiration from grasses, bushes, and trees, and water intercepted by the tree canopy and re-evaporated before it can reach the ground. There are some old drainage ditches and clay pipes in the area which may accelerate the movement of water out of the dunes. Storage Change is the difference in the amount of water in the dune system over a given time interval. Water can be stored in the dunes as saturated sand, in the soil moisture zone where plant roots extract water and in flooded dune slacks.

MODEL CONSTRUCTION

A water balance model was constructed using a daily soil moisture and runoff model combined with a groundwater flow model to simulate the changes in water table levels (Figure 5). Soil moisture deficit was calculated based on the balance between rainfall, daily potential evapotranspiration, and a root zone model. Groundwater flow was calculated using the Dupuit equation.

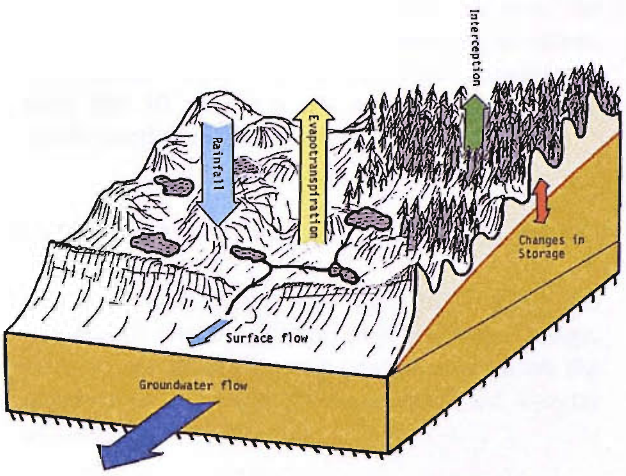


Figure 5. Components of the conceptual water balance model.

Data used in the model

Long term sets of key climatic data were assembled from measurements made on the Nature Reserve and from four nearby sites. This has provided a valuable data set for testing and calibrating the models. A consistent run of data from 1950 to data was assembled for the Reserve. The data consists of rainfall, and the data needed to calculate potential evapotranspiration using the Penman Montieth method i.e. average air temperatures (maximum and minimum), relative humidity, wind speed and sunshine.

Model structure

The model predicts the water table level at the end of each month by simulating a daily water balance in the dune system. Monthly climatic data is used to estimate potential evapotranspiration from a theoretical well watered grass surface and smoothed into daily values by polynomial interpolation. The soil moisture deficit in the vegetation root zone is then calculated at the end of each day.

Soil moisture deficit is calculated based on the daily potential evapotranspiration, rainfall and a root zone model that includes data for root depth, soil water holding capacity and a sub-model that calculates actual evapotranspiration based on the previous day's soil moisture deficit. If the soil is at field capacity or near saturation, any surplus water is assumed to drain to the water table.

Groundwater flow is calculated using the Dupuit equation, based on the saturated sand permeability and the hydraulic gradient between the current water table level and average sea level. The change in water storage is calculated from the balance between water that drains vertically into the water table minus the groundwater flow. The water storage change is then converted into a water table elevation change using a depth dependent root zone porosity function. At depths greater than 1m the effective porosity is set to 28% and this is increased to 100% at the surface.

If the calculated water table is above ground level then the regional porosity is adjusted to cater for the fact that a proportion of the water table is in open air (flooded dune slacks) whilst the majority of the water table is under the dune ridges (saturated sand). In exceptionally wet conditions with a very high water table level a series of heuristic rules are applied to simulate the removal of surface water by the drainage ditches.

The calculated water table level at the end of each month is used as the start point for the next month and the calculation procedure is repeated for each month of available data. A typical run of the model for well 11 located in the open dunes in northern part of the Reserve is shown in Figure 6.

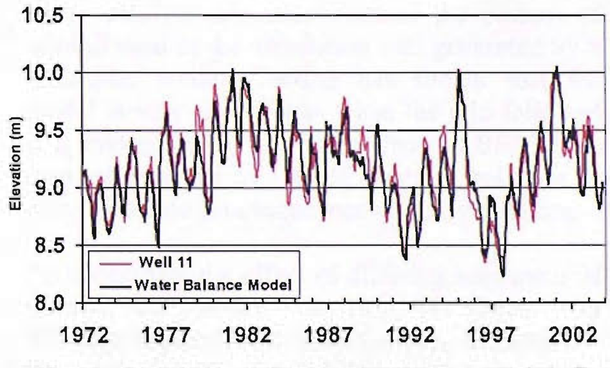


Figure 6. Water balance simulation model for Well 11 in the open dunes 1972-2002.

The model is able to describe the changes in water table levels with an accuracy of about +/- 0.2m over the 30 year period of available data. This model is based on extensive parameter optimization, where factors such as porosity, permeability, groundwater flow equations and root zone models were adjusted over physically realistic ranges until the best fit was obtained. The model has been tested against four of the eleven wells in the Reserve and all show good agreement over the 30 year run of measured water table levels starting in 1972.

INVESTIGATING IMPACTS ON THE MODEL

The calibrated model was used to simulate the impacts of climate change, tree coverage change, relative sea level rise and coastal erosion on the groundwater storage in an unconfined coastal aquifer.

Expected impacts of climate change

To investigate the likely effects of climate change on the water table levels in the Sefton dunes, climate predictions from the UK Climate Impact Programme (UKCIP, 2002) were incorporated into the water balance model. The prediction for climate change under a medium high emission scenario in this area is an increase in air temperature of about +3°C, together with a small decrease in rainfall by 2100. However the rainfall patterns will change so that the summers are drier and the winters are wetter.

Wetter winters would result in more recharge into the water table in winter but the predicted higher summer temperatures will result in higher potential evapotranspiration. However, our soil moisture deficit models suggest that even with higher potential evapotranspiration, the actual evapotranspiration will be limited by soil drying in summer. Also, drier summers may stress vegetation and result in long term change of vegetation types.

The UKCIP medium-high emissions scenario contains monthly average predictions for temperature, wind speed, humidity, sunshine and rainfall for the 30 year time periods centred on the 2020's, 2050's, and 2080's. The model for well 11 was run with repeated average years with UKCIP changes to the existing average climate conditions. The results show a gradual draining away of water table levels from a current average of 9.2mAOD to 8.75mAOD. However this model used repeated sequences of average climatic conditions and it failed to produce the inter-year behaviour seen in the observed data, so these resets may not be meaningful.

A stochastically generated time series of daily climatic data was obtained from the BETWIXT project (BETWIXT, 2005). These data embody the expected average and temporal variability in temperature humidity wind speed, sunshine and rainfall over the next 100 years in the study area. Output from the model for well 11 between 2005 - 2095 is shown in Figure 7. The modelled pattern shows an overall predicted decline in water table levels of between 0.8-1.2m but there are still short sequences (3-4 years) of exceptionally wet years.

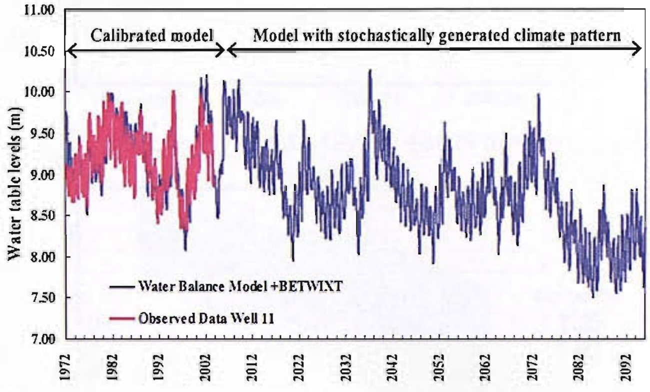


Figure 7. Calibrated model and simulation of impacts of climate change on water table levels at well 11 (1972-2002 observed and 2003-2095 simulated).

The results shown in Figure 7 are only one of many possible scenarios because the pattern of rainfall used in the simulation was generated by a stochastic model. Testing has shown that the model is very sensitive to when the rain falls and it is important to understand that the BETWIXT data set provided by UKCIP contains only one of many possible data sequences of rainfall patterns.

To investigate the effect of differing sequences of rainfall, the model was run 500 times with different sequences of rainfall events. In each case the total amount of rainfall remained the same. Each run of the model is equally likely to happen so a statistical analysis of these runs was carried out. The likely ranges of change in water table levels from 1972 – 2080's for wet conditions in March and dry conditions at the end of the summer (September) are shown in probability form in Figure 8. The overall pattern is a lowering of the water table levels with time, but also greater variability in these levels. The frequency plot in Figure 8 shows that the average water table level will fall from approximately +9.5m to +8.0m for wet conditions in March between now and the 2080's. This will affect both the vegetation and the wildlife in the sand dune system.

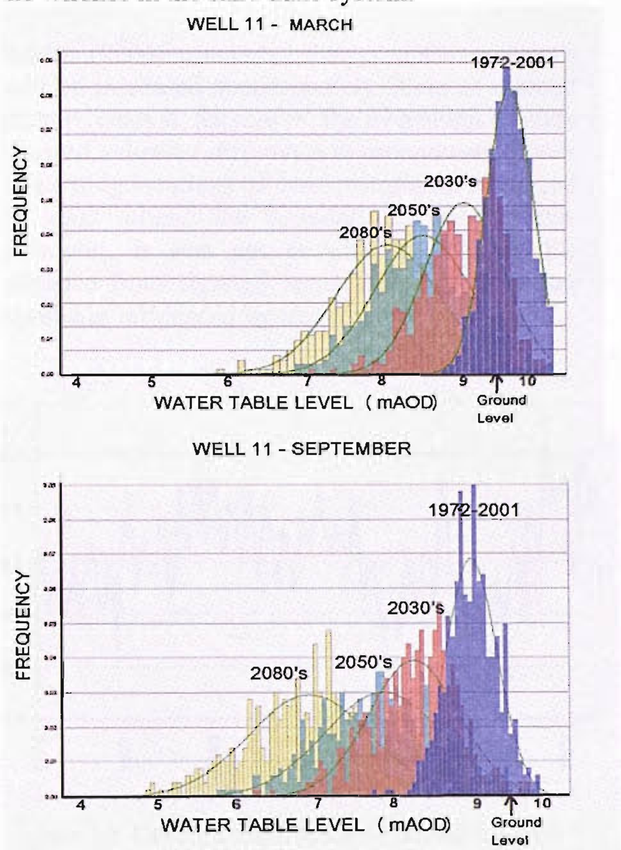


Figure 8. The expected frequency of occurrence of water table levels for well 11 for now and each of the UKCIP future time steps for wet conditions in March and dry conditions in September.

The same data are presented as a time series plot in Figure 9. These results suggest that there are likely to be significant changes in the eco-hydrological characteristics of the dune systems, especially in the dune slack areas which are of high bio diversity (Davy et al, 2006). It is expected that the inland slack floors will gradually dry out and will be damp rarely, suggesting that species dependent on standing water for breeding (such as the Natterjack Toad) will become threatened.

Impacts of trees on the water table levels.

The study area comprises a mixture of coniferous woodland, deciduous scrub, fixed dune and dune slack. Pine plantations were established in the 1930's in the southern part of the area. As mentioned above the forested areas coincide with an area of lower water table levels. Management to increase biodiversity in the dune system has resulted in the removal of some areas of the pine trees. This began in 1992 when 4.5ha of trees

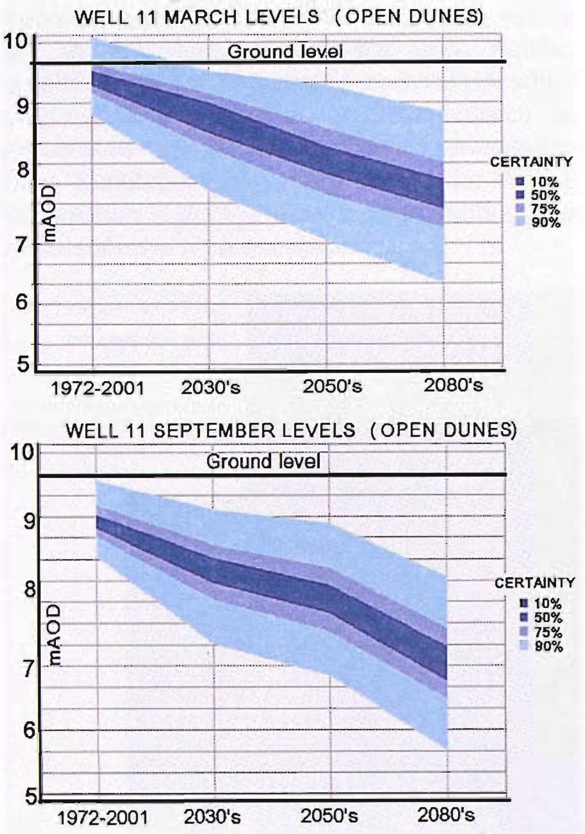


Figure 9. Time series plot of expected average water table levels at the end of winter and summer.

were removed and another 16ha were removed in 1997 (Atkins, 2004). To investigate the effect of pine trees on the water system, interception losses were calculated based on models suggested by Calder (2005) and incorporated into the water balance model. The revised model shows that pine trees intercept about 150mm of rain each year, equivalent to lowering the water table levels under the pine trees should by 0.5-0.6m. This is in agreement with water table contours observed in Figure 3.

The revised water balance model was applied to Well 9 in the areas where trees were removed. Results up to 1997 show good agreement but the observed water table levels diverge from the model following the clearance of the trees (Figure 10). This is in accordance with observations in the field and supports other work that suggests that pine trees have a significant effect in reducing aquifer recharge in temperate climates (Calder et al 2002).

Atkins (2004) concluded that groundwater levels will be increased approximately 30cm as a result of tree removal. Moreover, the hydrological study showed a distinct difference in groundwater levels in existing locations of dune restoration compared to areas around the boundary of the Reserve. However, it was not possible to identify the distance from clearfell areas where groundwater level was influenced by tree removal.

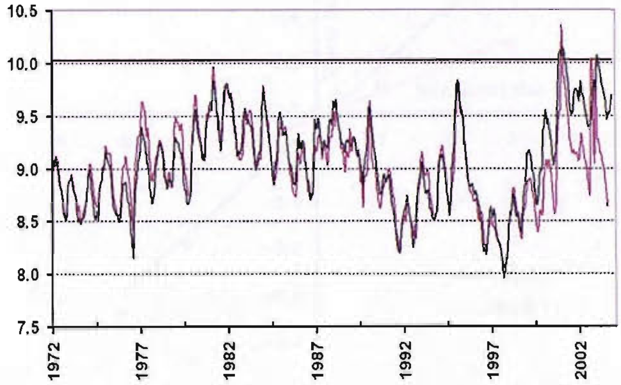


Figure 10. Revised water balance model for well 9 including tree interception loss. Note the rise in observed levels following tree clearance in 1997

Impacts of coastal erosion and relative sea level rise

Undefended coastal zones are vulnerable to erosion and sea level rise. As a result of climate change, a rising sea level may cause permanent inundation of wetlands and other lowlands, increase of the salinity of rivers, bays, and groundwater tables, and coastal erosion. Rising sea level will increase the salinity of both surface water and groundwater through salt water intrusion. A rising sea level can also result in the loss of land above sea level through erosion. Groundwater usually flows out from the land to the sea; therefore, an eroded shore would change the amount of groundwater flow. Sea level rise in this region of the UK is expected to be of the order of +3 to +7mm/y (UKCIP, 2005, DEFRA 2007).

The dune coastline at Sefton (Fig. 11) is currently being eroded at up to 4.5m/year, depending on location. (Lymbery et al, 2007). This will have an impact on the water table levels, by increasing the hydraulic gradient between the water table and the sea and increasing groundwater flow. Another possible impact will be that of sea level rise which will reduce the hydraulic gradient between the groundwater and the sea and reduce groundwater flow. Simulations have been carried out varying the position of the coastline, and also with a range of possible sea level rise scenarios.

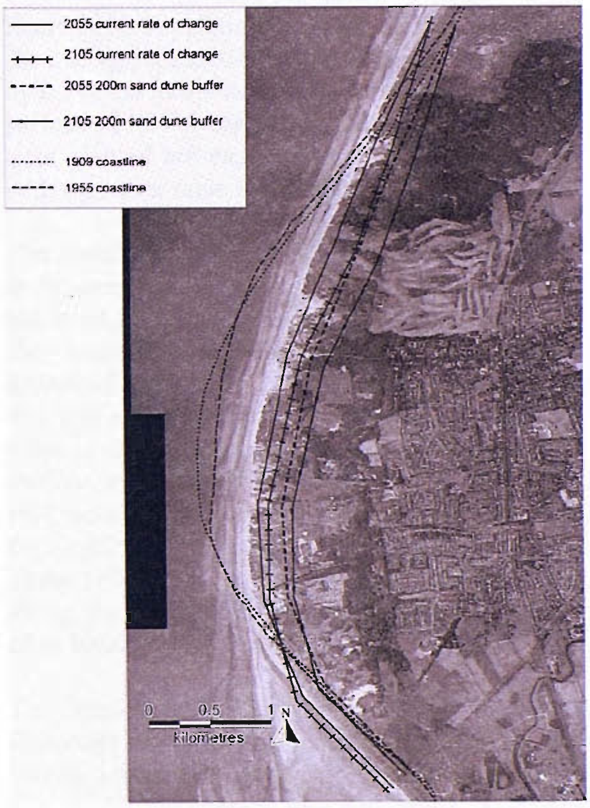


Figure 11. Estimated coastline by extrapolation of current trends (Lymbery et al, 2007)

The effects were modeled at different distances inland, at Well 7 (750m from the coastline) and Well 11 (1550m from the coastline). The water balance model was run by varying the average sea levels from -3m to +3m to explore the impacts of sea-level rise on average water table levels. Additionally, the coastline was varied from -500m to +500m from its present position to explore the impacts of coastal erosion and accretion on average water table levels.

The sea level is expected to rise by +0.6m by the year 2100 (UKCIP 2005, Lymberly 2007). This will cause water table levels to rise by about 0.4m inland and more nearer the coast (Fig. 12). Erosion and accretion will vary along the coastline but the model results suggest that the effect will be to raise water table levels by +0.14m by every 100 meters of accretion and decrease it by 0.18m for every 100m of erosion (Fig. 13). Furthermore, wells nearer to the sea show larger impacts from erosion and sea level rise than those further inland.

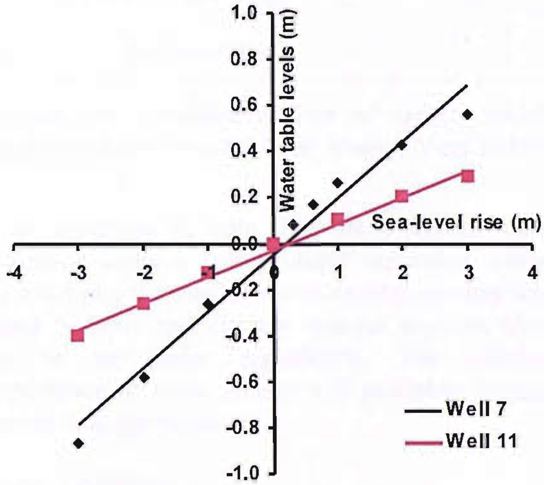


Figure 12. Impact of relative sea level rise on average water table levels

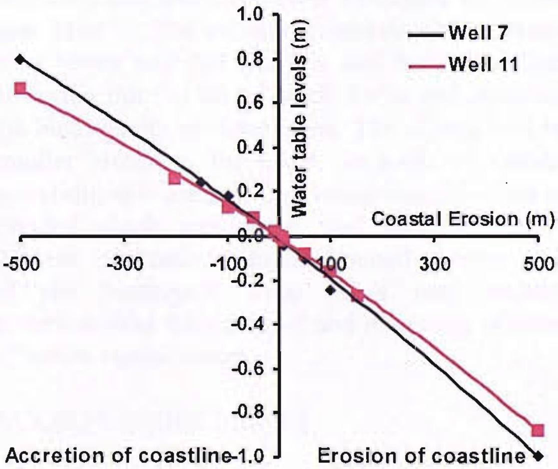


Figure 13. Impact of coastal erosion on average water table levels

DISCUSSION

The model was successfully calibrated against a 30 year set of observed water table level data. The water table levels calculated by the model depend on many assumptions, but these were based on physically reasonable estimates of parameters such as porosity, permeability and root zone depletion of soil moisture deficit. The climate change scenarios published by UKCIP are in four differing categories, depending on CO_2 emission scenarios. In this study we used the "medium-high" scenario. The modelling of future water table levels has been shown to be highly dependent not only on the amount of rainfall but when it falls and the size of each rain storm event, especially in the forested areas. The key result found in all simulation is that for this dune system the average water table levels are expected to fall by 0.5-1.0m in the next 100 years, with prolonged periods of low water table levels. Areas with pine trees planted are expected to become even drier, with the water table level falling by 1.5m or more.

The simulation of future water table levels shown in Figures 8 and 9 were carried out assuming that sea level remains constant in the future and that the coastline remains static. The analysis described in Figures 12 and 13 show that sea level rise will raise water table levels by no more than 0.6m in the next 100 in the dune system. Coastal erosion is occurring in this area and the impacts will therefore vary along the coastline, but over the next 25 years the effect on water table levels is likely to be no more than +/-0.15m. Further north along the coast, accretion will cause the water table levels to rise.

To identify which factors will be the most important in affecting coastal aquifers in the future, a sensitivity of the water balance model to key model parameters was performed. This was done for a "near future" scenario when the magnitude of coastal erosion was about 50m ie. for 25-30 years into the future. (Figure 14).

The most important parameters were ranked with rainfall amount being the most important, followed by change in tree coverage and coastal erosion. Smaller impacts were found from system properties such as sand dune permeability. Climate change effects were expressed in the evapotranspiration calculation which uses predictions of temperature, sunshine and humidity. The impact of sea level rise was relatively unimportant over this short time period.

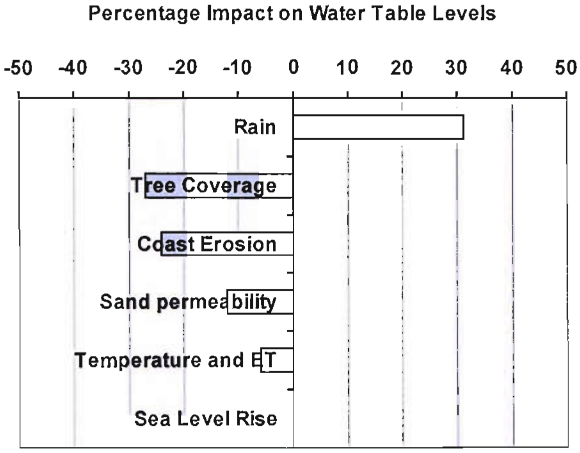


Figure 14. Sensitivity chart of factors which impact on average water table levels. (Year 2030)

It is important to note that these factors were evaluated under a "near future" condition when, for example, the magnitude of coastal erosion was about +/-50m and climate change impacts have yet to be come significant. The relative importance of these factors will probably change further into the future.

CONCLUSIONS

The key environmental factors that affect groundwater levels in a coastal sand dune system Northern England have been evaluated up to the year 2100 in. The expected changes are that water table levels will fall and this will have the effect of drying out the inland slack floors and reducing the biodiversity of these areas. The effects will be smaller closer to the coast. In areas of coastal accretion, new areas will develop that offer wet or flooded slack conditions that will provide a suitable environment for threatened species such as the Natterjack Toad. This may require proactive land management and re-zoning of areas of nature conservation.

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APPENDIX C

Example of the model and data

The following section presents an example of the water balance model and data used.

Table C.1: Example of the measured groundwater levels at Ainsdale NNR

Year	Month	Days	Water Table Level at Ainsdale (mAOD)						
			5.63	6.58	6.5	5.23	10.03	10.03	9.54
			BH3	BH4	BH5	BH1	BH9	BH10	BH11
1972-01	Jan	31							
1972-02	Feb	29	5.37	6.315	6.48	4.975	9	9.27	9.095
1972-03	Mar	31	5.365	6.285	6.45	4.955	8.985	9.25	9.1
1972-04	Apr	30	5.445	6.45	6.47	5.115	9.12	9.485	9.125
1972-05	May	31	5.365	6.26	6.465	4.97	9.085	9.365	9.035
1972-06	Jun	30	5.165	6.005	6.46	4.705	8.935	9.045	8.95
1972-07	Jul	31	5.235	6.16	6.455	4.83	8.84	9.155	9.07
1972-08	Aug	31	5.205	6.09	6.47	4.785	8.78	9.065	8.985
1972-09	Sep	30	5.025	5.82	5.97	4.5	8.665	8.915	8.77
1972-10	Oct	31	4.935	5.725	5.92	4.5	8.6	8.9	8.735
1972-11	Nov	30	4.965	5.715	5.96	4.55	8.52	8.85	8.955
1972-12	Dec	31	5.24	6.11	6.37	4.885	8.83	9.025	8.975
1973-01	Jan	31	5.31	6.14	6.375	4.825	8.89	9.115	9.07
1973-02	Feb	28	5.275	6.18	6.39	4.8	8.905	9.075	9.025
1973-03	Mar	31	5.405	6.285	6.49	4.965	8.945	9.145	9.095
1973-04	Apr	30	5.36	6.24	6.49	4.9	8.85	9.11	9.085
1973-05	May	31	5.185	6.05	6.28	4.765	8.72	9.09	8.925
1973-06	Jun	30	5.08	5.775	6.38	4.625	8.71	8.965	8.775
1973-07	Jul	31	4.935	5.795	5.91	4.445	8.595	8.865	8.67
1973-08	Aug	31	5	5.8	6	4.5	8.65	8.82	8.71
1973-09	Sep	30	4.955	5.73	5.925	4.525	8.475	8.77	8.67
1973-10	Oct	31	5.06	5.83	6.04	4.63	8.555	8.77	8.67
1973-11	Nov	30	5.115	5.895	6.1	4.665	8.62	8.855	8.755
1973-12	Dec	31	5.175	5.96	6.185	4.73	8.67	8.93	8.82
1974-01	Jan	31	5.24	6.055	6.305	4.79	8.755	8.985	8.94
1974-02	Feb	28	5.435	6.23	6.44	5.015	8.9	9.145	9.065
1974-03	Mar	31	5.605	6.405	6.5	5.13	9.05	9.31	9.265
1974-04	Apr	30	5.41	6.25	6.43	4.945	9.04	9.3	9.15
1974-05	May	31	5.235	6.12	6.295	4.775	8.88	9.175	9.02
1974-06	Jun	30	5.08	5.97	6.095	4.63	8.745	9.055	8.885
1974-07	Jul	31	5	5.89	6.105	4.585	8.66	8.98	8.815
1974-08	Aug	31	5.1	5.975	6.19	4.72	8.635	8.96	8.845
1974-09	Sep	30	4.98	5.91	6.035	4.56	8.675	8.86	8.705
1974-10	Oct	31	5.24	6.09	6.34	4.865	8.845	9.085	8.96
1974-11	Nov	30	5.365	6.2	6.44	4.93	8.89	9.21	9.11
1974-12	Dec	31	5.46	6.305	6.455	5.03	9.02	9.3	9.185
1975-01	Jan	31	5.41	6.22	6.435	4.93	8.98	9.305	9.165
1975-02	Feb	28	5.73	6.53	6.5	5.17	9.21	9.495	9.425
1975-03	Mar	31	5.59	6.38	6.465	5.055	9.17	9.58	9.345
1975-04	Apr	30	5.5	6.335	6.46	5.01	9.14	9.45	9.285
1975-05	May	31	5.51	6.425	6.49	5.03	9.145	9.49	9.375
1975-06	Jun	30	5.25	6.11	6.265	4.735	8.96	9.33	9.1
1975-07	Jul	31	5.055	5.97	6.05	4.52	8.78	9.18	8.905
1975-08	Aug	31	4.975	5.815	5.97	4.51	8.68	9.08	8.82
1975-09	Sep	30	4.98	5.81	6.01	4.52	8.625	8.99	8.785
1975-10	Oct	31	5.1	5.77	6.19	4.675	8.57	8.935	8.86
1975-11	Nov	30	5.03	5.77	6.03	4.55	8.56	8.905	8.72
1975-12	Dec	31	5.25	6.04	6.395	4.74	8.7	8.965	8.84

Table C.2: Example of the rainfall, climatic data and evapotranspiration

Year	Rainfall mm/month	Wind km/d	Tmax °C	Tmin °C	RHmean %	RHmin %	Sunhours hours/day	ET_o mm/month	ET_c mm/month
1972-01	71.10	290.63	6.73	-0.88	88.49	65.122	1.370	17.90	18.97
1972-02	46.60	269.30	5.56	2.91	86.66	78.630	1.750	15.78	19.58
1972-03	79.70	271.96	11.52	3.64	85.96	63.341	3.850	37.20	36.77
1972-04	62.90	301.29	10.26	5.74	81.39	68.950	4.950	52.77	55.00
1972-05	42.80	258.63	12.28	6.63	82.05	66.626	5.020	67.19	53.38
1972-06	79.30	223.97	12.95	8.24	83.04	70.101	5.570	71.79	73.60
1972-07	93.60	146.65	19.08	10.10	87.04	62.459	6.130	83.18	70.83
1972-08	29.70	199.97	15.39	10.58	84.59	71.405	5.060	66.32	55.80
1972-09	36.40	178.64	13.79	7.92	85.98	69.387	4.700	44.17	32.33
1972-10	48.40	242.63	13.03	6.79	87.39	69.346	3.790	28.24	21.81
1972-11	134.30	317.29	11.44	4.45	88.53	67.823	1.900	20.95	13.66
1972-12	74.00	298.63	9.17	2.91	89.44	70.364	0.910	16.12	13.37
1973-01	45.10	274.63	6.65	0.73	91.23	72.456	1.040	13.25	12.36
1973-02	54.10	330.62	6.06	0.65	89.97	72.959	2.620	16.07	14.81
1973-03	29.50	226.64	11.44	3.88	84.78	63.372	4.570	36.29	31.99
1973-04	57.10	293.29	8.83	2.43	79.93	62.436	6.050	54.04	44.80
1973-05	58.30	258.63	16.39	6.54	81.22	55.620	6.140	81.13	62.43
1973-06	35.30	183.98	18.24	8.97	83.01	58.674	7.270	91.24	44.03
1973-07	98.80	202.64	18.16	11.31	85.88	67.200	6.350	85.32	61.30
1973-08	83.30	255.97	20.76	10.42	82.70	56.241	5.620	85.81	74.67
1973-09	93.90	263.96	16.81	9.13	86.58	65.254	4.550	52.45	51.85
1973-10	65.30	261.30	12.87	5.58	87.13	66.133	2.840	31.83	27.40
1973-11	74.70	354.62	10.68	2.91	84.65	62.547	2.290	26.37	14.60
1973-12	78.30	378.62	6.90	2.83	87.61	75.235	1.650	15.36	10.35
1974-01	101.30	383.95	8.16	2.35	84.54	67.649	1.590	21.77	18.97
1974-02	88.30	298.63	7.40	3.56	85.02	73.719	2.060	19.99	18.91
1974-03	35.30	266.63	9.76	2.99	79.71	61.429	3.850	40.59	36.77
1974-04	4.70	202.64	13.54	4.69	76.01	53.955	6.550	64.69	29.57
1974-05	31.20	253.30	14.38	7.43	75.55	58.400	6.580	83.85	29.72
1974-06	73.80	231.97	18.24	9.21	77.07	55.050	8.170	100.58	61.31
1974-07	122.00	301.29	15.89	11.95	81.63	71.258	4.800	80.38	66.43
1974-08	67.90	234.64	16.31	9.53	84.59	66.125	5.160	68.98	64.82
1974-09	162.40	282.63	13.87	6.95	83.50	64.525	3.770	49.03	46.00
1974-10	90.00	301.29	8.41	5.66	82.66	74.862	3.120	29.55	28.49
1974-11	89.40	306.63	8.83	4.53	90.37	77.065	1.610	13.78	13.66
1974-12	47.90	418.61	9.25	4.61	91.15	76.721	1.200	13.98	13.37
1975-01	100.00	359.95	7.91	4.36	90.54	79.498	1.340	13.49	12.36
1975-02	30.00	242.63	7.40	2.67	89.69	74.999	3.300	15.46	14.81
1975-03	51.10	250.63	7.66	2.27	79.75	64.911	4.360	36.92	32.29
1975-04	60.40	229.30	12.36	3.64	86.45	61.489	4.440	50.25	46.49
1975-05	23.30	183.98	12.70	6.87	78.97	63.709	8.300	79.48	57.80
1975-06	9.80	191.97	19.34	7.43	77.62	48.905	10.210	109.36	17.62
1975-07	67.20	186.64	17.57	11.87	83.31	68.164	5.510	82.84	45.32
1975-08	78.50	146.65	23.79	12.28	82.58	53.925	7.880	92.99	66.28
1975-09	83.10	215.97	15.30	8.24	81.60	62.900	5.070	55.79	51.38
1975-10	32.40	213.30	11.44	6.71	86.22	72.565	3.510	26.84	27.40
1975-11	76.70	231.97	8.83	3.64	86.26	70.939	2.660	15.72	14.60
1975-12	71.90	234.64	6.82	2.10	89.10	74.513	1.390	10.69	10.35

Table C.3: Example of the input parameter page for the water balance model

FAO Penman-Monteith for soil moisture deficit model

Month	Kc	Root depth	(FC%-WP%)	p
Jan	0.90	0.5	0.1	0.4
Feb	0.90			
Mar	0.90			
Apr	0.90			
May	0.90			
Jun	0.93			
Jul	0.94			
Aug	0.95			
Sep	0.95			
Oct	0.95			
Nov	0.92			
Dec	0.91			

Tree coverage change

	% coverage
1972-1997	
Grass	50.00%
Tree	50.00%
after 1997 trees were removed	
Grass	70.00%
Tree	30.00%

Effective porosity

General	28%
Near surface	90%
Surface	100%
Ground level	9.54

GROUNDWATER PARAMETERS

dh	9	m
dx	1500	m
A	25	m2
thickness	60	m
K	11	m/d
Start drain at level	9.2	m
Start water level (model)	9.07	m
Start porosity level	8.6	m
% area of near surface effective porosity	10.00%	
% area with normal effective porosity	90.00%	

Model Calibration	Before 1997	After 1997
Start Drain Level	9.2	9.2
Surface flow	5	10

Table C.4: Example of the water balance model

Year	*1** Rainfall	*2** AET	*3** ETo	*4** Intercept (Calder)	*5** ET Glass 99.00%	*6** ET Tree 1.00%	*7** Total ET	*8** dh	*9** GW (Darcy)	*10** GW+Surface	*11** Predicted Storage Change	*12** Porosity 28% 90.00% 10.00% 90.00%	*13** Water levels	*14** Observed Well 11
													9.07	9.54
1972-01	71.10	18.97	17.90	43.47	18.97	0.00	18.97	9.07	30.40	30.40	21.72	63.51	9.13	
1972-02	46.60	19.58	15.78	31.85	19.58	0.00	19.59	9.13	30.62	30.62	-3.60	-10.53	9.12	9.10
1972-03	79.70	36.77	37.20	53.31	36.76	0.01	36.77	9.12	30.58	30.58	12.35	36.12	9.16	9.10
1972-04	62.90	55.00	52.77	56.15	54.99	0.01	55.00	9.16	30.70	30.70	-22.80	-66.67	9.09	9.13
1972-05	42.80	53.38	67.19	57.66	53.38	0.01	53.38	9.09	30.48	30.48	-41.06	-120.06	8.97	9.04
1972-06	79.30	73.60	71.79	77.81	73.59	0.01	73.60	8.97	30.08	30.08	-24.38	-87.06	8.89	8.95
1972-07	93.60	70.83	83.18	76.48	70.82	0.01	70.83	8.89	29.78	29.78	-7.02	-25.06	8.86	9.07
1972-08	29.70	55.80	66.32	48.18	55.80	0.00	55.80	8.86	29.70	29.70	-55.80	-199.30	8.66	8.99
1972-09	36.40	32.33	44.17	37.50	32.32	0.00	32.33	8.66	29.03	29.03	-24.96	-89.14	8.57	8.77
1972-10	48.40	21.81	28.24	37.16	21.81	0.00	21.81	8.57	28.73	28.73	-2.14	-7.65	8.56	8.74
1972-11	134.30	13.66	20.95	63.87	13.66	0.01	13.67	8.56	28.71	28.71	91.92	328.30	8.89	8.96
1972-12	74.00	13.37	16.12	44.01	13.37	0.00	13.37	8.89	29.81	29.81	30.82	110.07	9.00	8.98
1973-01	45.10	12.36	13.25	29.27	12.36	0.00	12.36	9.00	30.18	30.18	2.56	9.16	9.01	9.07
1973-02	54.10	14.81	16.07	37.93	14.80	0.00	14.81	9.01	30.21	30.21	9.08	32.44	9.04	9.03
1973-03	29.50	31.99	36.29	33.66	31.98	0.00	31.99	9.04	30.32	30.32	-32.80	-95.91	8.95	9.10
1973-04	57.10	44.80	54.04	50.73	44.80	0.01	44.80	8.95	30.00	30.00	-17.70	-63.21	8.88	9.09
1973-05	58.30	62.43	81.13	70.60	62.42	0.01	62.43	8.88	29.78	29.78	-33.91	-121.12	8.76	8.93
1973-06	35.30	44.03	91.24	60.86	44.02	0.01	44.03	8.76	29.38	29.38	-38.11	-136.10	8.63	8.78
1973-07	98.80	61.30	85.32	83.72	61.29	0.01	61.30	8.63	28.92	28.92	8.58	30.64	8.66	8.67
1973-08	83.30	74.67	85.81	76.02	74.66	0.01	74.67	8.66	29.02	29.02	-20.40	-72.84	8.59	8.71
1973-09	93.90	51.85	52.45	63.52	51.84	0.01	51.85	8.59	28.78	28.78	13.27	47.39	8.63	8.67
1973-10	65.30	27.40	31.83	46.22	27.40	0.00	27.40	8.63	28.94	28.94	8.96	32.00	8.66	8.67
1973-11	74.70	14.60	26.37	46.86	14.60	0.00	14.60	8.66	29.05	29.05	31.05	110.89	8.78	8.76
1973-12	78.30	10.35	15.36	45.15	10.35	0.00	10.35	8.78	29.42	29.42	38.53	137.61	8.91	8.82

*1** **Rainfall** measured record data (1972-2007) and Monte Carlo simulation based on UKCIP02 dataset (2007-2100)

*2** ***AET*** calculated by the soil moisture deficit model

*3** ***ETo*** calculated by FAO Penman-Monteith equation

*4** **Interception** loss calculated by Calder model

*5** ***ET* grass**

*6** ***ET* Tree**

*7** **Total *ET*** = %ET (glass) + % ET (tree)

*8** ***dh*** for calculating groundwater flow estimated from the groundwater levels in the previous day

*9** ***GW*** (groundwater) estimated by Darcy's law assumption

*10** ***GW*** + **Surface** flow = groundwater + surface runoff (when the groundwater levels reach the ground level)

*11** **Predicted storage change** = (Rainfall - Total ET - (GW + Surface))

*12** **Porosity** correction storage= (% near surface porosity * % area near surface) + (% normal effective porosity * % normal area) (when the groundwater levels reach the ground level)

*13** **Modelled groundwater levels** converted from the storage based on porosity functions

*14** **Observed water levels**

GLOSSARY

Technical Terms are generally defined where they first occur in the thesis. For ease of reference a list of definitions is also set out below.

Actual evapotranspiration: The sum of the quantities of water vapour evaporated from the soil and transpired by plants when the soil-water content is less than optimal. (See Potential evapotranspiration)

Albedo: The fraction of the incident short-wave radiation that is reflected by a particular surface on earth (e.g. water, a green canopy, bare soil).

Aquiclude: A geological layer that is virtually impermeable to water.

Aquifer: The formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. This implies the ability to store and transfer water.

Aquitard: A geological layer with a low, but measurable, permeability.

Available soil water: The quantity of water available to plants, defined as the quantity of water retained in the soil that is smaller than field capacity and large than the permanent wilting point.

Boundary condition: A flow, constant head, or transport condition on a section of the model boundary system.

Calibration: The process of repeatedly modifying the model input data until a set of the simulated values of hydraulic heads and/or concentrations are fitted within a chosen tolerance to a corresponding set of observed or target values.

Canopy resistance: A resistance encountered by water vapour diffusing from the internal cell walls, through the sub-stomatal cavities and the stomata, to the canopy surface.

Capillary force: The generally upward force acting on soil moisture in the unsaturated zone, attributable to molecular attraction between soil particles and water at an air/water interface.

Capillary zone: The zone in which water is held in the soil above the phreatic surface by capillary forces.

Conceptual model: A simplified representation of a system which enables it to be investigated by analytical or numerical techniques.

Confidence interval: An interval around the computed value within which a given percentage of values of a repeatedly sampled variate is expected to be found.

Confined aquifer: An aquifer in which ground water is confined under pressure which is significantly greater than atmospheric pressure; and whose upper, and perhaps lower, boundary is defined by a layer of natural material that does not transmit water readily.

Correlation coefficient: A measure of the linear interdependence of two variates, ranging from -1 (perfect negative correlation) to +1 (perfect positive correlation).

Crop coefficient: The ratio of evapotranspiration from an area covered with a specific crop, at a specific stage of growth, to the reference evapotranspiration at that time.

Crop water requirement: See Potential evapotranspiration.

Darcy's law: An empirical law which states that the velocity of flow through a porous medium is directly proportional to the hydraulic gradient assuming that the flow is laminar and inertia can be neglected. The constant of proportionality defines the effective hydraulic conductivity of the porous medium.

Direct runoff: That portion of excess rainfall that turns into overland flow.

Effective hydraulic conductivity: The hydraulic conductivity that is used in *Darcy's* law to evaluate the velocity of flow of water through a porous medium that contains more than one fluid, such as water and air in the unsaturated zone.

Effective porosity: (also called open porosity) refers to the fraction of the total volume in which fluid flow is effectively taking place (this excludes dead-end pores or non-connected cavities). This is very important in solute transport.

Evaporation: (1) The physical process by which a liquid (or solid) is transformed into the gaseous state. (2) The quantity of water per unit area that is lost as water vapour from a water body, a wet crop, or the soil.

Evapotranspiration: The combination of evaporation of water directly from the surface of plants, and the transpiration or transfer of water from the interior of leaves to the exterior, largely through small openings called stomata.

Excess rainfall: That part of the rain of a given storm that falls at intensities exceeding the soil's infiltration capacity and is thus available for direct runoff.

Field capacity: The volumetric water content of a soil after rapid gravity drainage has ceased. It usually occurs about two days after the soil profile has been thoroughly wetted by precipitation or irrigation.

Groundwater: Water in land beneath the soil surface, under conditions where the pressure in the water is greater than or equal to atmospheric pressure, and where all the voids are filled with water.

Hydraulic conductivity (*K*): A coefficient of proportionality describing the volume of water that will move through a medium in a unit of time under a unit hydraulic gradient through a unit area measured perpendicular to the direction of flow. The density and the kinematic viscosity of the water influence the value of hydraulic conductivity.

Hydraulic gradient (*i*): The change in static potential head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic head (*h*): The height above a datum plane (such as sea level) of the column of water that can be supported by the static hydraulic pressure at a given point in a groundwater system. Equal to the potential head.

Initial conditions: The value of the boundary condition parameters and the pressure heads and/or concentrations within the model, at an initial time, usually at $t=0$.

Interception: (1) The capture and subsequent evaporation of part of the rainfall by a crop canopy or other structure, so that it does not reach the ground. (2) The capture and removal of surface runoff, so that it does not reach the protected area. (3) The capture and subsequent removal of upward groundwater seepage, so that it does not reach the rootzone of crops.

Interflow: Water that has infiltrated into a soil and moves laterally through the upper soil horizons towards ditches or streams as shallow, perched groundwater above the main groundwater level.

Irrigation: The supply, distribution, and controlled applications of water to agricultural land to improve the cultivation of crops.

Mathematical model: A model that simulates a system's behaviour by a set of equations, perhaps together with logical statements, by expressing relationships between variables and parameters.

Mean Sea Level (MSL): The average water level in a tidal area.

Model: A model is a device that represents an approximation of a field situation. It can be represented as a conceptual, mathematical, or physical system. See conceptual model.

Observation well: A small-diameter pipe, at least 25 mm in diameter, in which the depth of the watertable can be observed. It is placed in the soil and perforated over a length equal to the distance over which the watertable is expected to fluctuate.

Open water evaporation: The theoretical quantity of water that leaves an infinite shallow water surface as vapour under the prevailing meteorological conditions. The rate of open water evaporation is often estimated with Penman's Equation.

Percolation: The gravity-induced downward flow of water through soil, especially in saturated or nearly saturated soil at hydraulic gradients of one or less.

Porosity (*n*): The ratio, usually expressed as a percentage, of the total volume of voids of a given porous medium to the total volume of the porous medium.

Potential evapotranspiration: The rate of evapotranspiration that would occur from a wet surface, or from a well-watered plant.

Precipitation: The total amount of water received from the sky (rain, drizzle, snow, hail, fog, condensation, hoar frost, and rime)

Pre- and post-processors (PPP): Pre-processing is assembling and preparing input data for a numerical model and post-processing is the process of reviewing and presenting the model results.

Reference evapotranspiration: The theoretical quantity of water lost by evapotranspiration from a specified crop or surface with no water stress, reflecting the prevailing climatic conditions on site. Multiplied by a crop coefficient, it gives the potential evapotranspiration.

Salinity: The content of totally dissolved solids in irrigation water or the soil solution, expressed either as a concentration or as a corresponding electrical conductivity.

Saturated zone: The portion of subsurface soil and rock where every available space is filled with water. Aquifers are located in this zone.

Seepage: The flow of groundwater through an aquifer. (1) The slow movement of water through small cracks, pores, or interstices of a material, in or out of a body of surface or subsurface water. (2) The loss of water by infiltration from a canal reservoir or other body of water, or from a field.

Sensitivity analysis: A set of model analyses to illustrate the model response to variations in model input data.

Simulation: The representation of a physical system by a device such as a computer or a model that imitates the behaviour of the system; a simplified version of a situation in the real world.

Specific flow (q): The rate of discharge of ground water per unit area of a porous medium measured at right angles to the direction of flow. Equivalent to the *Darcy* flow velocity or *Darcy* seepage velocity.

Steady state: (1) A condition in which the input energy equals the output energy. (2) A fluid motion in which the velocities at every point of the field are independent of time in either magnitude or direction.

Steady-state flow: A characteristic of a groundwater flow system where the magnitude and direction of specific discharge are constant in time at any point See also unsteady flow.

Subsurface drainage: The removal of excess water and salts from soils via groundwater flow to the drains, so that the watertable and rootzone salinity are controlled.

Unconfined aquifer: An aquifer in which the upper flow boundary is the water table.

Unsaturated zone: An area, usually between the land surface and the water table, where the openings or pores in the soil contain both air and water.

Unsteady flow: Flow in which the velocity changes, with time, in magnitude or direction. See also Steady-state flow.

Vadose zone: The soil between the surface and the watertable. It includes the unsaturated zone and the capillary fringe.

Void: Small cavities in the soil, occupied by air or water or both.

Void ratio: Ratio of the volume of pores to the volume of solids in a soil.

Water balance: The equation of all inputs and outputs of water, for a volume of soil or for a hydrological area, with the change in storage, over a given period of time.

Water table: The water level of an unconfined aquifer below which the spaces are generally saturated. Sometimes called phreatic surface.

Wilting point: The soil-water content at which plants wilt and fail to recover turgidity; also called the permanent wilting point.

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