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Institute of Hydrology

Modeling hydrological soil response in New Zealand

Diploma Thesis

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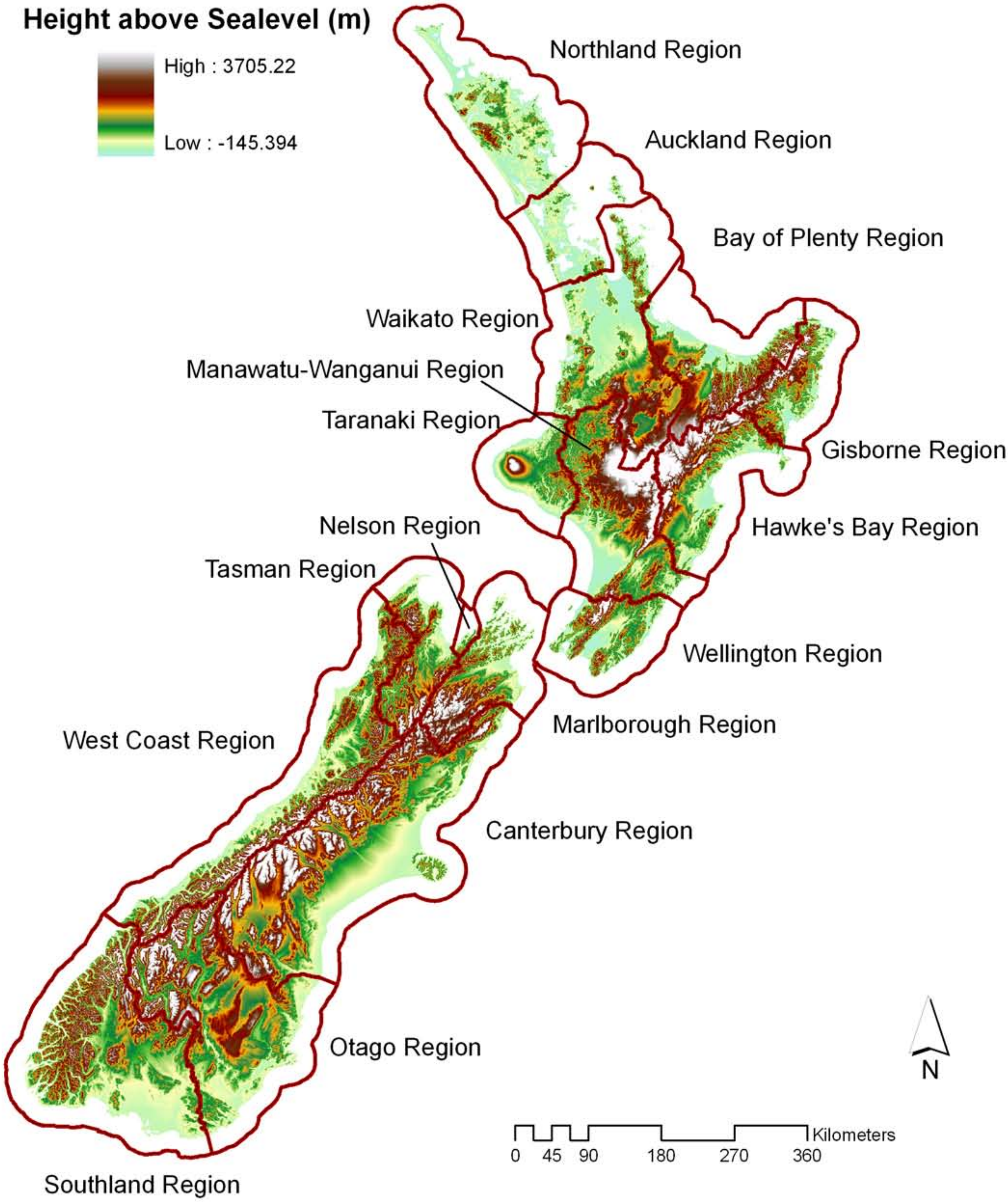
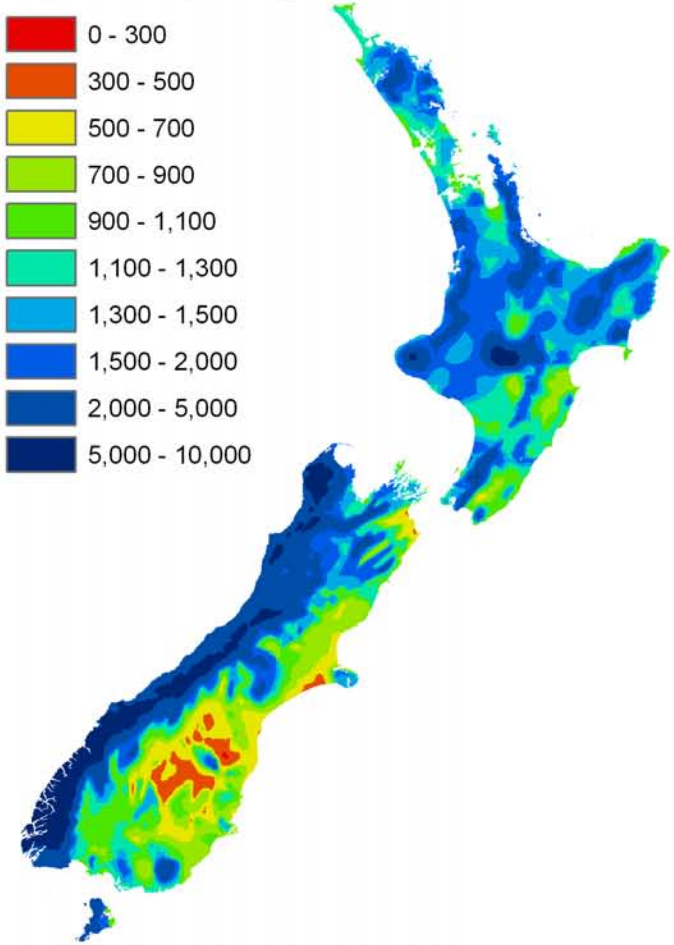
Topography and Regional Councils of New Zealand



Climate Features of New Zealand

This map gives an overview of climate features of New Zealand. For more detailed information refer to section 2.1.

Precipitation (mm/a)



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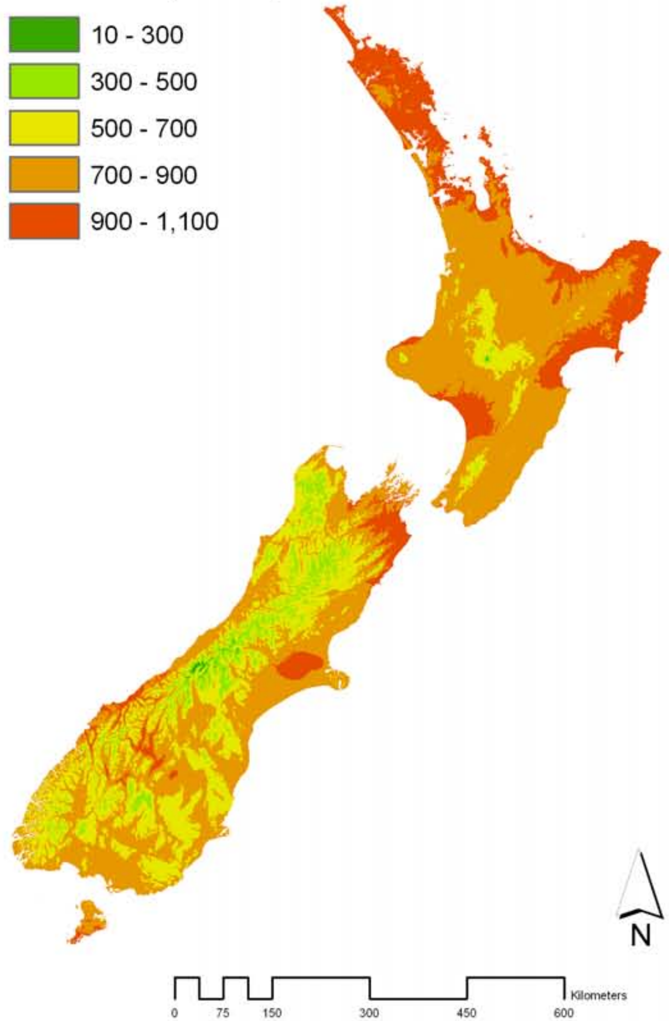
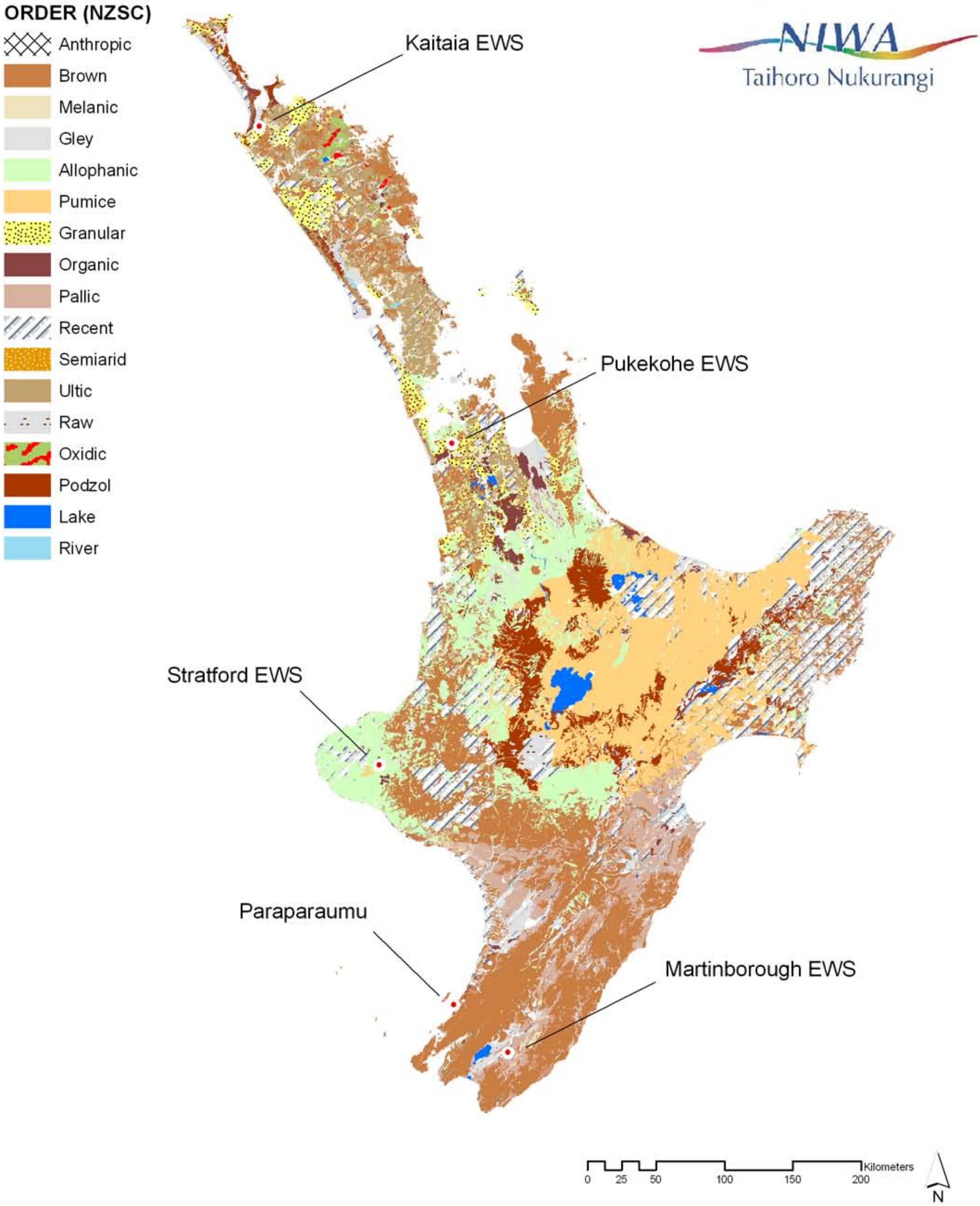
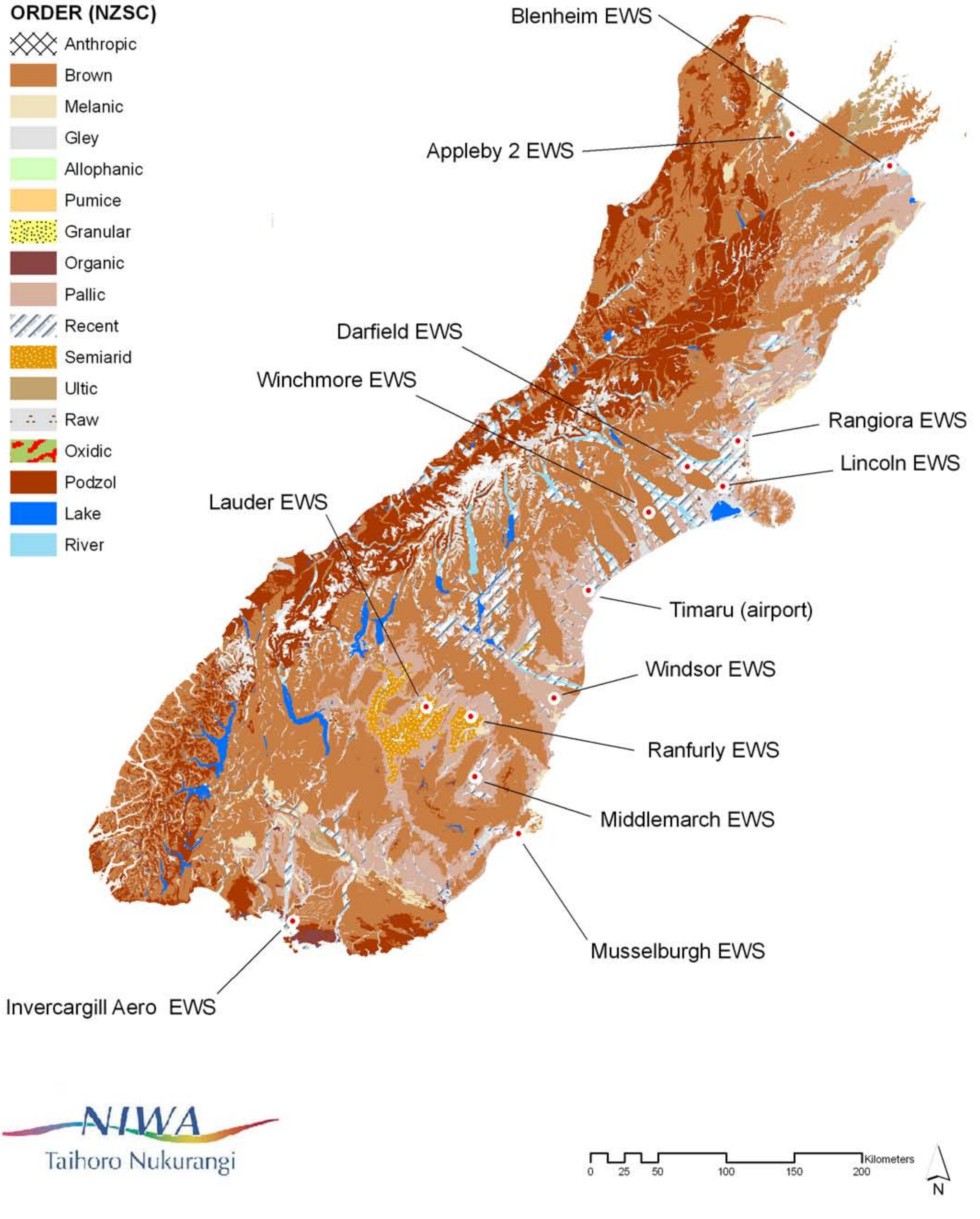


Soil Orders of New Zealand (Hewitt 1998), North Island



Soil Orders of New Zealand (Hewitt 1998), South Island

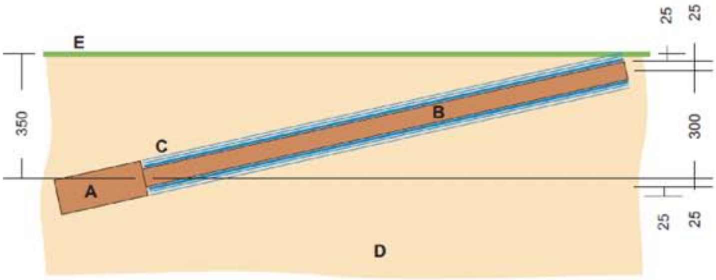


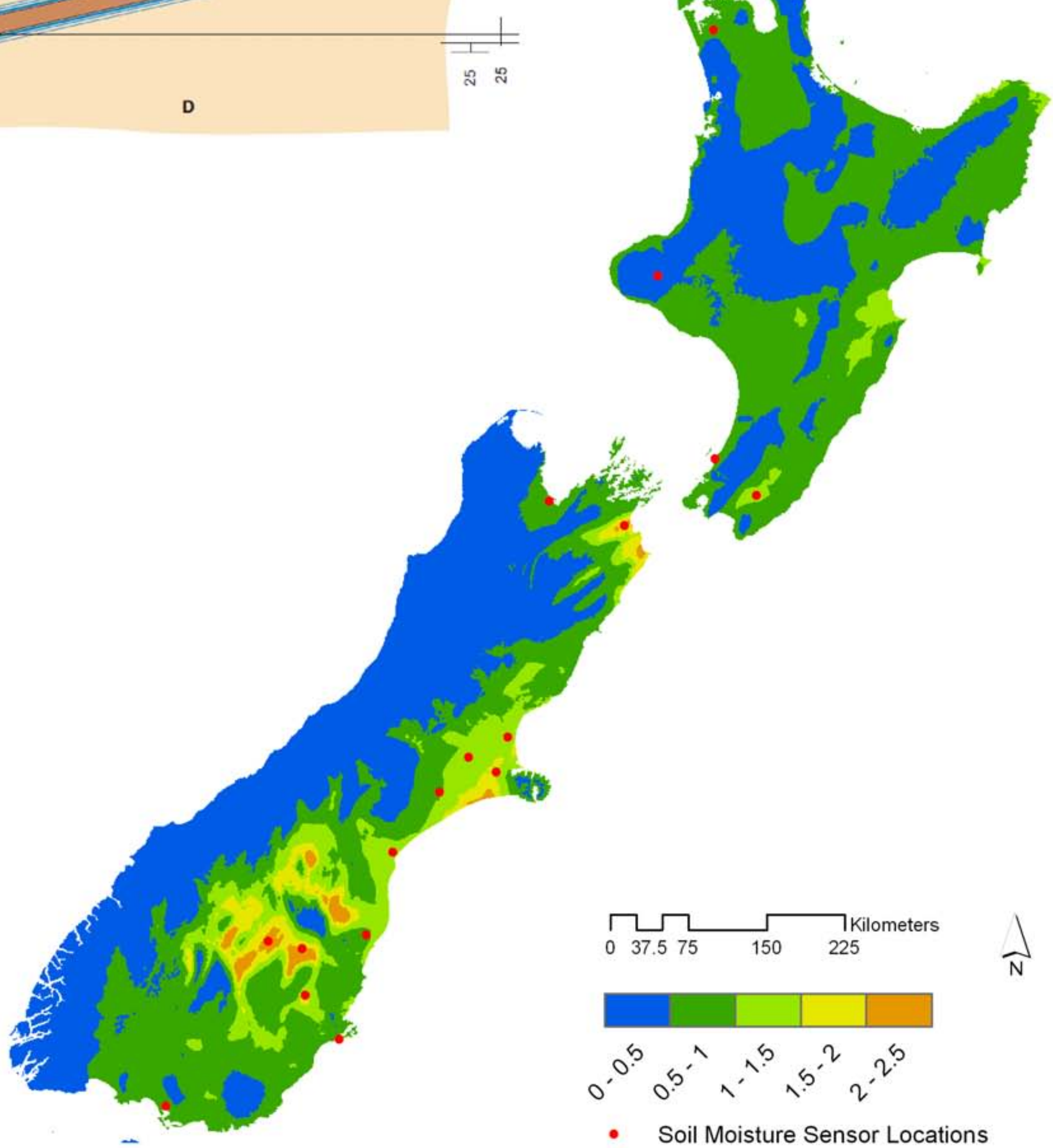
NIWA
Taihoro Nukurangi

Aridity Index (Milly 1994)

This descirbes the ratio of mean annual potential evapotranspiration to mean annual precipitation.
More detailed information in section 4.1.1

Figure: shown is installation of Aquaflex sensor. Stated dimensions are in [mm]. Electrical field is implied.
A- sensor electronic, B- sensorband, C- electrical field, D- soil, E- ground surface. [Kopman et al 2009]





List of Symbols

General Definitions

Variable	Description	Units
θ	Water content	%
θ_{FK}	Water content at field capacity	%
θ_{mean}	Mean soil moisture	%
θ_{max}	Soil moisture maximum	%
θ_{min}	Soil moisture minimum	%
θ_{sat}	Soil moisture at saturation - Total Porosity	%
σ_{soil}	Standard deviation of soil moisture	%
σ_{prec}	Standard deviation of Rainfall	%
h	Depth of soil layer	mm
P	Precipitation	mm
ETP	Potential Evapotranspiration	mm
k	Recession parameter of equation 4.4	-
R	Aridity Index	-
S	Seasonality Index	-
ρ_{spear}	Spearman Rank coefficient	-

Model state variables

Variable	Description	Units
S_1	Total water content in the upper soil layer	Mm
S_1^{Tens}	Tension water content in the upper soil layer	Mm
S_1^{TensA}	Primary tension water content in the upper soil layer	Mm
S_1^{TensB}	Secondary tension water content in the upper soil layer	Mm
S_1^{free}	Free water content in the upper soil layer	Mm
S_2	Total water content in the lower soil layer	Mm
S_2^{Tens}	Tension water content in the lower soil layer	Mm
S_2^{FreeA}	Free water content in the primary baseflow reservoir	Mm
S_1^{FreeB}	Free water content in the secondary baseflow reservoir	Mm
p	Precipitation	mm/day
pet	Potential evapotranspiration	mm/day
e_1	Evaporation from the upper soil layer	mm/day
e_2	Evaporation from the lower soil layer	mm/day
e_1^A	Evaporation from the primary tension store	mm/day
S_1^B	Evaporation from the secondary tension store	mm/day
q_{sx}	Surface runoff	mm/day
q_{12}	Drainage of water from the upper to the lower layer	mm/day
q_{if}	Interflow	mm/day
q_{urof}	Overflow of water from the primary tension store in the upper soil layer	mm/day
q_{utof}	Overflow of water from tension storage in the upper soil layer	mm/day
q_{ufof}	Overflow of water from free storage in the upper soil layer	mm/day
q_{stof}	Overflow of water from tension storage in the lower soil layer	mm/day
q_{sfof}	Overflow of water from free storage in the lower soil layer	mm/day
q_{sfofa}	Overflow of water from primary baseflow storage in the lower soil layer	mm/day
q_{sfofb}	Overflow of water from secondary baseflow storage in the lower soil layer	mm/day

Model parameters

Parameter	Description	Units	Lower Limit	Upper Limit
$S_{1,max}$	Maximum storage in the unsaturated zone	mm	25.000	500.000
$S_{2,max}$	Maximum storage in the saturated zone	mm	50.000	5000.000
θ_{tens}	Fraction total storage as tension storage	–	0.050	0.950
θ_{rchr}	Fraction of tension storage in primary zone (unsaturated zone)	–	0.050	0.950
θ_{base}	Fraction of free storage in primary reservoir (saturated zone)	–	0.050	0.950
r_1	Fraction of roots in the upper soil layer	–	0.050	0.950
k_u	Vertical drainage rate	mm/day	0.010	1000.000
c	Vertical drainage exponent	–	1.000	20.000
α	Vertical drainage multiplier for the lower layer	–	1.000	250.000
ψ	Vertical drainage exponent for the lower layer	–	1.000	5.000
$kappa$	Fraction of drainage to tension storage in the lower layer	–	0.050	0.950
k_i	Interflow rate	mm/day	0.010	1000.000
k_s	Baseflow rate	mm/day	0.001	1000.000
n	Baseflow exponent	–	1.000	10.000
v	Baseflow depletion rate for single reservoir	day^{-1}	0.001	0.250
v_a	Baseflow depletion rate for primary reservoir	day^{-1}	0.001	0.250
v_b	Baseflow depletion rate for secondary reservoir	day^{-1}	0.001	0.250
$A_{c,max}$	Maximum saturated area (fraction)	–	0.050	0.950
b	ARNO/VIC b exponent	–	0.001	3.000
μ_τ	Time delay in runoff	day	0.010	5.000

Ehrenwoertliche Erklaerung

Hiemit erklaere ich, dass diese Arbeit selbststaendig und nur unter der Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Christchurch, den 2 Juli 2010

(Marcel Gaj)

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1. Introduction

Soils are a very important natural resource, because they are essential for primary production. In general circulation models of water fluxes soil moisture often is represented with a conceptual model approach. An important factor is the capacity of soils as a water storage. Soils are directly connected to the atmosphere and therefore directly influenced by radiation. Water is stored in soils it is not only available for plants but also available for evapotranspiration from the ground surface. Thus predicting the behaviour and spatial distribution of soil moisture over a large area is essential for water management purposes.

Soil moisture is a key variable related to many climatological and hydrological processes. In Rainfall-Runoff models soil characteristics are a key variable that reflect interactions between vegetation, atmosphere, and subsurface flow. Soil characteristic also determine fast runoff components and recharge to the groundwater. Factors affecting interaction between soil and atmosphere are land cover, topography, climate features and the soil type itself.

1.1. State of the Art

In recent years there have been many approaches to understand soil moisture behavior on a spatial basis. Differences of mean moisture content are related to seasonal patterns in the catchment. Further it is established that topography plays an important role in controlling soil moisture variation in space (Qiu et al., 2001; Svetlitchnyi et al., 2003). Qiu et al. (2001) found that the relative role of environmental attributes such as landuse, topography and relative altitude differ at different depth. Interactions between soil properties and plant cover were also investigated. There have been some studies to address the role of plants in water controlled ecosystems (Laio et al., 2001; Porporato et al., 2001; Rodriguez-Iturbe et al., 2001). They developed a stochastical model to mimic soil moisture dynamic to measure vegetation water stress. They conclude that, plants adapt to climate features and soil texture and also to rainfall intensity with different rooting depths. With help of geostatistical methods it can be shown that environmental attributes such as more rainfall and higher mean soil moisture content are often associated with a lower spatial variability of soil moisture (Brocca et al., 2007; Western et al., 1999, 2004). Other investigations have been done to understand soil moisture on a temporal basis. Field studies were made to investigate temporal stability of soil moisture as a function of depth. Starks et al. (2006) concluded, that only two of eight locations of his experimental setup showed temporal stability. All other sites underestimated the mean soil moisture of the watershed. Lawrence & Hornberger (2007) explained soil moisture variability and their relation to mean soil moisture in different climate zones. He concluded, for semi-arid areas variance increased with increasing mean soil moisture because the mean soil moisture never approached porosity. He discovered for humid areas decreasing variance with increasing mean soil moisture. Finally Brocca et al. (2009) made a soil moisture temporal stability analysis and concluded that a continuous operating soil moisture measurement network is needed for investigations with regard to catchment hydrological modeling.

Because state variables describing soil moisture behaviour are such an important issue in rainfall runoff modeling, there are various investigations trying to use information of soil moisture measurements to improve rainfall runoff modeling approaches (Brocca et al., 2009; Pauwels et al., 2001). The use of hydrological models to determine hydrological response of runoff is very common and a lot of research has been done to understand processes of water pathways. Also there a various methods to calibrate hydrological models with observed data Beven (2002). However, this calibration process is sometimes leaded by a objective measure that exclude process knowledge of the system which can lead to unrealistic model parameters. It is also known that good agreement with observed data can result with different combination of parameters. These is known as equifinalty which is extensively discussed in the model community (Beven, 2006). Equifinality means that there a various possibilities of parameter combinations that lead to the same agreement of model output to observation.

In recent years researchers of other disciplines try to define new ways to combine hydrology with, for example pedological knowledge. These studies show that pedological knowledge is very important for an improved understanding of water flow within the subsurface. Lin et al. (2008) related pedological findings to hydrological processes and suggested to consider soil structure and soil forming processes to explain water flow within the soil. Lin (2009) further explains that Hydropedology addresses questions to subsurface heterogeneity such as how soil architecture influences preferential flow, how soil distribution patterns influence hillslope/watershed hydrology, and how the hydrologic cycle feedbacks to pedogenesis and controls hydrological soil responses. Allen et al. (2009) introduced a hierarchical theory to examine complexity in hydro-pedological investigations. Recent research tries to achieve new dimensions to characterize soil water properties. Braudeau & Mohtar (2009) concluded, the organization of the soil structure is related to thermodynamical interaction with water and introduced a concept of two embedded structural elementary volumes.

Other investigations focused on preferential flow paths at the hillslope scale and their conceptualization in hydrological models (Weiler & McDonnell, 2007). Furthermore, virtual experiments are found to be a useful tool to identify hydrological process and improve their representation in hydrological models Weiler & McDonnell (2004). Other investigations showed that, even for soils with similar pedological description effects of macropore flow to runoff generation can be different (Weiler, 2003). Macropore flow occurs in pores that are for example generated by earth worm channels, shrinking cracks and root canals. Weiler (2005) showed that hydrological response is underestimated without considering initiation of macropore flow in a hydrological model.The hydrological community seeks to achieve interdisciplinary theories describing hydrological phenomena. McDonnell et al. (2007) proposed, the hydrological perspective is to narrow and must be broadened. Further he suggested to find methodologies which target to generate tests and new theories with the aim to generalize observation from one place to another. Finally these approaches should be interdisciplinary to broaden the view of hydrological process understanding. Wagener et al. (2007) suggested a need of a classification system regarding the use of model structures and parameters for particular situations. It is the challenge of research to transfer process knowledge to a conceptual idea that leads to decisions about model structure and parametrization (Buytaert & Beven, 2009; Seibert & Beven, 2009). The transfer of information from gauged to ungauged catchment remains a crucial task in hydrology with several sources of uncertainty. These uncertainties are related to data quality, parameter uncertainty and model formulation (Beven, 2006; Clark et al., 2008; Liu & Gupta, 2007). A further source of uncertainty arise when implementing conceptual models (Clark & Kavetski, 2010; Kavetski & Clark, 2010). It was found that in addition to uncertainties in data, model structure and parametrization, depending on the numerical solution method inherent uncertainties arise.

To address the issue of model structural uncertainties a 'Framework for Understanding Structural Errors' (FUSE) was implemented (Clark et al., 2008). Bai et al. (2009) used a top-down approach to improve knowledge of structural errors in rainfall runoff models. He suggested to analyze suitability of model structures in greater detail at specific places. McMillan et al. (2010) demonstrates how field data (time series of precipitation, soil moisture, flow) can be used to test hypotheses about model structure to design a conceptual model for an individual catchment. It is proposed that a key to asses suitable model structure is the creative interpretation of field data by the experimentalist. A further paper of Clark et al. (2010) discussed weakness in model structures of rainfall-runoff models. It is concluded that calibrated hydrological models bring right answers for the wrong reasons with unrealistic parameters compensating structural deficits. As a consequence parameters derived by knowledge a priori did not adequately mimic the processes in the catchment. However, the calibration and validation of models with multi criteria soft data is suggested to be the way forward for the development of more realistic models (Seibert, 2000; Seibert & McDonnell, 2002). Zolezzi et al. (2009) suggested a framework that comprises information of soft and hard data to define limits of acceptability for the calibration of rainfall runoff models with the GLUE methodology. The present study has its focus on internal states of different rainfall runoff models within the FUSE framework.

1.2. Abstract

As a consequence of a drought in 1998/1999 the National Institute of Water and Atmospheric Research New Zealand established a soil moisture network. Soil moisture sensors are installed all over New Zealand covering different soil types but with similar plant cover. All sites are located under pasture on flat land. This soil moisture network enables investigations of soil moisture behavior over a broad range of climate conditions and with various soil types.

This study is an interdisciplinary approach to improve understanding of model structural errors in rainfall runoff models. It is a step into a detailed process based evaluation of model performance at different places. The focus of this study is hydrological soil response. For this reason FUSE was adjusted to output soil moisture data instead of flow data. Finally the internal model state for the upper soil layer can be compared to measured soil moisture.

Pedological knowledge is considered and related to hydrological processes. The resulting perceptual model is then transfered into different conceptual models of FUSE. This is made stepwise from a simple model to models with more complexity which is known as a top down approach. This investigation is done on the plot scale in a temporal context. The hydrological behavior of soil moisture within the annual cycle and its relationship to climate conditions and soil properties is studied in more detail. The time series of soil moisture that are used in this study comprises periods between four to six years.

Statistical methods are used for a qualitative comparison of various soil types under different climate conditions. For a more quantitative evaluation rainfall, evapotranspiration and soil moisture data is used to calibrate conceptual components representing the soil layer in common rainfall runoff models. On that basis sensitivity of parameters and performance of different model structures representing the soil layer are evaluated.

2. Study Area

This chapter gives an general introduction to New Zealand. Then particular weather patterns are discussed. Finally an overview of two main factors that effect soil genesis and soil moisture is given.

New Zealand is located in the southern hemisphere. Its surface area expanse is about 270000 km^2 and it comprises two main Islands. The islands of New Zealand are located between the 34 to the 47 degree of latitude and the 168 to 177 degree longitude. The two mountainous islands have an extent of about 1600 km length and at its widest part of 450 km width. Due to the geographical location the two islands experience a wide range of climate characteristics. The range of climate correspond to the climate found on a continents with a large land mass Mosley (2000). The Southern Alps are the dominant mountains with many peaks above 2500 m. The highest mountain (Mt. Cook / Aoraki) reaches an elevation of 3754 m and is located in the central of the South Island. The axis of the mountain chain crosses the South Island from south-west to north-east for a distance of 800 km. That is caused by the conjunction of the Pacific and the Indian-Australian plates. Generally, there are areas above 1000 m and peaks exceeding 1500 m. Mountains cause huge spatial variation in precipitation because of orographic effects. Volcanic activity is another feature of this plate boundary that caused highly heterogeneous parent rock material that together with climate patterns resulting in various soil forms and vegetation cover that characterizes the unique landscape of New Zealand. Main difference between the two islands is the shape of the topography. The North Island is more hilly with rounded hills at a slope between 12 - 28 degrees. The South Island has more steep land around the mountain chain with slopes above 28 degrees. Altogether this leads to regions of particular hydrological features within the two islands.

2.1. Regional Hydrology

Based on hydrological information in combination with general climate features of New Zealand's island position in the southern hemisphere it can roughly separated into particular regions from a hydrological perspective. The following section considers how to distinguish regions of certain hydrological features. Temperature, humidity and seasonality are important aspects driving soil genesis at different spatial scales and temporal scales Molloy (1998). Associated with parent rock material, particular soil types originate based on those features as will be mentioned in section on soil physics.

2.1.1. Climate

Climate in general is defined as a long term weather pattern of a region. Overall the climate of New Zealand can be classified as temperate oceanic. But the particular position of New Zealand and the heterogeneous shape causes strong regional climatic variability. Classification of climate is based on different measured observations describing physical properties of the environment (Thornthwaite, 1948).

New Zealand is surrounded by ocean which ensures that any approaching airmass is moisture laden. The south equatorial current of the Pacific is consistent all year long. In addition, weather systems such as fronts and depressions moving eastwards, the wave cyclones of the Tasman Sea to the west and the tropical cyclones from the north track across or near the country (Salinger, 1980). The successions of cyclones and anticyclones drive significant variability in the short-term climate. The climate is maritime because of minimal continental influence, except the central of the South Island which is sheltered from the prevailing mid-latitude westerlies.

Sea-surface temperature (SST) is of considerable relevance for the climate of New Zealand. Today there is an extensive network of Argo-floats that measure temperature, salinity and depth. More detailed information can be found at the NIWA webpage. However, in the past the lack of data has restricted the number of studies. The earliest research, which investigated the correlation of SST and Air-Temperature, reported that there is a high correlation between SST anomalies and MSLP anomalies if the SST lags by 1 month Mullan (1998). Further shifts in temperatures within the Pacific ocean occur in a decade scale. These shifts alter the value of annual precipitation. Compared with the period 1947, consistent decreases of up to 8 % occurred for the period 1978-1999 on the north and east of the North Island, and increases of more than 8 % occurred in the west and south oft the South Island. (McKerchar & Henderson, 2003).

There are two different terms. One is called the Pacific Decadel Oscillation (PDO) and the other Interdecadel Pacific Oscillation (IPO). There is a strong similarity between these indices. It is argued that these terms describe the similar phenomenon. More common is the IPO because it describes the oscillation for the whole Pacific basin. This oscillation shifted phase in the mid-1940s and in 1977/1978 (Salinger et al., 2001) and it was thought that it shifted again in 1999 (McKerchar & Henderson, 2003). The El Nino and La Nina phenomena are changed in occurrence frequency and intensity by those shifts. That can cause low rainfall that affect soil moisture and agriculture and river ecosystems.

2.1.2. Precipitation

The mean annual precipitation in New Zealand ranges from 300 to more than 10.000 mm per year. the highest values occur on the western flanks of the mountain chain in the South Island. The band of high intense rainfalls is less than 20 km width and runs parallel to the crest of the Southern Alps on the West coast. The reason the high rainfall intensity is the rapid rise in elevation of the mountains and their location close to the ocean. Behind the crest on the lee-side rainfall drops down to 1000 mm. Further east of the mountain chain in the Otago region as well as in the low lands of the Canterbury plains annual mean rainfall decreases to 500 mm. Rainfall is more consistent on the North Island. High rainfall is associated with increase in elevation around Mt. Taranaki and Lake Taupo which is a water filled volcanic crater.

On map III rainfall distribution over New Zealand is shown. The values are mean annual values from 1960 to 2001. This rainfall surface is derived from daily precipitation data using a second-order derivative trivariate thin plate smoothing spline interpolation method (Tait et al., 2006).

This interpolation method uses latitude, longitude and mean annual precipitation surface derived from a guided contouring of data by experts for the period 1951 - 1980. In addition interpolated precipitation surface were validated with flow data from 345 catchments. Considering New Zealands topography significant improvement could be shown using elevation as third independent variable (Woods et al., 2006).

2.1.3. Evapotranspiration

Woods et al. (2006) estimates evapotranspiration and figured out that when potential evapotranspiration is averaged over long time period, just insignificant differences were noticed. This were calculated with the Penman potential evapotranspiration. Different analyses showed that there is a significant variability in spatial as well as in temporal scales. Averaged over long time period the values vary about a stable mean. This average based on data from the National-Climate-Database over the period from 1972 to 2003. The required meteorological data to calculate the Penman potential evapotranspiration was not available for every location. In this case Tait and Woods (2006) accepted a correction factor using pan evaporation or Priestley-Taylor potential evapotranspiration. On map III the spatial distribution of annual mean potential evapotranspiration over New Zealand is shown.

Climate strongly effects the genesis of soils in long term (e.g. weathering) and also in short term (e.g. shrinking). The following chapter gives a brief introduction to genesis of particular soil types in New Zealand. How these soil types are classified and general methods to characterize soils from a hydrological perspective are also described. Finally measurement techniques to quantify water storage are briefly discussed.

3. Soil Properties

How soils behave from a hydrological perspective is aligned to their composition of sand, silt and clay as well as the content of gravel and stones together called as texture. In combination with the moisture status the hydraulic properties are affected by texture and therewith transport, storage and release of water. Water movement occurs between places where the potential energy is high to places where the potential is low with the aim to find an equilibrium with its surrounding (Warrik, 2002).

3.1. Soil Type Genesis

From a geological perspective New Zealand is young and very mobile. Volcanic activity is another feature that formed the landscape. The land was covered with forest over 80 million years ago. Therewith the soil was influenced by water percolating through the canopy and forest floor litter dissolved soluble elements of the soil. Biological activity of micro-organisms, insects and earthworms playing a role in transforming the soil. These processes have not been time constant. Climate began to fluctuate, periods of warmth began to alternate less frequently ending up in several ice ages during the last 600000 years. As a consequence forest retreated from the high country areas of the South Island and the axial ranges of the North Island. Glacial activity and lower tree lines allowed vast quantities of gravel and sediment to be washed onto the lowlands. After this periods of ice ages (10000 - 14000 years ago) until the arrival of the Polynesians 1200 years ago the pattern of soils was relatively undisturbed. (Molloy, 1998)

Probably small changes in the natural vegetation took place after the first Polynesian settlements. Particular in the eastern regions large areas of forest was destroyed by fire in the dryer lowlands. The coastal lowlands of the North Island were later slightly affected by agricultural land use of the Maori. Major change of vegetation cover occurred after arrival of European settlers. Forest and tussock grassland changed to pasture and arable crops. Pasture were successfully established on the ashes of the former forest and where the climate was suitable. Browsing by herbivores and overgrazing by domestic stock degraded the vegetation cover of large areas. The hill country of Gisborne-East Cape, Wanganui-Rangitikei the Hawkes Bay Waipara and central Otago were strongly affected by those land use changes. This has happened in the last 100 years since the european settlements. (Molloy, 1998)

The natural development of a soil cover takes a lot of time. Rocks fragment by weathering to smaller particles such as sand, silt and clay. This is aligned to external forcing such as rain, heat, cold and wind furthermore to the underlying geology. After plants become established organic matter merges with the rudimentary top-soil and fertility rises.

Nutrients could be solved and transported by water within the soil where they can be taken up by plant roots. Gradually, the soil matures at a rate that is strongly depended on the local climate pattern. As the soil develops vegetation cover increases progressively. Forest become established at the final stage of soil development. Molloy (1998) Those soil forming factors of parent material, climate and biota lead to design New Zealand's soil pattern and landscape. Hence a broad variety of soil types originate within the islands. The distribution of soils regarding their order can be found on map IV and V.

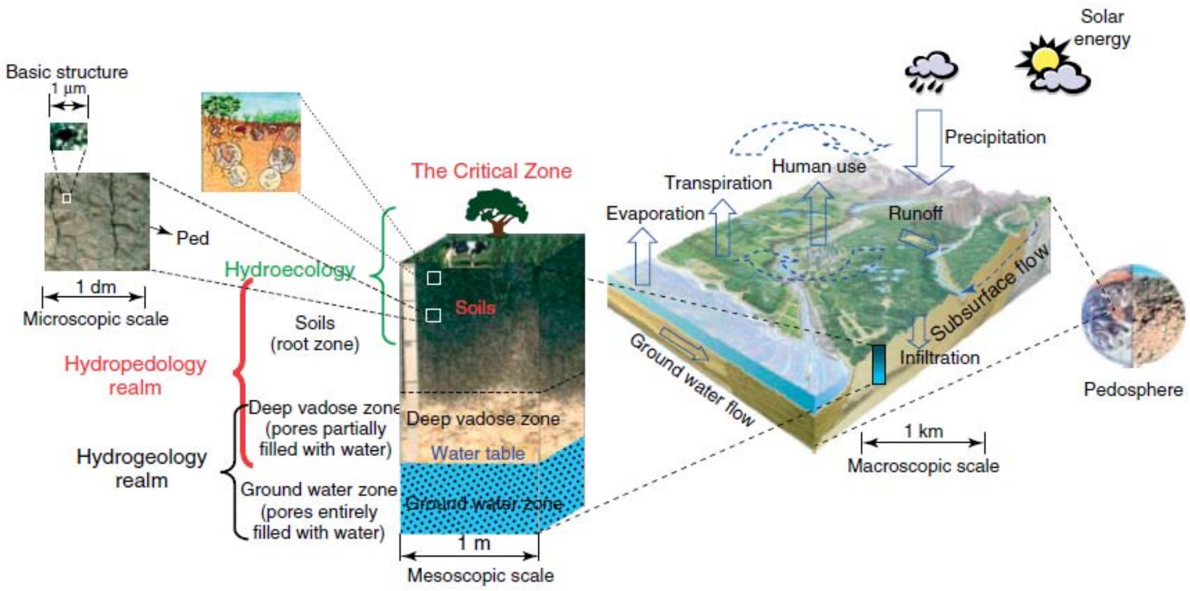

Figure 3.1.: Soil as critical link between surface subsurface processes. (Lin et al., 2008)

3.1.1. Soil structure

The two clay and soil organic matter bind soil particles to form aggregates in the soil resulting in a certain soil structure. Small aggregates formed by non- crystalline clays with a very high surface area are most effective in binding particles. Those micro aggregates are very stable when wetted. In contrast crystalline aluminosilicate clays tend to fall apart when wet. Other organic components can act as glue in holding soil particles together. Humic substances do this job in the smallest microaggregates (0.2 - 20 μm) by holding clay particles together. Polysacharides excluded by plant roots and microorganism are very important in holding this small micro aggregates together. Other microaggregates can be seen by the naked eye. Those are loosely hold together by fungal hyphae or plant roots (200 - 2000 μm). Larger aggregates vary in their structure and are illustrated in table 3.1.

The parent rock has a major effect on soil texture. Also chemical properties are influenced by the underlying geology. For example sandy soils generally appear on weakly weathered rocks. Those soils are also very common in coastal regions. Conventional sandy textures are derived from weathering resistant mineral such as quartz and titano-magnetit(west coast main islands), Coarse-grained igneous rocks like granite are found in glacial out wash and river alluvium (often Quartz and feldspar-rich sands from granite and greywacke).

Silty textures are more common in the downlands where silty grained particles are transported out of the river on to the floodplains. Clay soils are a characteristic of strongly weathered soils. If the parent rock of fine grained material such as mudstone, clay soils result. These soils occur most on the North Island. Basically the moist climate there accelerates the rate of weathering in an extent that those soils can be found on young basalt that is only a few hundred years old. Molloy (1998)

3.1.2. Soil classification of New Zealand

New Zealand developed its own particular classification system in 1980. It was influenced by the United States soil classification system. The present classification system is based on the current knowledge and classifies New Zealands various soil forms (Hewitt, 1998).

It comprises 15 orders, 73 groups, 272 subgroups and soil forms. Soil orders show generalized overview about soils in New Zealand. Orders separate soils regarding their parent material as well as chemical and physical properties (refer to map IV and map V). Subgroups provide more detailed information about soils in every group. Finally, those subgroups contain various soil forms that provide more detailed information about soil parent material, texture and permeability (refer to table 4.1). However, this classification system does not contain sufficient information about hydrological soil response. It is not necessarily true that different soil types respond hydrologically differently. From a hydrological perspective there could be another classification system that separates soils based on their hydrological response to their external forcing.

Nevertheless, to characterize a soil profile requires technical terms that describe texture, structure and development. Before we going deeper into characteristics of soils and considering properties that influence ability of water storage and conduction of water some pedological meanings are introduced.

Soil structure refers to the size, shape and degree of development of aggregates. Appearance of aggregates is shown in figure 3.1. Structural units can be naturally or artificially formed by soil forming processes. Spatially arrangements of these units include pores and fissures between and within aggregates. Peds for example are naturally formed aggregates. In weak developed soils there is lack of soil forming processes and instead one will find a more massive structure that is single grained, earthy or cloddy. “These soils have a low pedality or are apedal. Pedality is the physical constitution of a soil material expressed by the size, shape and arrangement of peds” (oral information Ichythus (2010)). Lin et al. (2008) explains these features of soils in a hydrologic context.

3.2. Soil characteristics

If we look closely there is a connection between soil characteristic and hydrological response. However, hydrological soil response also depends on climate, vegetation, connection to groundwater and land use. Water content can change structure and effects soil strength especially if aggregates are loose and apedal. Also the structure affects water transmission, porosity and the potential to keep water. Penetration resistance gives information about soil characteristics mentioned above. Also there is an inverse relation to hydraulic conductivity (Shanley et al., 2003). An increase of penetration resistance in a uniform soil profile decreases pore space volume and therewith water storage capacity.

3.2.1. Porosity

Porosity is characteristic of soil that defines the pore space volume per cubicmeter of soil. On a mass basis one can say that the difference between a completely wet and a oven dry soil package is the total porosity. The gravimetric soil water content can be derived from the following equation.

$$Porosity = \frac{Soil_{wet}[g] - Soil_{ovendry}[g]}{Soil_{ovendry}[g]} \tag{3.1}$$

This amount of water per cubic meter soil can then be compared with other aboveground water dimensions of rainfall, evaporation and runoff. Modern measurements like Time Domain reflectometry (TDR - see below) or the later mentioned Aquaflex sensor measuring soil water content for a given soil column in percentage. Considering soil forming processes (structure) acknowledged earlier the porosity and the maximum water retention can vary depending on structural state. This in turn is depends on the soil texture and on climate conditions. (Warrik, 2002)

3.2.2. Soil water potential

Soil water potential is strongly dependent on texture and structure of soil. One approach to simplify soil hydraulic properties is the concept of potentials. Resulting from the different effects of capillary and adsorptive forces within the soil the total soil water potential can be defined by:

$$\psi_T = \psi_m + \psi_s + \psi_p + \psi_z \tag{3.2}$$

The matrix potential ψ_m results from the structure of texture. Dominating mechanisms are adhesion of water molecules on particles and capillary forces resulting from the irregular geometry of soil pores. The absolute value of ψ_m is measurable as tension suction and ranges between 0mm when saturated to 1000 mm for very dry substrate.

Solute or osmotic potential ψ_s is determined by the presence of solutes in the soil water. This effect is neglible if only liquid water flow is considered. It is important at interfaces where diffusion takes place. For example at the soil-water-air boundary where water evaporates salt will left behind. At the soil-root interface, semipermeable membranes are barriers to water with its solutes. As mentioned before in section 3.1.1. solute transport and exchange at this interface is a soil forming factor.

Pressure potential ψ_p processes free water and is also defined as the hydrostatic pressure head. This potential affect water which is not attracted by forces from the matrix. It is only under the influence of gravity and the overlying water. Although ψ_p is positive underneath the water table and zero if it is above. The gravitational potential ψ_z is equal to the energy needed to pull a body against the gravity from its present point to another reference level. (Warrik, 2002)

3.2.3. Field capacity, Wilting Point and Plant-Available Water

If internal drainage of water becomes negligible the soil moisture reaches field capacity (Warrik, 2002). Field capacity is defined as a amount of water that soil is available to hold against gravity. This stage is in some cases reached between 24 to 48 hours. This is a rule of thumb and does not ensure that this is the actual value for field capacity. But it can be estimated directly from the time series where it is visible at the change of slope in the recession slope after a rainfall event occurred. Depended on antecent moisture content and depth of wetting there are uncertainties by estimating field capacity.

1. If the soil is very moist before new wetting occurs the rate of redistribution of water is slower and the value for field capacity seems to be higher.

2. Impeding layers or a high water table in the soil profile also affect redistribution of water.

Some other basic soil hydraulic properties are related to plant physiological aspects. Wilting point is often defined as the point at which plants are not longer able to extract water from soil to cover their demand and begin to permanently wilt and die (Warrik, 2002). Commonly this value is defined as - 1.5 MPa matric potential. However, this can vary between different soil species as well. Finally water content of soil between field capacity and wilting point is defined as plan available water. It is calculated as, $(\theta_{FC} - \theta_{WP})$, considering that water above θ_{FC} will not stay long in the soil column under normal conditions. Estimating plant available water is very important for the determination of irrigation amounts.

Warrik (2002) suggested a rule of thumb to estimate θ_{FC} as $\theta_{Sat}/2$ and θ_{WP} as $\theta_{FC}/2$. There are also more complex methods to analyze relation of wilting point and corresponding plant reaction (Porporato et al., 2001). In this study field capacity will be derived by analyzing the time series. Maximum water storage is assumed to be measured by the sensor.

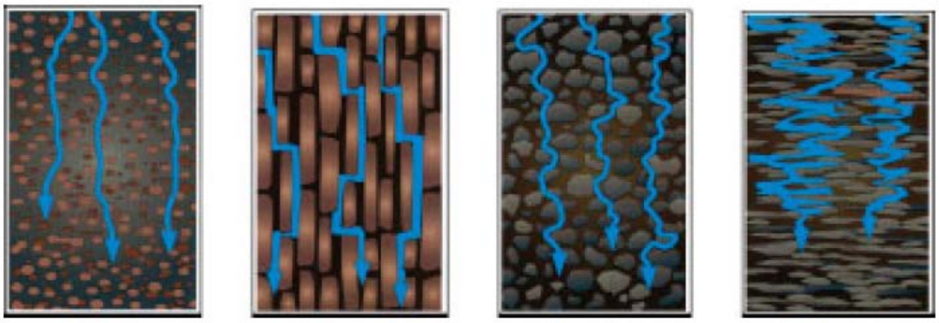

Figure 3.2.: Different types of aggregation. Blue lines show possible water flow paths between peds. (Lin et al., 2008)

3.2.4. Preferential Flow

Drainage of water occur through the matrix of soil if the water content is above θ_{FC}. A further aspect are preferential flow paths that occur in soils. Those flow path allow fast drainage of water to lower parts of the soil. There are different subtypes of preferential flow processes. Macropore flow occur in pores that are for example generated by earth worm channels, shrinking cracks and root canals. It could be shown that hydrological response is underestimated without considering initiation of macropore flow (Weiler, 2005). Even for soils with similar pedological description effects of macropore flow to runoff generation can be quite different (Weiler, 2003). The aggregation of soil is linked to geology and climate. Peds are formed by water, minerals and biological processes. Further those structures provide space for macropore flow. The shape of those macropores is depending on the type of peds that occur in the soil. Figure 3.2 illustrates possible path ways for water between these peds.

3.3. Soil Moisture Measurement

Some soil patterns are measurable on a physical basis. The main focus in this study is the soil moisture. Out of this reason a brief introduction to soil moisture measurement technic is given in the next subsection.

3.3.1. Time Domain Reflectometry (TDR)

This measurement method uses high frequent electrical impulses passing through an electrical conductor. The sensor looks like a fork with two or more sticks where the signal passes through. If soil moisture content rises the permittivity of the soil package that attends as dielectric rises to delay the signal. Empirical relation are then used to determine the soil moisture content.

3.3.2. Time Domain Transmission (TDT)

The time domain tramission technique is a further development of the TDR technology. The basic principle is a current flow through a conducter that induces a electromagnetic field sourrounding the conductor. Expansion of this electromagnetic field is dependent on the electromagnetic permittivity of the medium. Water has a much higher dielectric constant than most other materials. For this reason permittivity rise and falls with moisture content of the soil package. As the induced signal arrives at the frequency reflectometer it is allieviated by the moisture content in the soil. This relation is used to transform soil moisture content in a electrical signal that can be interpreted by a datalogger and saved on a digital storage. (Kopmann, 2009)

3.3.3. Soil moisture sensor: Aquaflex

Aquaflex is the name of the standard soil moisture sensor of NIWA. It is composed of a 3 meter wire installed across a certain soil profile of interest. The reflected signal provides information about soil water content and salinity. The raw measurement is a volumetric moisture content based on the cubic meters of free water per cubic meter oven dried soil. The precision of this measurement is influenced by temperature, texture and salinity. On this regard, the precision improves with an increase of the applied frequency to the sensor.

TDT as well as TDR are sensitive to discontinuities in the soil. That means changes in soil bulk density, variable water table and textural change. TDT tends to produce more noise than TDR. But TDT is a lower cost alternative to TDR and another advantage is that it measures an average soil moisture content over a larger area. (Kopmann, 2009)

Shape	Structure	Properties			Illustration
	crumb	like breadcrumbs but more rounded up to 5 mm across	do not fit neatly together on place	soak up water easily; roots penetrate easily and wrap around aggregates	Figure 6.13
	granular	like breadcrumbs but more rounded up to 10 mm across	same as above		Figure 3.2
	nut	like small nuts - blocklike but with rounded edges;up to 50 mm across			Figure 6.4
	blocky	like blocks - with sharpish edges;can be any size			Figure 3.2
	columnar	standing like columns flattened at top; can be any size	fit neatly together in place within the soil	water and roots penetrate more slowly down cracks between aggregates	
	prismatic	standing like columns flattend at top; can be any size			Figure 3.2
	platy	layered like plates; can be any size		impedes water and root penetration; can be induced by bad land management	Figure 6.15,3.2

Table 3.1.: Shape and properties of soil macroaggregates based on Molloy (1998), modified

4. Methods

Soil moisture behaviour is controlled by external forcing, such as rainfall, evapotranspiration and groundwater. On the other hand it controls transfer and it controls the transfer and storage of water. Thus it is a critical zone where a lot of processes interact (refer to Figure 3.1). These processes are very heterogeneous depending on geology, climate and landuse. The soil moisture network of NIWA enables the investigation of soil moisture behaviour under a variety of soil types and climate conditions. All these soil moisture sensors are located under pasture on flat land. Therefore factors such as landuse and topography can be widely excluded. The experimental setup in this study covers 17 sites where measurements of soil moisture, precipitation and potential evapotranspiration are available. This study focus on the hydrological response of soil moisture in relation to climate, soil texture and structure.

This will be realized with pedological knowledge (Ichythus, 2008; Lin, 2009; Lin et al., 2008), common statistical methods (Brocca et al., 2009; Western et al., 2004) and a framework to locate structural errors in conceptual rainfall runoff models (Bai et al., 2009; Clark et al., 2008).

General statistics are used to show averages and variability of soil moisture, precipitation and evapotranspiration. In addition their links to pedological features on different timescales are investigated. In addition dimensionless numbers are used to classify location into groups with similarity (Milly, 1994; Woods, 2003). Further it is thought to relate these numbers to parameters that are used to calibrate conceptual models. Standard deviation of rainfall is only calculated for days with an occurrence of rainfall. Considering that days without rainfall will cause a lower value for standard deviation ς. To characterize the drainage behaviour a simple one parameter soil water balance equation is used and calibrated for different years and periods in the annual cycle(Kavetski et al., 2003).

In addition the performance of different model structure is evaluated by the use of 'Framework for Understanding Structural Errors' (FUSE). FUSE enables experiments with different model structures. It is known that parameter selection can compensate model structure differences. It is also known that parameter can compensate errors in input data. If this occurs processes in the system are wrong described by the chosen formulation of the problem . For a more detailed discussion of uncertainties arising from factors mentions above refer to chapter 4.2.

Monte-Carlo-Markov-Chain (MCMC) simulations are used to evaluate sensitivity and optimization routines like the Shuffled-Complex-Evolution (SCE) algorithm to get a global optimum. Because the objective function has an important influence on parameter optimization, a graphical calibration will also be used and compared with MCMC and SCE results. The advantage of this method is that based on process understanding and knowledge a priori (soft data) of each site, decisions about model performance can be made. Based on the derived results soil moisture response will be discussed regarding:

1. Soil properties (i.e texture, structure).
2. Model performance.
3. Parameter sensitivity.
4. Regionalisation possibilities.

4.1. Time Series Analysis

A time series of hydrological and climate data describes a physical behaviour of water over time. The outcome of a time series analysis is information that can be expressed in attributes. Attributes can be numbers describing a certain pattern, characteristic, behaviour or interaction. They may relate to rainfall, river flow, soil moisture or evapotranspiration (Woods, 2003). Hydrological models use catchment attributes or their relation to model parameters to represent certain processes driving equations that have are solved through numerical implementation.

4.1.1. Rain and Evapotranspiration

Precipitation and evaporation is strongly related to soil moisture behaviour. Climatic features are distinguished by the use of different indices. Representation of dominant forcing is shown by the use of a aridity index proposed by Milly (1994). This is a reasonable index considering that soil structure and variability of soil moisture at a spatial and temporal scale is related to mean soil moisture (Brocca et al., 2009, 2007; Western et al., 2004).

$$R = \sum E_t / \sum P_t \tag{4.1}$$

Where E_t is the amount of evapotranspiration and P_t the quantity of precipitation for a particular period. In figure this index is calculated based on the information of the precipitation and evapotranspiration layer (figure).

4.1.2. Hydrological Soil Response

A specific soil attribute is the ability to keep water against gravity forces. For this reason an index is used to describe the recession behaviour of the soil moisture storage.

$$\frac{\delta\theta}{\delta_t} = P - D \tag{4.2}$$

$$D = k * \theta_t \qquad \text{D: a fraction of } \theta \tag{4.3}$$

$$\theta_{t+1} = \theta_t + (P - \kappa * \theta_t) \qquad \text{as percolation} \tag{4.4}$$

Where θ is the soil moisture at a certain time step, p the precipitation and κ a time constant that describes the recession time of the soil moisture storage. This differential equation is solved by varying the value of k. Results for every run are compared with the measurement by using a spearman rank correlation as an objective measure. This is a first order Runge-Cutta scheme for integrating ordinary differential equations (Kavetski et al., 2003). Results of time series analysis for every single year and every of the 18 sites is shown in table 1 - 18 in the Appendix.

4.1.3. Scaling Soil Moisture

The soil moisture data is normalized using the field capacity and the wilting point. Both are derived directly from the time series as explained in chapter 3.2.

$$\theta_n = (\theta_{data} - \theta_{wp})/(\theta_{fc} - \theta_{wp}) \tag{4.5}$$

Where θ_{data} is the measured moisture content of the soil, $\theta_f c$ the moisture content at field capacity and θ_{wp} at the permanent wilting point. Soil moisture is also scaled in the model representing moisture content over the depth $S_{1,max}/\theta_{sat} - \theta_w p$, where θ_{sat} equals total porosity and $S_{1,max}$ is the maximum water storage (Clark et al., 2010).

There are different methods to estimate soil moisture content of soil at wilting point. The minimum of the time series will be used here because the time series is normalized by equation 4.5. Soil moisture should not have a value below zero in FUSE, which implies the assumption for the choice of wilting point. Therefore wilting point for the modeling part is not representing the "stress point" for plants rather, the lower limit for the model result.

Field capacity is defined as the amount of water that can be hold by the soil matrix against gravity forces as mentioned in section 3.2.3. The change in slope of the recession curve indicates that the dominating force on the water changes. The residual water in the soil from that point to the wilting point is defined as plant available water (Warrik, 2002).

4.2. Quality and Uncertainty

In this chapter is given a brief overview of sources of uncertainty. There are three main sources of uncertainty. These are input data quality, model formulation and parameter uncertainty (Beven, 2006; Clark et al., 2008; Liu & Gupta, 2007). Errors in data can further be separated into random and systematical errors. Especially rainfall measurements tend to produce systematical errors because of design and location of rain gauges (Beven, 2005). Errors can also arise by the use of rain radar. As a consequence uncertainties in model results can even be dominated by errors in forcing data (Yatheendradas et al., 2008). Therefore investigation are made to adress the issue of input data uncertainty (Kavetski et al., 2006). Consideration of errors in calibration data is also very important because the objective measure relies on those to calibrate the model.

4.2.1. Observed Data

Soil moisture measurement contain uncertainties that arise from the installation and position of the sensor. The signal response of the sensor provides information about water and salt content. Soils with high quantities of iron and organic matter can cause a signal response that differ from the expected one (Hallikainen et al., 1985). Also the sensor settings have to be adjusted to soil type and range of possible soil moisture states. Quality regarding sensor adjustment to texture is shown in table 4.1 (Kopmann, 2009) together with measured maximum and minimum values of soil moisture time series. Moreover, changes dependent on the soil texture have to be considered. Furthermore, strong changes in texture can effect accuracy of the measurement. Signal strength and shape can be distorted from those changes (Dalton & Van Genuchten, 1986). In summary soil moisture measurement uncertainties can be attributed to:

1. Installation (representativeness)
2. Textural changes (heterogeneity)
3. Measurement range (adjustment)

This uncertainties appear as systematical errors that can be considered for interpretation.

4.2.2. Parameter Uncertainty

In this section will be explained how MCMC simulations are used to provide information about uncertainties of model parameter. To explore the parameter space MCMC are widely used in hydrological modeling approaches. Interrelations of parameters can be highlightend as well as sensitivity of particular parameters. One approach of uncertainty

Table 4.1.: Listing of Soil groups and texture of the NZCS (Hewitt, 1998). Also shown corresponding measurement range of soil sensors (Kopmann, 2009) and observed maximum measured values.

Station	**Subgroup**	**Group**	**Order**	**Texture**	**Range** [%]	θ_{max} [%]	θ_{FC} [%]
Appelby	mottled	albic	ultic	fine sandy lm	15 - 65	65.5	50
Blenheim	typic	fluvial	recent	fine sandy lm	10 - 45	52.3	40
Darfield	weathered	orthic	recent	silt lm	0 - 40	46.2	34
Kaitaia	humose	densipan	podsol	silty lm	15 - 55	55.4	50
Lauder	aged	argillic	pallic	sandy to silty lm	0 - 60	56.0	35
Lincoln	typic	immature	pallic	silty lm	5 - 45	46.0	36
Martinborough		immature	pallic	fine sandy lm	10 - 50	54.0	42
Middlemarch	aged	argillic	pallic	fine sandy lm	5 - 45	43.6	35
Musselburgh	typic	gley	recent	silty lm	10 - 45	44.3	40
Paraparaumu	typic	sandy	recent	sandy lm	0 - 30	43.3	22
Pukekohe	typic	orthic	granular	clay lm	10 - 50	54.8	35
Ranfurly	typic	argillic	semi-arid	silty lm	5 - 60	56.2	40
Rangiora	typic	orthic	gley	silty lm	-	51.0	40
Stratford	typic	orthic	allopanic	fine sandy lm	15 - 50	51.2	35
Timaru	pallic	orthic	brown	silty lm	5 - 35	37.6	30
Winchmore	pallic	orthic	brown	silty lm	0 - 40	56.1	30
Windsor	mottled	immature	pallic	silty clay lm	5 - 35	38.8	30

assessment in modeling complex environmental systems is the GLUE method (Beven & Freer, 2001).

Relation between parameter values derived from a model calibration with flow data to catchment characteristics were widely investigated. It was found that the difference of calibrated model parameters for sub periods are a measure of the sum of uncertainties. It means uncertainties due to poor parameter identifiability or data problems. If the differences are small then the uncertainty is assumed to be small (Merz & Bloeschl, 2004). But this method doesnt tell if uncertainties arise from data, model structure or parametrization. Hence it is no tool to identify sources of errors which would be more meaningful (Yatheendradas et al., 2008).

Updating of parameter values during a model approach can improve model performance. However it allows many more degrees of freedom and therefore a compensation of model structure deficiencies. It might be better finding a model structure that can represent the time varying nature of the parameter characteristic without varying in time (Choi & Beven, 2007).

4.2.3. Model calibration

Often models have a lot of parameters that should represent processes in the investigated catchment. One have to consider that these models, independent if they are distributed, semi distributed or lumped models, are a rough simplification of the natural system (Uhlenbrook et al., 1999). Nevertheless, models can help to understand how the hydrological system works and capture the purpose of forecasting river flow and soil moisture once it is adjusted for the investigated site. In many cases adjustment means that optimizations routines (e.g mentioned above) are used to fit model parameters to measurement data, the so called calibration procedure. That can mean dependent on the performance measure different parameter sets will be the result (Wagener et al., 2003).

Monte-Carlo-Simulations

Monte Carlo sampling is used in many cases where uncertainty analysis of model behaviour is investigated. This sampling method is based on a Bayesian (posterior) Analysis and can be used to produce parameter sets in a specified parameter space. There are different algorithm to obtain parameter values from a likelihood or posterior density. The Gibbs sampler and the Metropolis algorithm (Greenberg, 1995) can be used for this purpose. Furthermore these algorithms can be classified in non-Monte-Carlo, non iterative Monte-Carlo and iterative Monte-Carlo methods. Where the non Monte-Carlo methods do not require an input stream of random numbers. Other Sampling Methods like importance sampling and rejection/acceptance algorithms require such a stream and a sample is taken from the posterior density. In this study 5000 simulations runs are made for every site and model structure. The result is a parameter sampling in the parameter space that is here depended on input data and model structure. This is used to evaluate uncertainty and parameter sensitivity. Furthermore, values with the highest likelihood measure are used to simulate hydrological soil moisture response.

Shuffled Complex Evolution

The shuffled complex evolution optimizer is known for its robustness. These optimizer is used to calibrate a model to observed data. This algorithm finds with a high success rate a global optimum even for complex parameter spaces. The underlying theory is an evolution within the sampling. Each sample is treated as a vertex of a simplex. This evolution strategy prevents entrapment in a local optima by periodically shuffling every vertex of different simplex to exchange information (Kavetski & Clark, 2010).

Objective Functions

The choice of an objective function for the use of calibration has a strong effect on the resulting parameter set. There can be several parameter sets with the same "goodness of fit" according to their objective function criteria. This was proposed for Nash-Sutcliff, Log-Nash-Sutcliff and a volume by combining those measures with a fuzzy measure (Seibert, 1999). In this study Nash-Sutcliff is used to compare results of the different optimization strategies. For the visual optimization the users subjective / objective measure is his process understanding. The here called visual calibration uses two main criteria:

1. parameters that are used should represent values that are physically based
2. those parameters that are calibrated, if their is no direct physical relation, will be fitted in a way that observed and modeled output show a reasonable agreement

In the last chapter some examples are given of how is dealt with data to provide an overview of process characteristic. In addition some tools used for classifying climate pattern, are introduced and a simple water balance equation was derived for the purpose of recession analysis of soil moisture data. Finally sources of uncertainties have been discussed and a brief overview of the experimental. In the next chapter architectures of conceptual models which describe the soil layer in common rainfall-runoff models are briefly discussed.

5. Architecture

Using rainfall-runoff models one has to choose between a variety of model types and structures. They can be classified as lumped, semi-distributed or distributed as well as physically based or conceptual. Conceptual models are a strong simplification of a realistic system (Uhlenbrook et al., 1999). Considering that it is impossible to take all real process fully into account, the advantage of conceptual models is the simple implementation and the short computational time. The obvious disadvantage is the parametrization which is representing a physically based process without being physically based by itself. In recent years there has been a trend back to lumped model approaches, because it could be shown that results of distributed models are not representing catchment responses any better than those from lumped models (Carpenter & Georgakakos, 2006).

5.1. The FUSE Model

Structures of different conceptual lumped rainfall runoff model are used to investigate model structural differences regarding hydrological soil response. For this purpose a modular 'Framework for Understanding Structural Errors' (FUSE) is used in this study (Clark et al., 2008). This case study is focused on the response of soil moisture at different sites under various climate conditions and soil types. Therefore model structures with diverse formulations and different grades of complexity are tested. For this purpose FUSE was adjusted to output the internal state of soil moisture instead of flow.

To discuss the behaviour of parameter sets, it is mandatory to know how the different model structures work. For this reason model structures that are important for the representation of soil moisture behaviour are briefly introduced. Consequently formulations concerning the upper layer architecture and structures that affect this layer are discussed. As shown in table 5.1 there are three architectures for the upper layer. Simplified flow diagrams for each of the models that are implemented in FUSE are shown in figure 5.1. The following introduction to fuse is aligned to Clark et al. (2008).

5.1.1. Upper layer architecture

Three different conceptual models were implemented that describe the upper layer. Those models have two different evapotranspiration schemes, three different percolation schemes and three different surface runoff systems. Those different architectures are taken from common rainfall-runoff models.

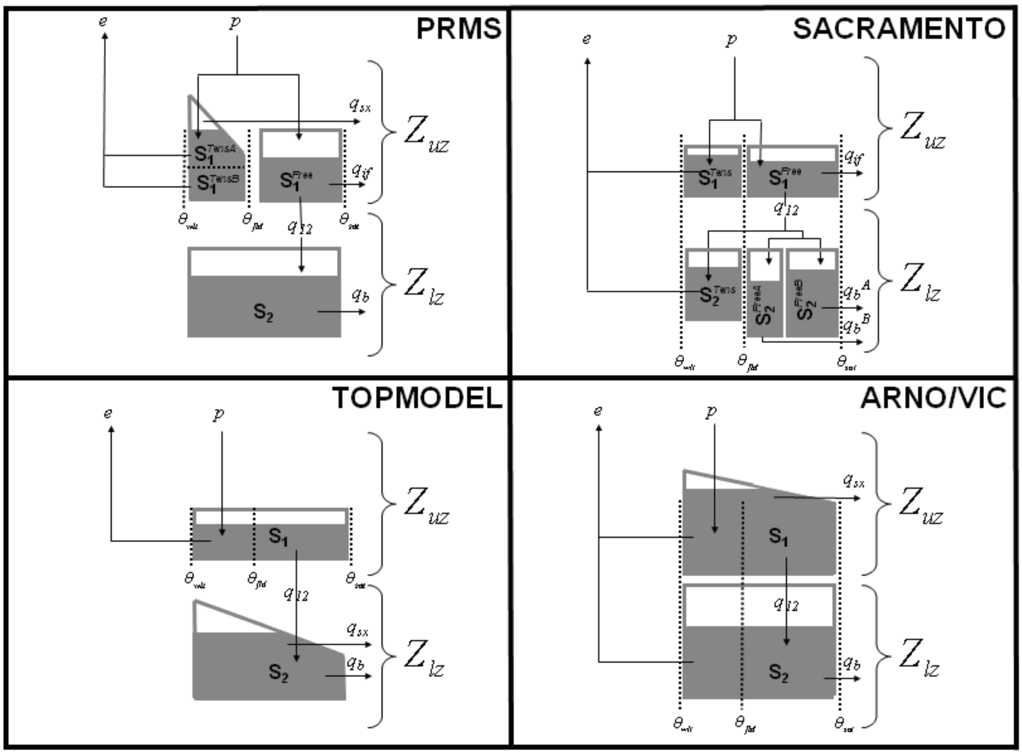

Figure 5.1.: Simplified wiring diagrams for each of the submodes in fuse. The state variables are and fluxes are summarized in table IV. Image with permission Clark et al. (2008)

Topmodel and Arno/VIC

Defining the upper layer storage by a single state variable is the simplest structure for the upper layer. This architecture is used in from TOPmodel and ARNO/VIC. The state equations shows how single parameters effect the upper layer storage.

$$\frac{dS_1}{dt} = (p - q_{sx}) - e_1 - q_{12} - q_{if} - q_{ufof} \tag{5.1}$$

Defining the amount of surface runoff (q_{sx}), that will be simply substracted from the input of precipitation. There is an option to activate interflow. Subsequently residual water percolates into the lower layer storage (S_2) where it does not effect the soil moisture anymore. Percolation is defined by two state variables, the percolation rate k_u and the percolation exponent (c) (see table IV) which controls the shape of function 5.7. The flux q_{ufof} represents additional surface runoff if the free storage is full.

Sacramento

The next more complex possibility to define the upper layer is to divide it into tension and free storage. In this case loss from the upper tension storage S_1^T and the lower S_2 storage depends on the evaporation scheme and, percolation takes place only from the free storage. There are two state equations; one for the tension storage (equation 5.2), and one for the free storage (equation 5.3) of the upper layer.

$$\frac{dS_1^T}{dt} = (p - q_{sx}) - e_1 - q_{utof} \tag{5.2}$$

$$\frac{dS_1^F}{dt} = q_{utof} - q_{12} - q_{if} - q_{ufof} \tag{5.3}$$

Surface runoff is also subtracted from the input first. Evaporative demand is provided from the upper layer depending on the evapotranspiration scheme either 'sequential' or 'rootweighting'. Overflow q_{utof} from the tension storage of the upper layer goes into the free storage of the upper layer. As a result of this structure percolation q_{12} and interflow q_{if} occurs only from the free storage. Similar to the concept of Topmodel and Arno/VIC additional surface runoff is generated if the maximum capacity of S_1^F is reached.

PRMS

The most complex structure for the upper layer divides the upper layer into two buckets where the tension storage is subdivided into cascading buckets. As a result there are three state equations to derive for the upper layer architecture.

$$\frac{dS_1^{TA}}{dt} = (p - q_{sx}) - e_1^A - q_{urof} \tag{5.4}$$

$$\frac{dS_1^{TB}}{dt} = q_{urof} - e_1^B - q_{utof} \tag{5.5}$$

$$\frac{dS_1^F}{dt} = q_{utof} - q_{12} - q_{ufof} \tag{5.6}$$

The two buckets for tension storage provide the water for the demand of evapotranspiration. Overland flow is only generated from S_1^{TA} and as bucket overflow from the free storage S_1^F. Bucket overflow from the first tension storage feeds into the second tension storage, while the overflow of S_1^{TB} feeds into the free storage S_1^F.

5.1.2. Percolation

Percolation is the vertical movement of water within the unsaturated zone to the saturated zone. There are different possibilities to describe this process. FUSE uses three conceptual model structures to describe percolation with parameters.

$$q_{12} = k_u(\frac{S_1}{S_{1,max}})^c \quad (5.7)$$

$$q_{12} = k_u(\frac{S_1^F}{S_{1,max}^F})^c \quad (5.8)$$

$$q_{12} = q_0 d_{lz}(\frac{S_1^F}{S_{1,max}}) \quad (5.9)$$

The percolation rate q_{12} defines the amount of water that 'flows' from the upper to the lower layer the percolation exponent c describes the characteristic. This means for the structure with equation 5.7 that the percolation exponent restricts drainage from the tension storage. Equation 5.9 could be used in cases were the groundwater level is close to the surface. By using this case the percolation demand of the lower layer is described as follows.

$$q_{12} = 1 + \alpha * (\frac{S_2}{S_{2,max}})^\psi \quad (5.10)$$

5.1.3. Surface Runoff

There are diverse possibilities for the origin of surface runoff q_{sx}. For ARNO/VIC surface runoff is controlled by the upperlayer, which means it is directly subtracted from the input. The PRMS formulation has the surface runoff as a fraction of the upper tension storage.

$$q_{sx} = p, \min(\frac{S_1^{Tens}}{\theta_{tens} S_{1max}}, 1) A_{c,max} \quad (5.11)$$

$$q_{sx} = p[1 - (1 - \frac{S_1}{S_{1max}})]^b \quad (5.12)$$

$$(5.13)$$

5.1.4. Interflow

Fuse offers only a simple parametrization for Interflow. Actually this formulation is similar to equation 5.8 with c set to unity. Therefor, the effect to soil moisture will either be the same. But for Rainfall-Runoff modeling flow this becomes more important because this flux goes as fast flow to the channel.

$$q_{if} = 0 \quad (5.14)$$

$$q_{if} = k_i * (\frac{S_1^F}{S_{1,max}^F}) \quad (5.15)$$

5.1.5. Evapotranspiration

Evapotranspiration is a leading factor for soil moisture behaviour. Fuse offers the possibility to choose between 'sequential' and 'root weighting' schemes. The sequential evaporative demand is first satisfied by evapotranspiration from the upper tension storage. The residual demand will then be taken from the second tension storage if present or from the lower zone. Evapotranspiration that is taken from the upper zone (soil layer) is influenced by the size of S_1^T. Because the size of the tension storage depends on the maximum storage capacity, S_1^F has also an influence to the amount of Evapotranspiration. Evapotranspiration is defined by the following state equations:

$$e_1 = pet * \frac{min(S_1^T, S_{1,max}^T)}{S_{1,max}^t} \tag{5.16}$$

$$e_1 = pet * r_1 * \frac{min(S_1^T, S_{1,max}^T)}{S_{1,max}^t} \tag{5.17}$$

Generally the sequential structure leads to a higher evapotranspiration. There for the other structure will only be used if evapotranspiration is over estimated. In the 'rootweighting' method evaporation is defined by the relative root fraction in every soil layer.

5.1.6. Bucket Overflow

As mentioned above some internal flow occurs if the bucket capacity is reached. In that case water flows from one bucket to another. If that happened, flow would suddenly appear and cause a spike in the model output. FUSE uses a logistic function to avoid those turbulent behaviour and a raspy parameter space (Kavetski et al., 2003).

Table 5.1.: Shown are model components used in this study. Main features are briefly described. (Clark et al., 2010),modified

Model Decisions	**Parameterization Name**	**Model Code**
Upper layer architecture		
A. Single state	Single State	694
B. Separate tension and free storage	Separate Tension Storage	630
C. Separate tension and free storage, with tension storage further disaggregated into cascading buckets	Cascading Buckets	632
Evaporation		
A. Evaporation restricted to the upper layer, and is a linear function of storage between wilting point and field capacity.	Single layer evaporation	694
B. Evaporation in the upper and lower layers, where evaporation in the lower layer is restricted by the potential evaporation satisfied in the upper layer	Sequential	630, 632
C. Evaporation in the upper and lower layers, where evaporation in each soil layer depends on relative root fraction in the upper and lower soil layers.	Root weighting	
Drainage		
A. Nonlinear function of total storage in upper layer	Gravity drainage	694
B. Nonlinear function of free storage in upper layer	Drainage above field capacity	630, 632
C. Linear function of upper layer free storage and nonlinear function of total lower layer storage	Saturated zone control	
Interflow		
A. Linear function of free storage in the upper layer	Interflow allowed	
B. No interflow	Interflow denied	694, 630, 632
Surface Runoff		
A. Saturated area is a linear function of tension storage in the unsaturated zone	Unsaturated zone linear	694, 630, 632

6. Results

6.1. Setup

It is possible to group those sides under different criteria. One criterion is the soil texture. The soil texture defines quantities of sand, silt and clay in soil known as texture. As a result of climatic forcing over hundreds of years texture leads to a particular structure in soil. But structure can also change over shorter periods under extrem conditions. Imagine a soil with a high clay content that drys during a summer with extrem low rainfall building cracks that can only slowly get back to its old structure after supply of water.

Table 6.1.: Mean annual precipitation $P[mm]$ and potential evapotranspiration $ETP[mm]$ and yearly soil moisture averages θ_{mean} for the observed period from 2001 to 2006. Also shown minimal and maximum values for soil moisture in % and the maximum soil depth h for every site. For soil texture refer to table 4.1

Station	θ_{mean}	$\sum P$	$\sum ETP$	θ_{max}	θ_{min}	h [mm]
Appelby	45.67	820.26	1028.26	65.6	17.7	930
Blenheim	29.00	555.60	1117.12	63.30	14.50	100
Darfield	22.25	674.09	1003.76	46.20	2.70	490
InvercargillAero	30.52	1059.38	781.28	65.30	9.60	230
Kaitaia	40.86	1318.30	1027.37	62.75	15.70	305
Lauder	19.02	377.65	979.17	56.00	1.30	530
Lincoln	25.00	583.87	944.02	46.00	7.90	1000
Martinborough	28.34	796.94	994.78	54.00	12.20	510
Middlemarch	20.68	391.82	853.40	65.30	6.91	570
Musselburgh	31.84	626.88	881.30	44.60	12.00	530
Paraparaumu	12.26	998.67	937.75	45.40	1.10	1000
Pukekohe	32.39	1044.78	863.15	54.80	12.60	1000
Ranfurly	23.37	423.67	882.52	56.20	8.90	500
Rangiora	23.34	602.66	844.41	51.00	0.10	790
Stratford	29.95	1990.22	803.20	51.20	6.20	1000
Timaru	21.29	524.72	778.54	37.60	8.50	520
Winchmore	18.81	716.67	854.70	56.10	0.00	480
Windsor	22.18	480.20	825.70	38.80	4.20	970

There are seven sites classified with a fine sandy loam texture, six sites as silty loam, one site as loam, one site as sand and one site as clay loam. Also the depth varies between sites as shown in table 6.1. This has an influence on the maximum water capacity for those sides. Values for field capacity and wilting point shown in table 6.1 are a first estimate to normalize the soil moisture time series. This values are estimated as it is described in chapter Soil Physics. One should keep in mind that this values especially those for wilting point are not reflecting realistic soil moisture characteristic. Wilting point in this context is the minimum value that exist in the time series. This assumption made to ensure that soil moisture does not fall under zero in the model. It is assumed that maximum values measured are indicating effective porosity. Therefore yearly maximum values from the years 2001 to 2006 are averaged and treated as they represent maximum water storage capacity. In addition those values are compared to literature values to ensure realistic parameter (Rawls et al., 1982). Maximum water storage S_{1max} and field capacity θ_{max} are shown and discussed for every site in chapter Final Steps.

6.2. The Modelers Decision

In the following sections decisions regarding the development of a Rainfall-Runoff model will be discussed. For particular interest here the response of soil moisture is evaluated. First most common concepts for guiding through parameter estimation and uncertainty estimations are discussed. Then for every site mentioned in sections before are prepared, discussed and finally model decisions are evaluated. This includes general description of enclosure, climate and the resulting perceptual model. Finally different model structures are evaluated based on outcomes of the perceptual model decisions.

6.2.1. Calibration of Soil Model

To measure up uncertainty means not only face those in data, model structure and parameter. The right choice of parameter is accompanied by decisions regarding the conceptual model of a catchment. In this study soil moisture is focused. The implementation of FUSE uses normalized soil moisture as input (see equation 4.5). As mentioned above here the derived maximum value of soil moisture time series is used for θ_{sat}. Fraction of tension storage to total storage S^1_{tens} is treated as field capacity θ_{FK}. There are no information of percolation quantities. Qualitative it is assumed that soils with a high penetration resistance have low values for percolation. As discussed earlier there is a inverse relation of penetration resistance to saturated hydraulic conductivity. In contrast percolation is assumed to be high if subsurface is free draining or soil is based on gravel. It is also assumed that there is a relation between k in equation 4.4 and the exponent used in the conceptual model for percolation (refer to equation 5.7). It has to be considered that because of normalization of observed soil moisture uncertainties exist for inverse calibration. Finally this has to be considered when interpreting results of modeling and optimization of soil moisture response.

6.2.2. Model Structure

Before we get started modeling hydrological soil response general sensitivity of parameters for each model structure is assessed. There are three main conceptual models that describe upper layer storage. As follows model 694 refers to equation 5.1 with sequential evapotranspiration, rainfall multiplier, unlimited baseflow reservoir, no interflow and no rooting for surface runoff. As can be shown in figure 6.1 there are four main parameter for this particular site that effect soil response to their forcing. In addition there is a rainfall multiplier that in the case of modeling soil response this can eventually correct bias caused by normalization. But for further modeling this value will be constraint. This would simply shift soil moisture time series up or down and effects regarding normalization will be discussed later. Also parameter b for surface runoff does substract a certain amount of water from the input referring equation 5.1. We go more complex with model 630 where storage of upper zone is seperated into tension storage S_1^T and free storage S_1^F. Further percolation from the upper to the lower zone is only possible from the free storage. For the state equation refer to equation 5.2 and 5.3. All other parts of the model are kept as for model 694. As can be shown in figure 6.2 model structure with seperated tension storage there is a interrelation between tension storage and maximum water retention parametrization. Finally there is one more concept implemented in FUSE here called model 632. Refer to model state equations 5.4, 5.5 and 5.6 for description of the upper layer architecture. Basically this model structure shares abilities of model 630. But the tension storage is subdivided into two different tension storages. Finally there is one more parameter θ_{rchr} that effects the upper layer.

6.3. Final steps

In this section every site is described in more detail. Soil profile descriptions are taken from the report “Representativeness of NIWA Soil Moisture Sensors: Eastern Sites” of Ichythus (2008). Further outcomes of climate features for each site are related to hydrological soil response. Soil moisture behaviour is discussed based on simple statistic methods. Results of this discussion lead to first classification of those sites from a hydrological perspective.

On the basis of the first classification a perceptual model is built for each class of sites. The perceptual model allows first hypotheses to be made about model structure and parametrization. Decisions about model structure is based on soil texture and structure. The first impression of parametrization can extracted from soil moisture data and values derived with statistical methods. Then information from the soil profile description, statistical analysis and the perceptual model is transfered into different model structures to

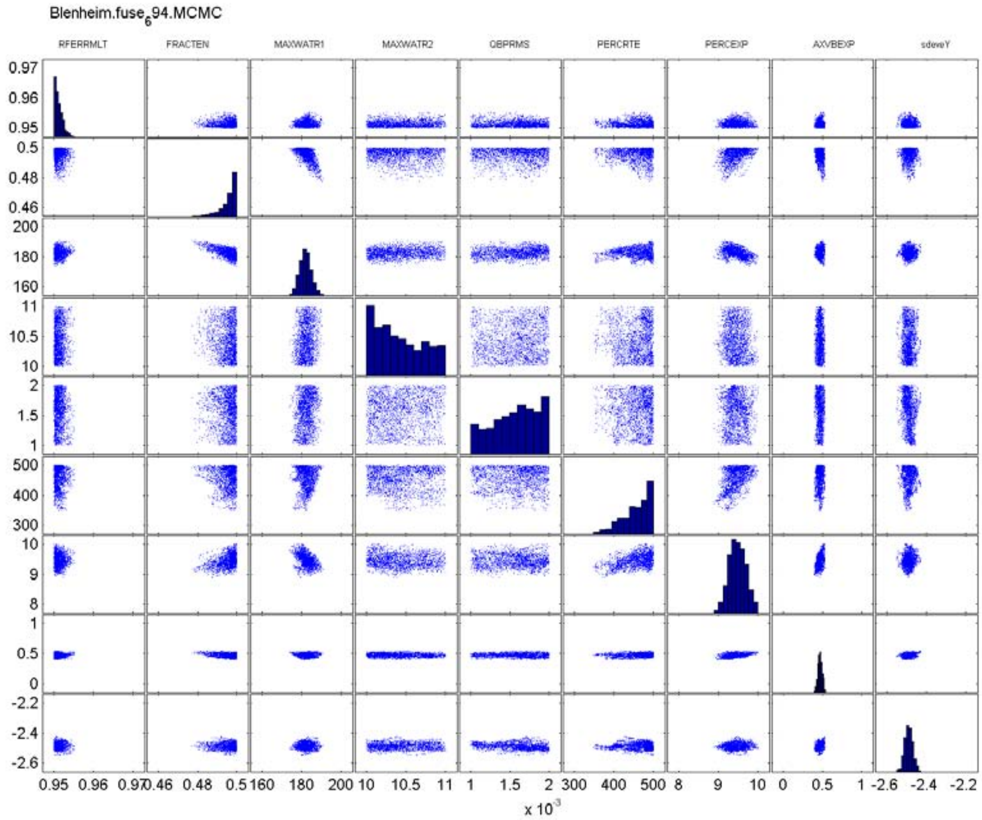

Figure 6.1.: Results of 5000 Monte-Carlo simulation runs for Blenheim. Model structure 694: percolation from wilting point to saturation, sequential evapotranspiration

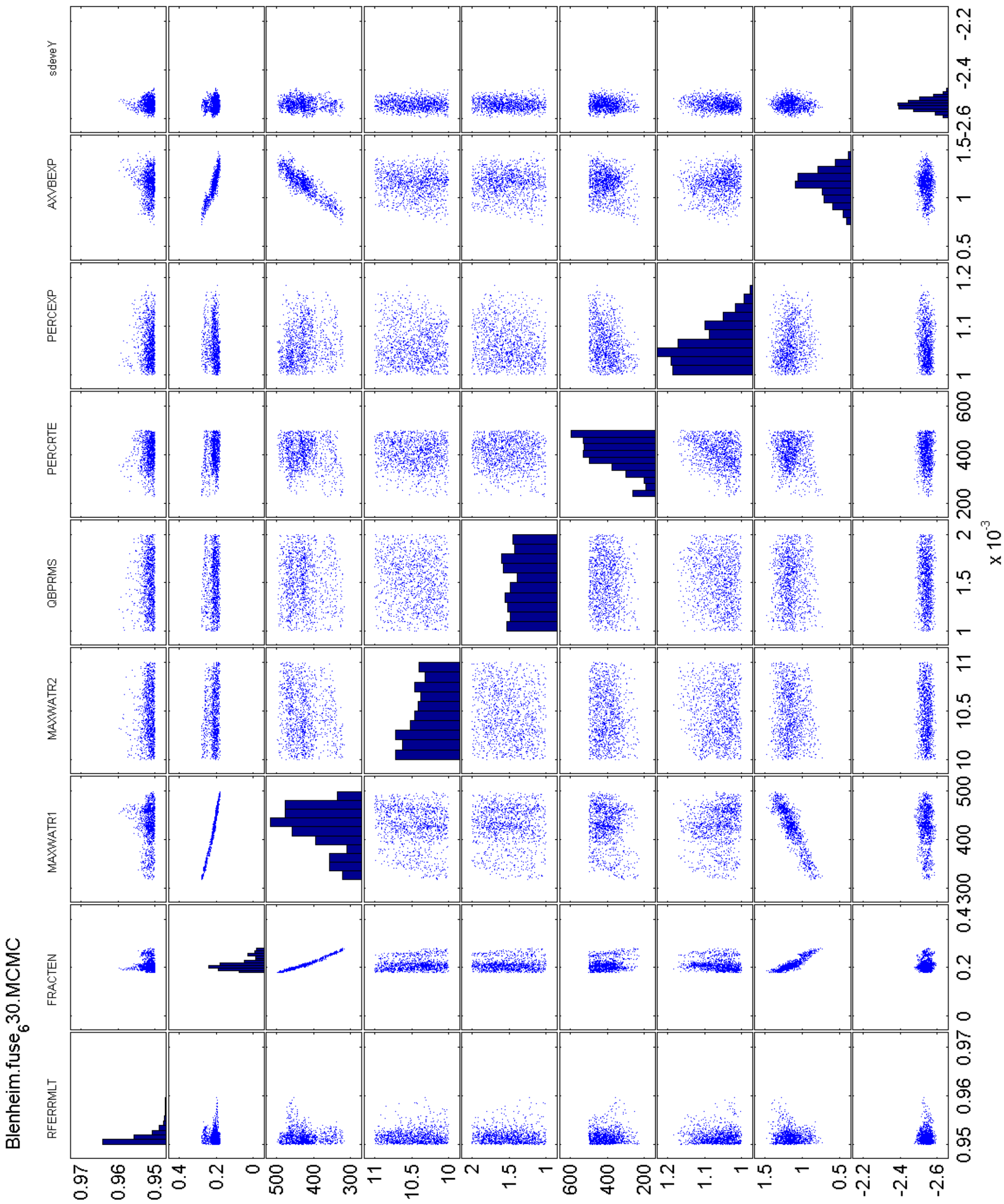

Figure 6.2.: 5000 MCMC model runs with model structure 630, upper layer is split into tension and free storage. Site: Blenheim.

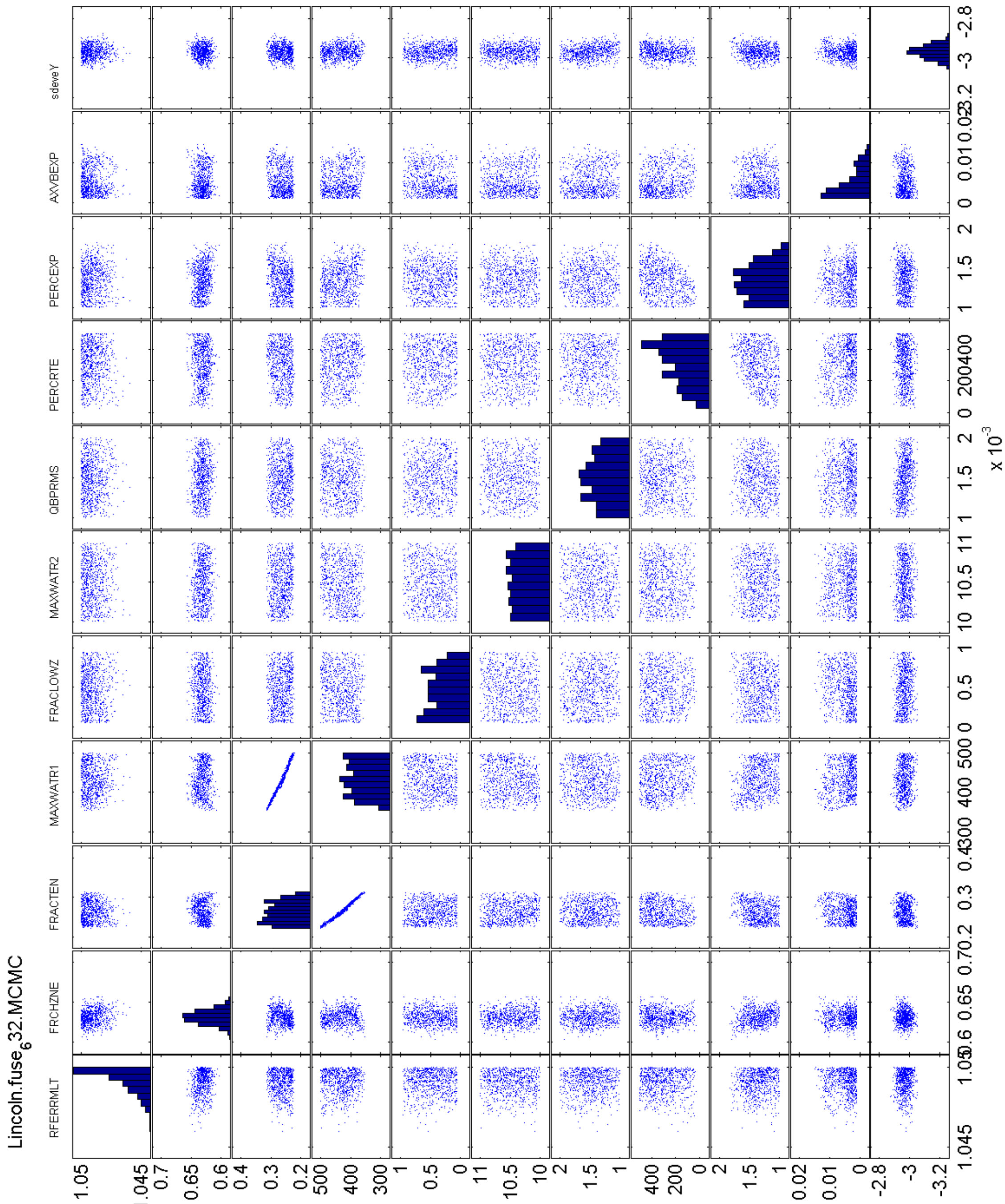

Figure 6.3.: 5000 MCMC model runs with model structure 632, upper layer tension storage is subdivided into two tension storages. Site: Lincoln

Table 6.2.: Constraints for the realized model calibration runs of FUSE

Parameter	**Description**	**Units**	**Lower Limit**	**Upper Limit**
$S_{1,max}$	Maximum storage in the unsaturated zone	mm	100	500
θ_{tens}	Fraction total storage as tension storage	–	0.1	0.50
θ_{rchr}	Fraction of tension storage in primary zone (unsaturated zone)	–	0.05	0.95
r_1	Fraction of roots in the upper soil layer	–	0.05	0.95
k_u	Vertical drainage rate	mm/day	1.00	500.00
c	Vertical drainage exponent	–	1.00	10.00
k_i	Interflow rate	mm/day	0.01	1000
b	ARNO/VIC b exponent	–	0.001	3.000

test these assumptions mentioned before. Finally soil sites are re sorted into groups on the basis of model structure and parameter values. It can be expected that various model structure and parameter possibilities arise for each site where parameters can compensate each other. Therefore, an evaluation of model structures based on knowledge a priori (soft data) of process understanding is compared to the results derived by Monte-Carlo sampling and Shuffled complex evolution optimization. This is an attempt to explain model performance by process representation. Hydrological soil response is modeled for three different model structures. This is made step wise started with the simplest model structure towards more complexity Bai et al. (2009). Parameter sampling and optimization methods will tend to compensate model structure deficiencies with unrealistic parameter sets. These model runs for all sites were set with the parameter constraints shown in table 6.2. This ensures that the effects of parameter on the objective measures are related to model structure and that only parameters that are sensitive to soil response are considered. The other parameters are constrained to fixed values to minimize the parameter space.

The categories in which the sites are organized is based on pedological similarity. However, there are exceptions and differences within those groups, as will be discussed, which can help to select parameter values for their particular circumstances. The categories can be seen as a guide to build decisions for usage of model structure and parameter settings, transfered to locations where basic pedological information is provided.

Table 6.3.: Estimated values characterizing hydrological soil response of soils in regions with an dryness coefficient between 1 and 2, strong annual cycle.

Parameter	Appelby	Blenheim	Lincoln	Rangiora
$S_{1,max}$	422	286	400	377
θ_{tens}	0.40	0.40	0.36	0.40
θ_{rchr}	0.3	0.7	0.6	0.7
k_u	10	10	10	10
c	3	3.5	1	1

6.4. Soils with a good developed toplayer in a moderate climate with defined annual cycle

A good developed toplayer generally indicates seasonality of weather pattern and is predominantly found for young soils. All sites in this group have a similar texture and similar hydrological behaviour regarding water retention. Values for S_{max}, field capacity and even percolation rate are similar. There are differences but the hydrological response of this soils can be represented by same structures and same parametrization with similar quality. Estimated values for sites of this group are shown in figure 6.3 and derived with the methods mentioned in section 4.1.3. It should be noted that values for field capacity and maximum water retention are interrelated as it is shown in figure 6.1.

6.4.1. Blenheim

Blenheim belongs to the order of recent soils. The suborder fluvial defines th occurence in more detail because these soils occur predominantly on floodplains. Blenheim is located at the very north east of the South Island. The area is part of the Marlborough lowlands. This is shown on figure (V) in more detail. The fine sandy loam of this site is suggested to be a Wairau or Gibson soil regarding Wilde, Willoughby & Hewitt (Wilde et al.). Ichythus (2008) suggested this soil to be an Opawa silt loam, but the modal profile does not correspond to the soil profile at the enclosure. Similar soils are found on both sites of the Opawa river.

Profile Description

There are no strong textural changes or permittivity changes at this site that could influence the soil moisture measurement. The soil profile at the site is a fine sandy loam with a maximum depth of 1000 mm. Clay content increases at a depth of 600 mm but there are no iron or gley mottles. At a depth of 800 mm there is a further increase of clay and silt and also iron mottles visible. The Top layer (140 mm) has a good developed structure 70 % is pedal with 3 - 20 mm nuts dominating. Penetration resistance is very low (263 kPa).(Ichythus, 2008) In contrast the lower layer has less marks of soil forming processes (apedal structure) which is typical for soils of the order recent soils (Hewitt, 1998). Figure 6.4 shows the soil profile at the Blenheim site.

Figure 6.4.: Soil profile at the Blenheim site with a good developed top layer (nuts). Very homogenous matrix, low penetration resistance (263 kPa) in the toplayer, silt and clay content increases slighty with increasing depth, pedality decreases. Image with permission (Ichythus, 2008)

Climate

Annual rainfall varied between 449 mm and 713 mm between 2002 and 2007. Potential evapotranspiration exceeded the mean annual rainfall in every year where soil moisture measurements are available (1067 - 1162 mm). The aridity index for every year is close to 2 or above. It can be shown that the intraannual variability of soil moisture has a linear relationship to the variability of rainfall (not shown). The relation between precipitation and soil moisture on a monthly basis in figure A.4 shows more scatter in summer and autumn indicating a periodic wetting and drying of the soil in these seasons. If soil moisture is under 20 % or above 32 % variability decreases which is consistent with observations of Western et al. (2004).

Perceptual Model

Because this site is well drained, gravity drainage is likely to occur. Beside the fact of a higher clay content there are no traces of a perched water table. Mottling occurs only at a dpeth of 800 mm. Roots penetrate easily to a depth over 500 mm. Maximum measured values of soil moisture are between 42 % and 52 % during 2002 to 2006 (refer to table A.2 in Appendix). Because of mottling in the lower part of the soil profile active soil depth is defined between 600 mm to 800 mm. Following those assumptions total storage would be between 264 and 352 mm in the soil column. A value of 286 mm was assumed to be feasible because of the occurrence of stones. The field capacity is assumed to be between 39 to 41 % derived from time series analysis (refer to section 3.2). For model 632 it is assumed that the percentage of soil development (pedality) is correlated with θ_{rchr}, the fraction of tension storage in recharge zone. If the percolation exponent is correlated to k of the simple water balance equation 4.4, this value can be estimated from values in table A.2 for the structure where gravity drainage controls the soil moisture response. The values defined for the following modeling approach are summarized in table 6.3.

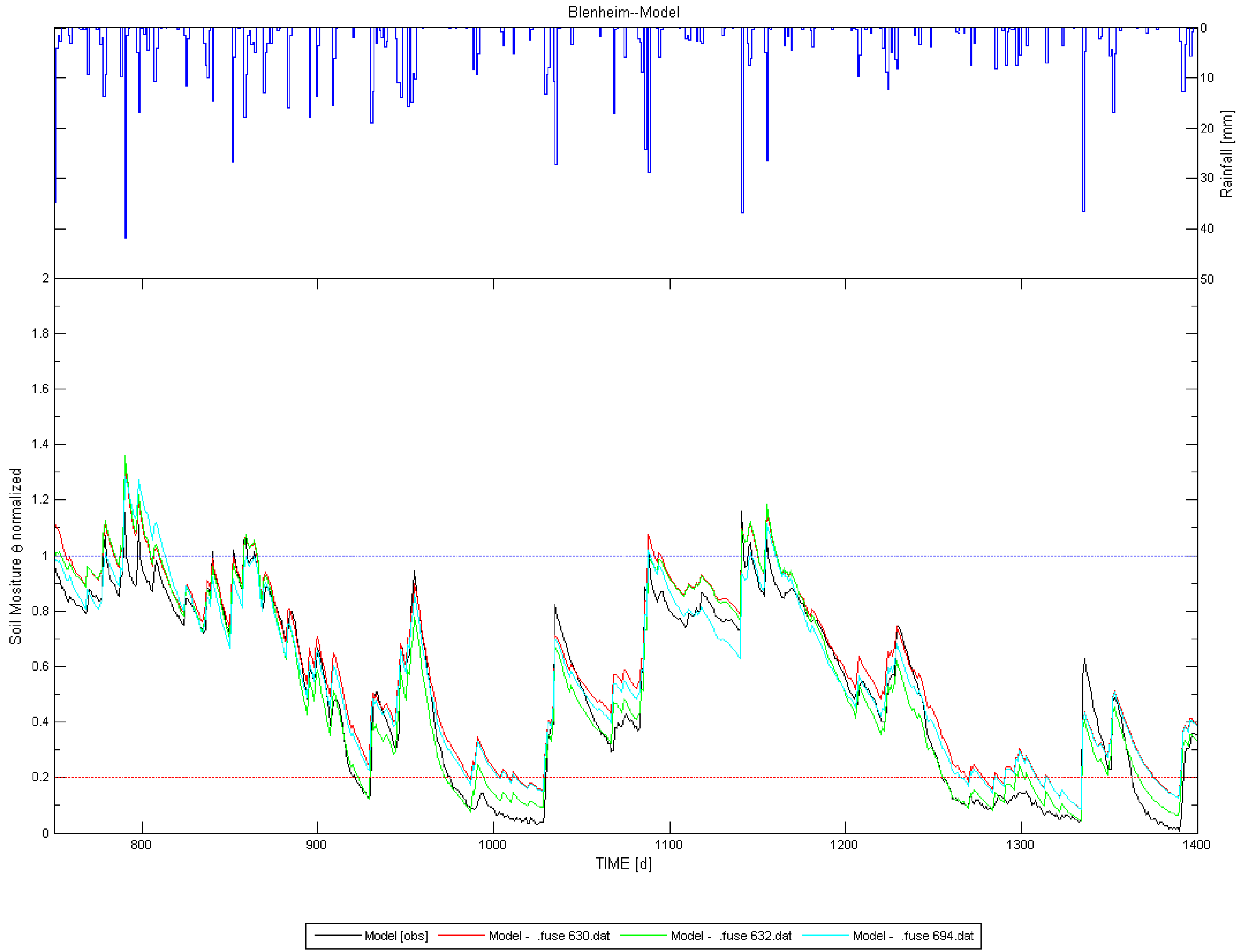

Figure 6.5.: Lower graph: Soil moisture time series of three model structures of similar complexity for Blenheim site. Parameter were derived by comparing values of the time series with Rawls et al. (1982). Values are shown in table 6.3, upper graph: time series of rainfall.

Modeling Soil Response

All models have a high goodness of fit according to the objective function as can be shown in figures A.7, A.8 and A.9. However, by taking a close look at the soil moisture time series shown in figure 6.5, differences are visible. Model 694 (gravity drainage) and 630 (separated tension storage) show very similar performance. Model 630 performs better at the beginning of the wet season, while model 694 shows a better behaviour for the recession at the end of the wet season. Model 632 does the best job during dry periods, but wetting up and drying period are slightly underestimated because there is more evapotranspiration from the tension storage. Drainage behaviour above field capacity is similar to the other two models.

It can be shown that model 694 and 630 have similar performance with similar parametrization, except that model 694 compensates for its lack of a tension storage with the percolation exponent. Better performance of model 632 is associated with the structure of soil, which has a more significant impact to evapotranspiration under dry to moderate conditions. Plants have strong impact to evapotranspiration (Rodriguez-Iturbe et al., 2001). It is observed that roots occur between and within aggregates and the rooting depth rises to 800 mm (Ichythus, 2008). Finally it is most likely that aggregates provide space for a tension storage which has different abilities as the rest of the matrix.

Furthermore soil development (pedality) can be associated with the parameter for θ_{rchr}. As a consequence the output represents the evapotranspiration much better. This in turn could mean that soil development, the strength of aggregates as well as their structure influence the water uptake from the soil. But this relationship can not be explicitly defined because roots penetrate to a depth of 800 mm. Most of the roots occur in the first 500 mm (75%) and first 400 mm (66 %) (Ichythus, 2008). It should also be noted that soil development is an indicator for biological processes as well as it indicates seasonality of climate patterns (Molloy, 1998). This in turn means the active zone of water exchange is located in the first centimeters if the soil. Thus most likely water uptake during the dry season occurs predominantly in the upper part of the soil profile. In conclusion a relationship between θ_{rchr} can be implied. Further estimates of parameters from the time series seem also to be reasonable.

6.4.2. Oxyaquic Conditions, Site:Lincoln

This site is located 30 km east of Darfield in the Canterbury plains (compare Figure V and I). In the case of Lincoln features of the suborder immature pallic are probably more meaningful to the hydrological response than general features of this order. Finally this site is more similar to soils of the order Recent. Basically soils of the order Pallic have a high density in the deeper subsurface that can cause a perched water table (Hewitt, 1998). In contrast Lincoln has good drainage and it is possible that there is groundwater influence which causes a transient water table in the subsurface. These conditions are known as Oxyaquic (Lin et al., 2008).

Profile Description

Ichythus (2008) suggested this site to be a silt loam of the Templeton series. The maximum depth is 1000 mm. The lower layer of this profile becomes more sandy (C-horizon). This sandy horizon is covered by a layer with prismatic structure. Down to a depth of 280 mm soil development is 50 %. At a depth of 280 mm the texture changes pedality decreases to 30 %. The last 620 mm are apedal with a pale fawn sand texture (Ichythus, 2008). The layer with aggregation (0 - 280 mm) covers most of the soil column where the sensor is located. For installation diagram refer to figure VI.

Climate

The Annual rainfall and the annual potential evapotranspiration is similar to Darfield. Annual rainfall varies between 442 mm and 778 mm per year. Annual evapotranspiration is more consistent between 862 mm and 1020 mm. Every year evapotranspiration exceeds rainfall amount and ranges. Fewer stones and higher grade of soil development result in a slightly higher mean annual soil moisture than for Darfield. Mean soil moisture is low to moderate between 22 and 27 % percent on a yearly (table A.7) but 10 to 40 % on a monthly basis (figure A.2) which indicates a strong seasonality. In figure A.5 can be shown that soil moisture variability σ_θ compared to other seasons is most consistent in Winter. Further observation in figure A.2 of decreasing standard deviation of soil moisture to increasing mean soil moisture are consistent with observations at Blenheim and of Western et al. (2004). Wetting of soil causes an increase in temporal variability to a certain threshold. After reaching wet condition (above) 28 % the variability decreases to under 2 mm. The same observation can be made for mean soil moisture under 18 % with some exceptions. This is shown in figure A.2.

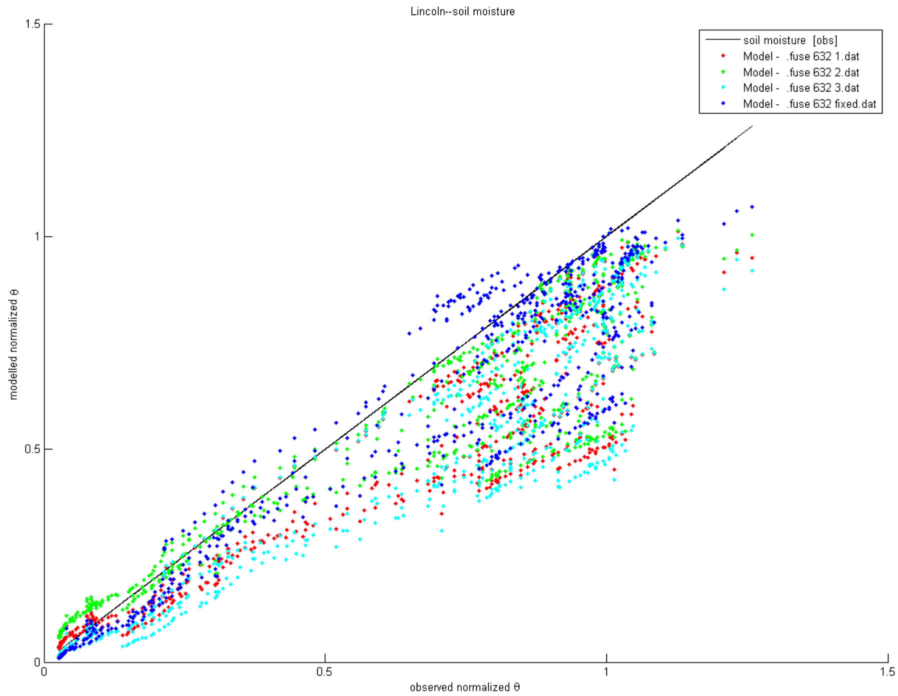

Figure 6.6.: Sensitivity to parametrization for model 632 (cascading buckets) for site Lincoln. Only values for θ_{rchr} are: (1)= 0.85, (2)=0.45, (3)=0.25, (fixed)=0.65 are changed.

Perceptual Model

Field capacity and maximum water storage capacity are derived from the time series and are shown in table 6.3. For model structure 694 with gravity drainage the evidence of an relationship between k and the percolation exponent derived of equation 4.4 is tested. Soil development in the upper part of soil layer is 50 %. The depth of this layer covers almost the depth within the sensor is installed. For model 632 the relationship between θ_{rchr} and the percentage of aggregates in the soil is evaluated.

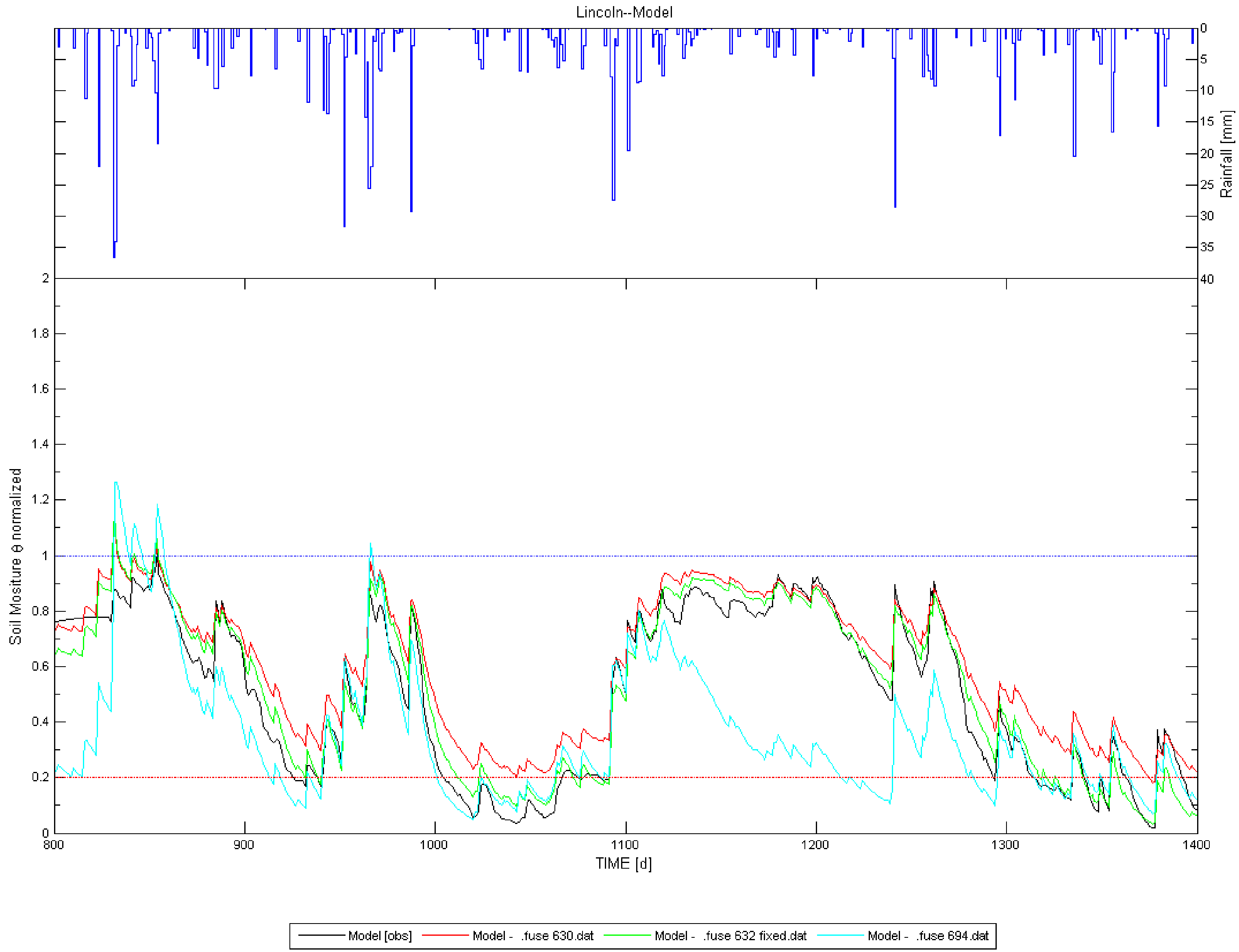

Figure 6.7.: Lower graph: Comparison of model output of model 694 (gravity drainage), 630 (seperate tension storage) and 632 (cascading buckets) for site Lincoln. Parameters were derived from time series analysis. Model parameters are shown in table 6.3. Upper graph: Rainfall time series.

Modeling Soil Response

As can be seen in figure 6.7 the annual cycle is well aligned to the observed data for all shown structures except model 694. This suggests that evapotranspiration behaviour is well modeled. Variability of soil moisture is sufficiently represented by the parameter for S^1_{max}, the maximum storage. For model 694 the tension storage parameter is set to 0.2 and is fitted to the recession behaviour beneath wilting point (e.g evapotranspiration control). However, there is to much drainage allowed which leads to an underestimation in the wet season. Model 630 and 632 slightly over estimate observed data. In figure 6.7 it can be shown that the more complex the conceptual model structure gets the better the hydrological response is represented. Even if model 694 can represent the recession after high rainfall, it is not capable of representing the wet season without tension storage ($c = 1$). Model 630 has a separated tension storage though there is less water available for percolation. The dry season is better represented with model 632 as is the shape and magnitude of the wetting-up a drying period. The value for $\theta_{rchr} = 0.6$ corresponds to the portion developed aggregates in the soil (50 %) for the shown model result in figure 6.7. It seems reasonable to test different parameter of θ_{rchr}, the fraction of tension storage in the recharge zone to test if this hypothesis is reasonable. Model 632 is then provided with the same parameters from model 630/632 except with θ_{rchr} is changed. The results are shown in figure 6.6. The value of θ_{rchr} is changed to 0.65 (fix), 0.85 (1), 0.45 (2) and to 0.25 (3). It can be shown that overall performance of value 0.65 results in the best output. Value (2) leads to more water in the upper layer for the dry season which is over estimated. While the wet periods have less water and are underestimated. Output with a parameter for $\theta_{rchr} = 0.25$ underestimates the observed data for the hole observation period. Which implies that less aggregation would allow more evapotranspiration. In contrast a higher portion for the second tension storage leads to higher values in the dry season. Further a value of 0.45 leads the model output closer to observation in the dry season but wet periods are worse represented. This observation is consistent with those from Blenheim.

It can be shown that the model provided with information a priori is able to represent soil moisture response. The value for θ_{rchr} that correspond to the portion of developed soil (peds) leads to the best output for model 632.

6.4.3. Aquic Conditions, Site: Rangiora

Rangiora is located 34 km north of Lincoln (see figure V). Rangiora represents soils of the Gley order because of redox features in the lower part of this profile. These conditions are also known as Aquic (Lin et al., 2008). Basically orthic gley soils occur in stable areas that are effected by groundwater (Hewitt, 1998). The main similarity to soils of the suborder Immature Pallic and Fluvial Recent is given because of the good developed toplayer (pedality over 50 %). Rangiora and Blenheim even share the feature of an increasing silt and clay content in the lower horizons of the soil.

Profile Description

Ichythus (2008) suggested this site to be representative for soils of the Waterton series. Drainage is poor and the maximum depth can be affected by high water table. The maximum depth is 790 mm. The maximum rooting depth is 330 mm. The soil has a high pedality of 70 % in the first 300 mm. Sub-angular nuts (5 -12 mm) breaking to very fine nuts (1 - 2 mm) under moderate pressure. Aggregates are root bound, building a very dense turf mat in the first 150 mm. Roots occur predominantly (75%) above 110 mm together with worms. The next horizon is 80 mm and is less pedal (30 %) with nuts brittely break into smaller nuts (3 -5 mm then to 1 - 3 mm) under moderate pressure. Compaction increases with increasing depth. The clay content rises at a depth of 350 mm and the structure becomes apedal in this layer which is drier then those above. (Ichythus, 2008)

Figure 6.8.: Top- (left) and sub-soil (right) close to the sensor at Rangiora. Image with permission Ichythus (2008)

Climate

This silt loam shows a strong annual cycle except for the year 2002 were high amounts of rainfall in summer mask the effect of evapotranspiration. Rainfall at this site is much more variable compared to Darfield and Lincoln. Probably because it is located closer to the coast.(back up with reference) However, the annual amount of rainfall is low (520 mm to 736 mm) and potential evapotranspiration varies from year to year between 782 mm - 886 mm. On a monthly basis the relation between standard deviation of rainfall and standard deviation of soil moisture is linear (see figure A.5). But values scatter most in the spring, indicating a fluctuation of days with and without rain. The standard deviation of soil moisture is high (above 4 percent) between 14 and 38 percent, but drops down to under 3 percent for the remainder of the year. The shape of the distribution of this relationship (see figure A.3) is not as cleary defined as it is for Blenheim and Lincoln (see figure A.1 and A.2). The reason for this can be either related to subsurface processes (eg. groundwater influence) or to the cover of this layer (turf mat) that comprises the first 150 mm of this soil profile.

Perceptual Model

The drainage behaviour of Rangiora and Blenheim should be similar because both sites show a similar soil development in the upper layer. Furthermore there is small textural change in the lower layer and both sites have a high rooting depth that is greater than 330 mm. The percentage at the field capacity and the maximum water storage capacity are derived from the time series analysis. Maximum water storage is calculated as a percentage of the soil depth with the mean of maximum measured values for every year that is shown in table A.14. Values are in a reasonable range for this texture consistent with observations of Rawls et al. (1982). Percolation is assumed to be low as it is the case for Blenheim and Appleby because the higher clay content here reduces the velocity of water drainage. Values for percolation are adjusted visually and only interpreted on a qualitative basis.

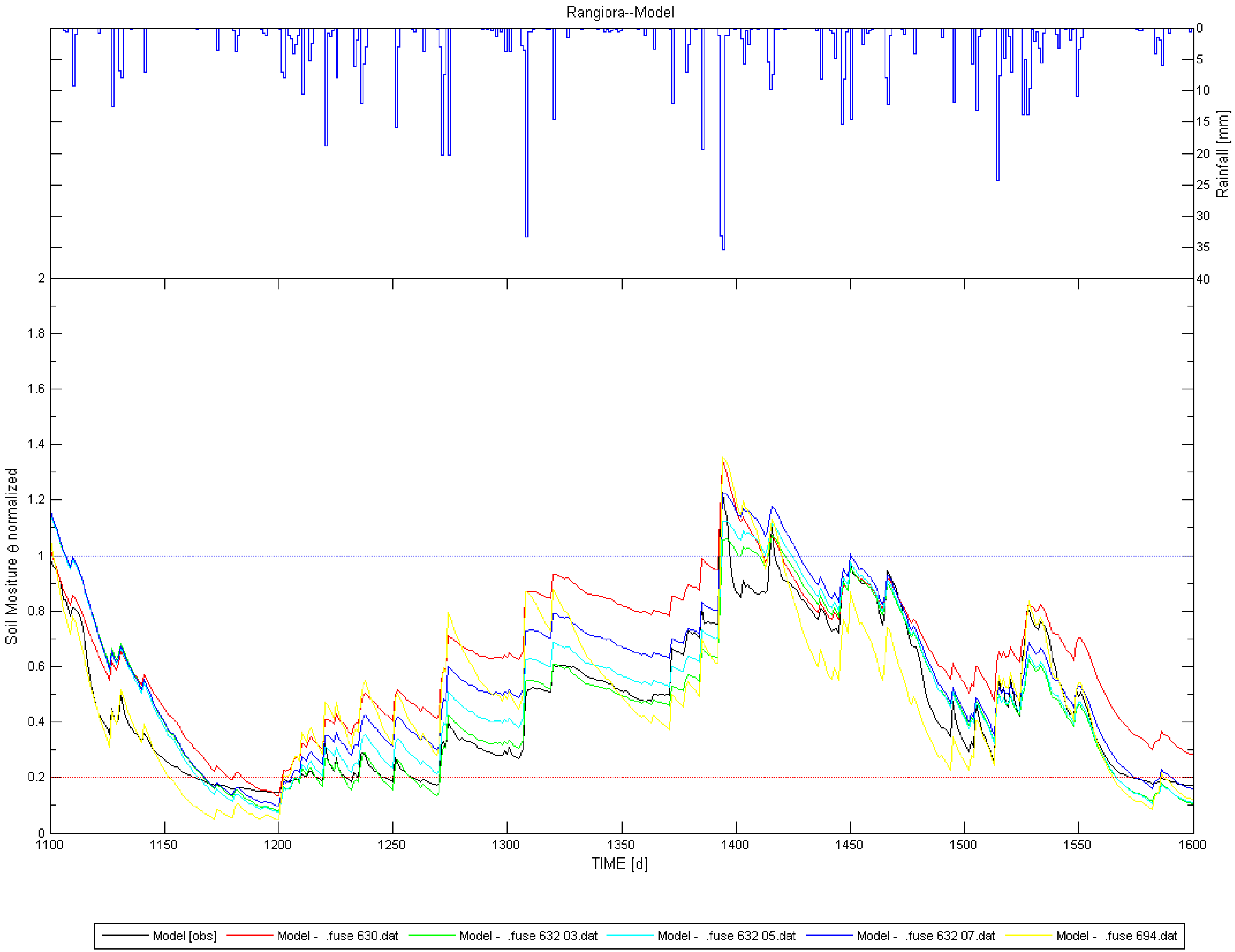

Figure 6.9.: Lower graph: Model output of Rangiora for model structure 694 (gravity darinage), 630 (seperate tension storage), and 632 (cascading buckets) and model 632 with different values for θ_{rchr} of 30 %, 50% and 70%; upper graph: rainfall timeseries

Modeling Soil Response

Genrally, model results of model 694 shows reasonable results for the wet season (not shown). The increase in autumn is over estimated by the model, but not in every year by the same magnitude. Overall as shown in figure 6.9, the recession after the wet season is most poorly represented by model 694. The percolation exponent limits percolation from the tension storage, but with an increase of this parameter the output will over estimate soil moisture in the wet season. With a separation of total storage to S_1^T tension storage and S_1^F free storage the slope of the recession limb is less steep because percolation is constrained to occur only from the free storage. As a consequence the wetting-up period is over estimated. Because there is not enough evapotranspiration. This can be improved with the model where tension storage is further subdivided (model 632) into two cascading buckets. In particular the output with a parameter for θ_{rchr} of 0.3 (see 630 03 in figure 6.9) represents the wettting-up period but underestimates at the lower part of the recession limb. The value for θ_{rchr} correspond roughly to the inverse portion of aggregates in the upper part of the profile. The lower part of the recession limb is better represented with a value for θ_{rchr} of 0.7 (see 632 07 in figure 6.9). This in turn can be related to the portion of aggregates in the top layer. On the basis of soil development it can be argued that the percentage of aggregates in the matrix is correlated with θ_{rchr} for the model with cascading buckets. For the wetting up period that will mean the upper layer tension storage is mainly responsible for fluxes at the surface. This tension storage is subdivided into portions of pedal and apedal soil parts. It has been observed that the developed aggregates are root bound (Ichythus, 2008) which leads to the assumption that those aggregates hold water more effectively and may work as a separate tension storage within the matrix. Finally this could be a reason why model 630 03 has a better performance during the wetting up period. The model storage S_1^{TensA} is filled first, then S_1^{TensB} and at least the free storage S_1^{Free}. If S_1^{TensB} is small there is higher portion of water evaporating from S_1^{TensA} which results in a lower soil moisture during the wetting up period. As a consequence the dry period is underestimated. Finally the performance of model 630 03 and model 630 07 are similar for the recession limb but not for the wetting up period, though the behaviour of the model for processes during the recession can not be clearly separated. This is a hypotheses that need more detailed information from soil moisture that is measured at different depths. The assumption of a correlation between the portion of aggregates and the parameter $\theta rchr$ is more likely and should be considered for parameter estimation. Summing up it is possible to provide knowledge a priori (soft data) to provide the model with parameter values that lead to a reasonable output. Further processes can be identified by applying different architectures to the data. The top-down approach at this location brought more incites into the role of tension storage regarding soil moisture control. Further it could be shown that either model structure and parametrization shifts the model performance towards a particular season. This in turn illustrates that predominating processes change and that these processes can not be represented by only one model structures and one parameter set which are used here.

6.4.4. Exception: Impeding layer, Site: Appelby

Appelby is located in the Nelson region (map V and I) within a basin surrounded by hills with a gentle slope (shown in figure 6.10). The soil belongs to the Ultic order. Generally soils of this order are poorly drained, water movement occurs mainly along planar voids (Hewitt, 1998). For Appelby this means the soil moisture measurement reaches the sensor limit in the wet season. Therefore automatically optimization fails (systematical measurement error). This must be considered when interpreting the results that are shown in figure A.7 to A.9. Similarity to Blenheim, Lincoln and Rangiora is given because of the soil development in the upper layer and a maximum rooting depth which is higher than 330 mm. It can also be shown that hydrological soil response, model performance and parametrization compared to the other sites is similar.

Profile Description

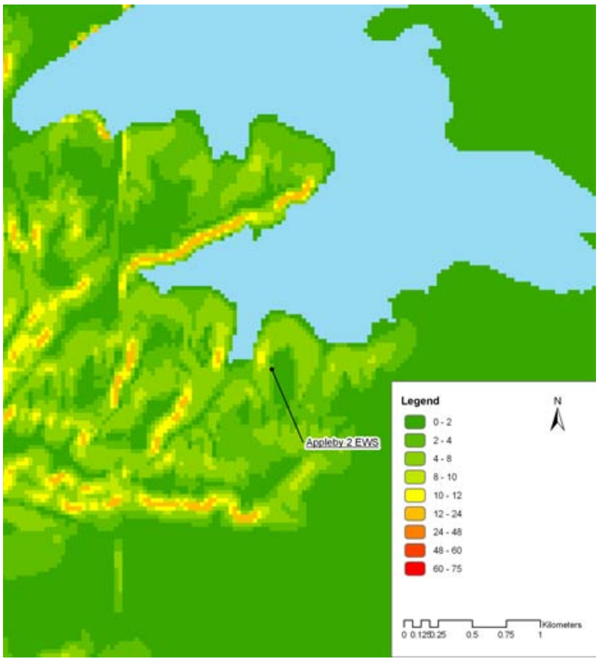

Figure 6.10.: Site: Appelby, Slopes calculated based on a 30 m DEM

The soil at this site is a fine sandy loam. Ichythus (2008) suggested this soil to belong to the Mapua series. The depth to parent rock at the profile is at 930 mm. The underlying rock is very hard weathered greywacke or argillite. The soil at the profile has a maximum depth of 930 mm. But at a depth of about 650 mm color change and strong iron mottling indicate a drainage impediment (fragipan). The first 250 mm is a fine sandy loam with aggregates that fail smoothly. Roots penetrate between and within peds. They occur to 75 % in the first 250 mm. Pedality os low to moderate. Biopores of 0.5 mm to 2 mm in diameter are visible. Some biopores from 0.1 mm to 2 mm that penetrate aggregates are also visible. Some gleying within aggregates is observed. At a depth of 650 mm the clay content rises with increasing depth and the color changes progressively to blue-grey sand. Clay is much less conductive and constrains percolation and interaction with the upper layer (anoxic conditions). Vertical fingering of pale grey colors down into the a orange pale grey matrix also occur indicating vertical drainage. (Ichythus, 2008)

Climate

Annual Rainfall is also variable from year to year between 666 and 1073 mm. Potential evapotranspiration varies between 990 and 1000 mm per year. Standard deviation of rainfall on a yearly basis against soil moisture θ shows a linear relationship (not shown). On a monthly basis it can be shown in figure A.4 that variability of rainfall has a higher to standard deviation of soil moisture has a strong scatter in particular for the dry periods. It is shown in figure A.1 that there is a shift towards high values of mean soil moisture. Standard deviation of soil moisture is high compared to Blenheim, Lincoln. The scatter pattern of these data points is compare able with Rangiora. It should be noted, the soil at Rangiora has mottles and gley features at higher depth. Maximum observed soil moisture reaches the upper limit of soil moisture measurement which should be considered building when a perceptual model based on the data.

Perceptual Model

Values of soil moisture are quite high especially in winter. These values are probably higher than those measured. Estimation of field capacity with regard to the soil texture would imply comparable values to these sites in this group. As mentioned in section 'Soil Physics' values for field capacity can be influenced by impeding layers. At this particular site the reason for the high values of soil moisture is probably the surrounding topography (refer to figure 6.10) and the drainage impediment at a depth of 650 mm. This results in periodic saturation particulary in the lower part of the profile as redox features indicate. As a consequence, velocity of drainage is reduced which leads to a high value of field capacity. It seems to be reasonable to normalization the time series of this site with a value of $\theta_{FK} = 50$ %. The model can handle this feature with a lower percolation rate rather then an increase in field capacity. Thus other than the fact of gley feature parametrization of the Appelby site can be considered similar to other sites in this group. Based on these findings our perceptual model for the active layer for the tension storage is reduced from the total depth of 930 mm to a depth of 650 mm because of the higher clay content and initial iron mottling at this depth. The blue line in figure 6.11 indicates were field capacity is defined. As mentioned above this value is identified with 50 percent, but only used to normalize the data. Beside the fact that the measurement limit of the sensor is reached every year, a value of 422 mm of maximum water storage seems to be reasonable compared to another estimation suggested by (Warrik, 2002). Warrik (2002) suggests that if total variation in tension storage is 35 % and if total storage is double of the tension storage, than this results in a maximum water storage of 455 mm.

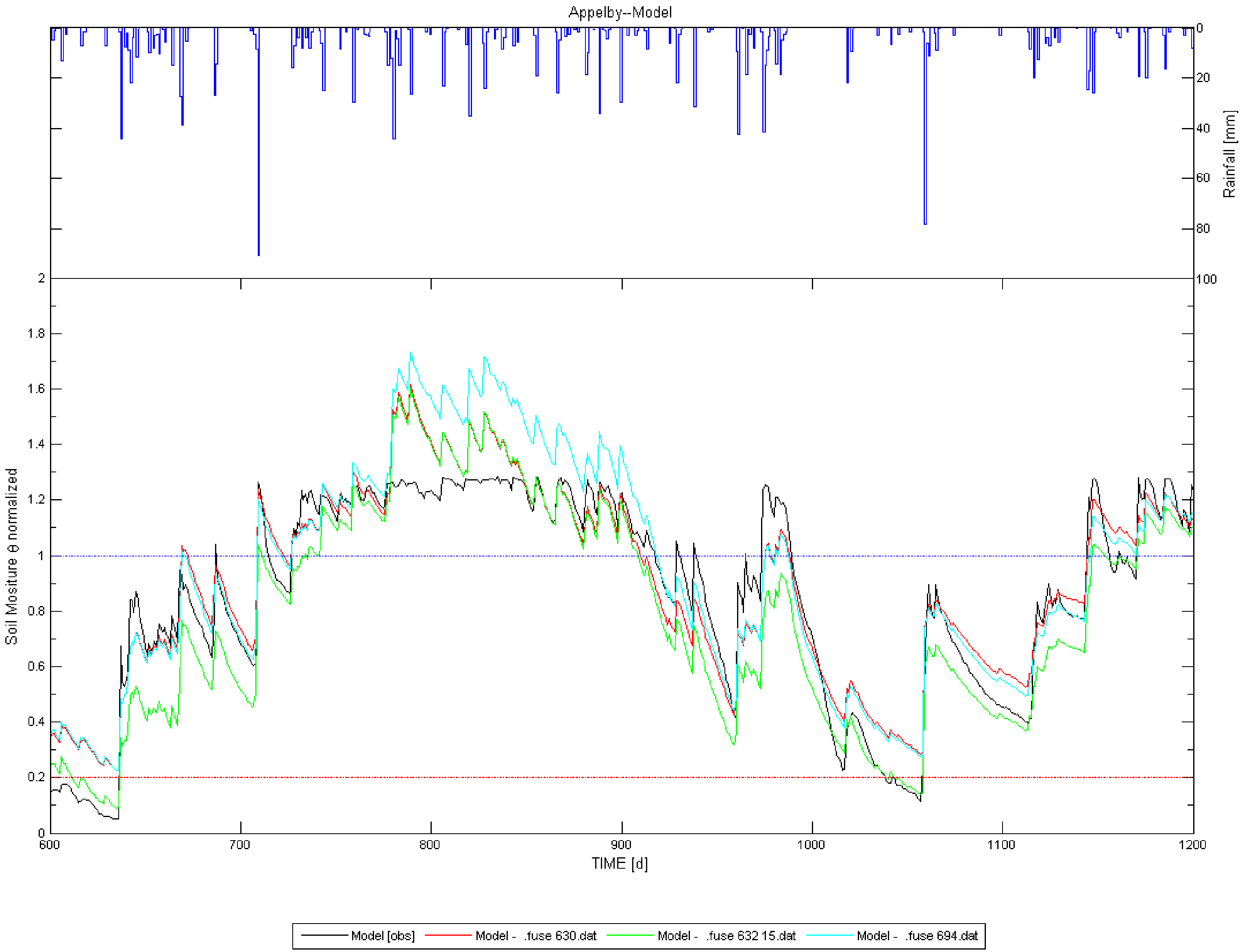

Figure 6.11.: Upper graph: Model results compared with observed data for Appelby of model structure 694 (gravity darinage), 630 (seperate tension storage), and 632 (cascading buckets); upper graph: timeseries of rainfall

Modeling Soil Response

Estimated parameters which are used to calibrate the model are shown in table 6.3. Realistic values could cause over estimated modeled soil moisture response in the wet season if the model structure is suitable for this site because of the mentioned weakness of the observed data. Model 632 and 630 were provided with the the parameters that they share. The percolation exponent for model 694 has been calibrated to a value of $c = 3$. As can be shown in figure 6.11 all model over estimate soil moisture in the wet season were rain is consistent through out the season. It is most likely that water level increase up to the surface occur (saturation excess). The sensor is not able to capture the amount of water that can be stored in the soil. Thus model results could be more realistic representing soil moisture in winter than observations.

All models show a similar recession behaviour after the wet season when S_1^F is depleted. For low values of soil moisture model 632 has more evapotranspiration as the other two models. But the wetting up is better represented with models 630 and 694. The soil here has a less developed soil (pedality) then the other soils in this group. It is observed that aggregates are soft and fail smoothly (Ichythus, 2008). For the wetting up period this could mean there is no separation of tension storages in the soil. Thus there is only one active tension storage to be filled. Ichythus (2008) observed that there is some gleying inside aggregates and rare iron mottling. This means there is water present inside aggregates for a longer period. Those aggregates are separated from the matrix. As mentioned in the conclusion of Lincoln and Rangiora there is a possibility for a second tension storage within the matrix. It is further observed that there are 40 % of interpedal roots and 40 % of intrapedal roots (Ichythus, 2008). As can be shown in figure 6.11 there is a better representation of low soil moisture values with parameters of 0.4 and 0.6 for θ_{rchr}. Though evaporative demand is probably provided from two seperate tension storages in the dry period.

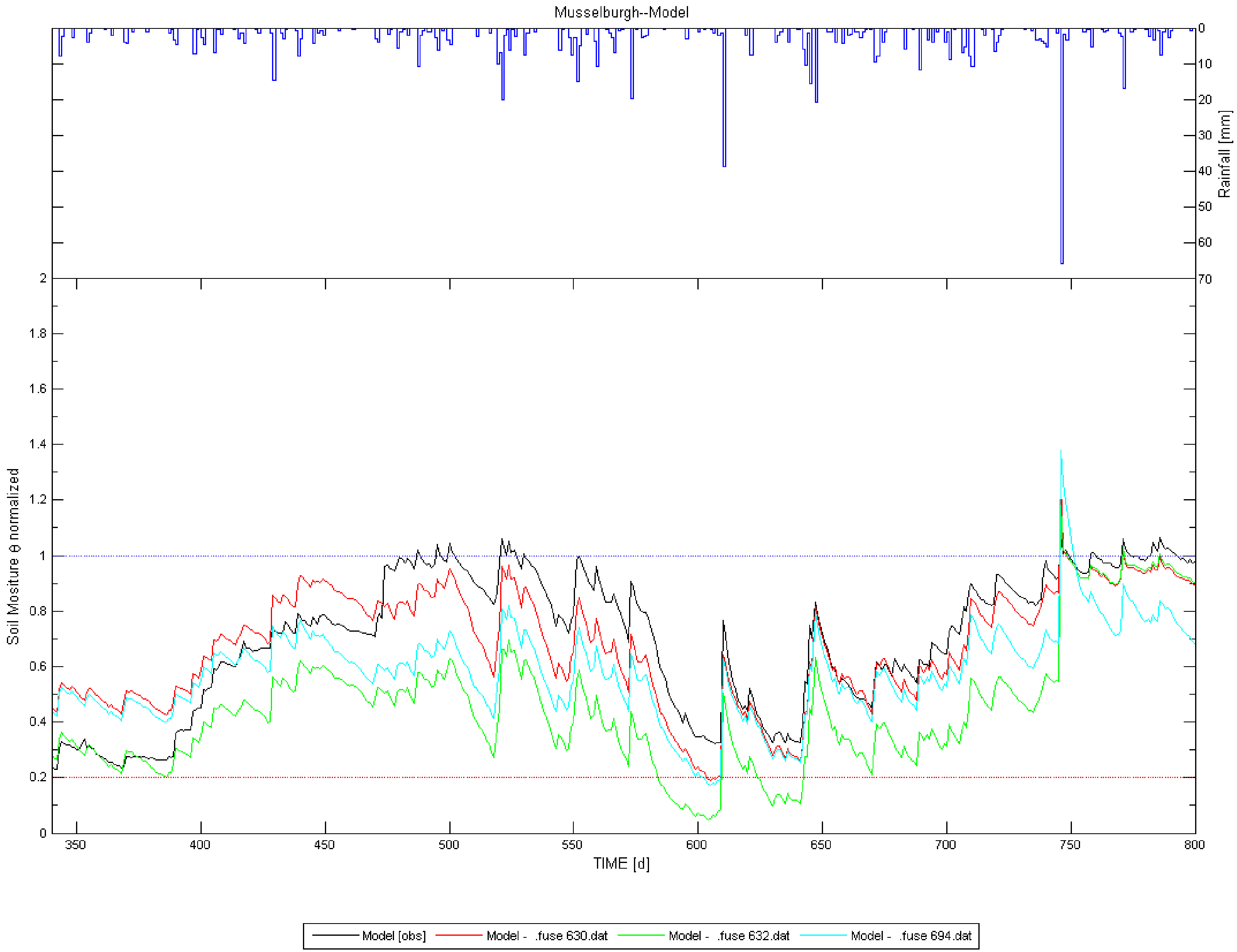

Figure 6.12.: Lower graph: Soil moisture time series of three model structures of similar complexity for the Musselburgh site. Parameter were derived by comparing values of the time series with Rawls et al. (1982). Values are shown in table 6.3, upper graph: time series of rainfall.

6.5. Typic gley recent

6.5.1. Musselburgh

Musselburgh is located far south of Middlemarch close to the ocean. It is classified as silt loam. The soil can be associated with caversham silt loam. Those soil are based on alluvium derived from sedimentary and basic volcanic rocks and loess.

Profile Description

The present profile is covered by a dense turf mat. Underneath the first 4 cm dark brown silt loams present with a pedality of 50 % and few biopores. Pedality becomes low at a depth of 13 cm an stones occur with a diameter of up to 100 mm x 60 mm. Stones become more regular with increasing depth. Extensive diffuse iron mottling and weathered rocks occur. The matrix is compact there are no visible pores. Penetration resistance is low through out the profile. (Ichythus, 2008)

Climate

Mean annual rainfall never exceeds potential evaporative demand. In years with an annual mean rainfall above 600 mm the annual cycle gets compensated. Mean annual rainfall varies between 487 mm and 837 mm. Probably because of the location close to the ocean rainfall amounts are very variable. Standard deviation of soil moisture and standard deviation of rainfall are clustering in a square (refer to figure A.5). The limit for soil moisture here is 4 %. For Rainfall it is 8 mm with five exception for summer and autumn month. However, there is no threshold for rainfall that causes high or low variability in soil moisture. Soil moisture variability on a monthly basis is similar through out the entire year. In wet condition above 37 % standard deviation decreases rapidly and is clustering around 40 %. Penetration resistance is low for the covering layer (200 kPa) increases with soil development and keeo 925 kPa to a depth of 130 mm where it increases to 2365 kPa. Down to the maximum depth of 530 mm it increases to 2885 kPa.

Perceptual Model

Maximum measures values of soil moisture are between 37 % and 44 %. That result in a range for the maximum water retention around about 197 to 215 mm. A amount of 215 is to be assumed. Field capacity is identified from the data between 40 and 42 %. The mat covering the top layer acts probably like a swamp absorbing occurring rainfall. This could possibly related to model structure. Thus Water transport is probably good to a depth of 130 mm where penetration resistance increases to a double of the layer above.

Modeling Soil Response

The model does not capture the processes that occur in the annual cycle. Probably dominating processes change during the seasons. If we keep in mind that the percolation exponent constraints water loss from the upper free storage it can be shown in figure 6.12 that recession after the wet season is captured with a value for the percolation exponent of 5. By setting the value to 1 the increasing some of the increasing parts of the graph are better represented (not shown). The more comples model Other model structures can not fix those problems. The model where the upper zone is seperated into free and tension storage represents the annual cycle better. Both models show variability of soil response sufficiently. The dry period in the time series is over estimated. It is possible that water is absorbed by the upper part of soil where dense roots occur. This causes that water actually stored in the soil does not reach the sensor.

To conclude observations of this group, the distribution of mean soil moisture and standard deviation of soil moisture can be related to features of the hydrological behaviour of soil . Blenheim and Lincoln show a similar scatter of these data points. Annual Rainfall is lower at Blenheim and annual potential evpotranspiration is higher (compare table A.2 and A.7). There are obvious differences between these soils. The texture, the layering and the structure of these layers, but similarities in hydrological response are visible with view to the distribution of data points in figure A.1 and figure A.2. The modeling with different structures show similar quality for models with tension storage (630 & 632). It is possible to estimate the field capacity and the maximum water retention from the soil moisture time series. Further it is found a relationship between soil development and the parameter that defines the size of θ_{rchr} for these sites. For the Blenheim site a relationship between k and the percolation exponent c can not be explicitly defined neither for Appely. There are years with a value of k where such a relationship can be implied. For Appelby refer to table A.1 years 2002, 2003 and 2006. Blenheim has values that can be related to c for the years 2002 and 2005 (shown in table A.2). This relationship is not found for Rangiora and Lincoln.

6.6. Stony Orthic Brown Soils with Summer Dryness

Brown soils are most extensive in New Zealand. They also cover a wide range of mineralogically classes. Generally they have no summer dryness and are not waterlogged in winter. Underlying parent rock mostly is weakly weathered. Status of gravel or rock substrates usually is fresh to moderately weathered. There are also groups that appear from acid igneous rocks or sedimentary rock such as schist or greywacke. This soil group comprises only soils that are well drained. Macroporosity is generally moderate (10-14%). They provide low amount of plant available water. (Hewitt, 1998) further suggested that those soils occur in areas with a mean annual precipitation above 1000 mm or they have low plant-available water. The latter is the case for site and Timaru. Further they have summer and are probably representative for shallow stony brown soils in areas where aridity k is close to one or higher with features of parent underlying rock material mentioned above. Peds are common in the topsoil except for soils that are limited by coldness or acidity and in addition roots of native plants can generally penetrate deeply into the soil (Hewitt, 1998).

Figure 6.13.: An exposure of Lismore stony silt loam in a drain at Winchmore. Image with permission (Ichythus, 2008)

High stone content in the lower part of soil profile is the most obvious similarity for the following examples. Also climate patterns at those locations are similar. All sites belong to groups that have a similar modal profile. Darfield is an exception because of compaction by heavy machinery or bad land management. Nevertheless, it is also based on gravel stones and the high stone content is a main characteristic of this group. This causes a low water storage capacity which is similar for all sites in this group. Table 6.4 illustrates parameter estimated by knowledge a priori (soft data) from the measured time series of soil moisture. Furthermore in figure 6.13 a modal profile for a Lismore stony silt loam is shown.

Both Winchmore and Timaru belong to the subgroup Pallic Orthic Brown. Basically orthic brown soils have a weak or very weak soil strength to depth. They occur most commonly on hilly or steep slopes and also on Holocene land surfaces. (Hewitt, 1998). This sites show similarity to the group of section 6.4 regarding soil development in the

Table 6.4.: Parameter for the sites of Darfield, Winchmore and Timaru. Estimated from time series

Parameter	Darfield	Timaru	Winchmore
$S_{1,max}$	207	178.000	200.000
θ_{tens}	0.34	0.30	0.30
θ_{rchr}	0.12	0.80	0.80
k_u	500	500	500
c	4	5	5

top layer.

6.6.1. Winchmore

As shown in figure V Winchmore is geographically 74 km north east of Timaru and 44 km south west of Darfield and 161 m above sea level. The shore line is about 24 km in the south east. This silty loam is very stony and lies on greywacke gravels in the Canterbury plains.

Profile Description

Maximum soil depth is 480 mm. The rooting depth is 190 mm. Soil is covered by a dense root mat. There is a high pedality (80 %) in the first 190 mm. This soil volume has 2 - 5 mm nuts. The remaining soil volume is apedal with fine crumb. Less then 5 percent of the soil volume is occupied by stones to a depth of 250 mm. With increasing depth stone content increases to 10 percent (diameter 250 mm - 480 mm) and finally up to 80 percent at the maximum depth of the profile. With rising stone content pedality decreases and clay content rises. There are neither visible macropores nor visible mottling (Ichythus, 2008).

Climate

Annual rainfall is low as elsewhere in the Canterbury Plains (560 mm to 850 mm). Potential evaporative demand is exceeds annual rainfall every year except for 2007. It moves from 791 mm to 901 mm between years. The annual cylce is not consistent for the entire period. The rainfall pattern at Timaru and Winchmore appears quite similar concerning the data. However, values are higher at Winchmore (see table A.17). The relationship between standard deviation of rainfall and standard deviation of soil moisture is shown in figure A.3 on a monthly basis. It is linear with a lower scatter as for sites with a higher soil depth and a free draining subsurface (e.g. compare to Lincoln figure A.2). Further the distribution of θ_mean mean soil moisture versus σ standard deviation of soil moisture does not show a clear dependency as for Blenheim (compare Blenheim figure A.1 and Winchmore figure A.3). Regarding table A.17 highest observed θ_{max} soil moisture values are observed in the R driest years. In contrast lowest values of observed θ_{max} water content are observed in moderate R years. There can be high amounts of rainfall which is not consequently related to the yearly sum of rainfall for the entire year. In turn there can be a very dry period but the total amount of rainfall can be high for this year.

Perceptual Model

The high stone content reduces the ability to hold water and increases the speed of drainage. This is consistent with observed time series. As can be shown in figure 6.14 the observed soil moisture data has spikes after rainfall with a steep recession limb. Further the good soil development in the upper part of the profile implies that there is a tension storage to be considered. There is no drainage impediment nor indicators for presence of water for a longer time (e.g. mottles). The subsurface is well drained thus percolation of free water can occur without constraint. As shown in figure 6.13 stones are dominating the lower parts of the profile. That lead to the assumption of high percolations rates for model parametrization. Maximum water storage is defined as a highest measured percentage of soil moisture (effective porosity). As a portion of soil depth this is between 120 mm and 270 mm. The field capacity occurs at 30 percent soil moisture. The model is provided with values that are shown in table 6.4. It is questionable if the measured values are reliable especially for response after high amounts of daily rainfall, because of the high stone content and the way the sensor is installed.

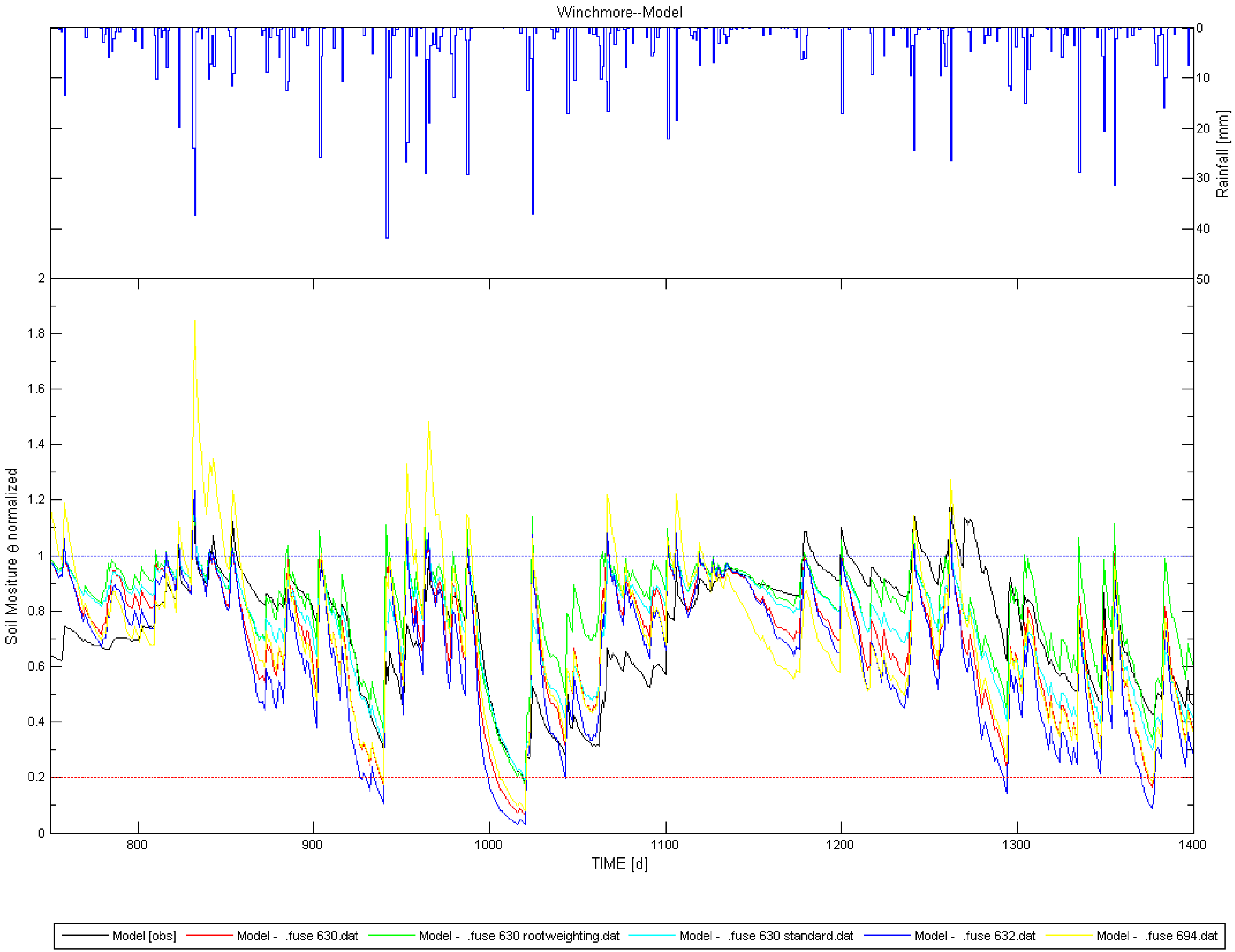

Figure 6.14.: Lower graph: Model output of model 694 (gravity drainage), 632 (cascading buckets), 630 (seperate tension storage) and observed data of the Winchmore site. Model 630 is also tested with the 'rootweighting' evapotranspiration scheme with r_1 0.55, and a standard parameter set shown in table A.19. Upper graph: rainfall timeseries.

Modeling Soil Response

In figure 6.14 results of the modeling with four different model structures are shown. The usage of the percolation exponent in the Model 694 tells us that a separation of tension and free storage should be considered. Furthermore if we consider that fraction of tension storage S_1^T restricts evapotranspiration than this adjustment has to be compensated by the maximum water storage parameter S_{max}^1. If that is done model performance of the two models are similar. The rooting scheme reduces evapotranspiration from the upper layer. The recession is better represented by applying this evapotranspiration scheme, but a similar result is made with model 630 and the standard parameter set in table A.19. Soil response to rainfall is over estimated by the model in most cases when rainfall is more than 10 mm a day. It is possible that the sensor does not measure water after days with high rainfall. Because this water is simply passing through the soil without being measured. The increase after the dry period is generally over estimated. For smaller events fluctuation in soil moisture content is better represented and even underestimated for all models expect model 630 with 'rootweighting' and the standard parameters. The wet season is even underestimated which could be related to systematical errors in rainfall or soil moisture measurements. Further there are uncertainties for estimating parameter. The model outputs shown in figure 6.14 illustrate that there are different possibilities to derive reasonable results. Usage of a random parameter set shows even better results as for parameter derived by information of the time series and the soil profile description. Probably maximum water storage is badly represented when using the measurement. Further it is probably crucial to estimate maximum active depth in a soil with such a high stone content. Finally it is most likely that the maximum water retention is underestimated with this method. Basically overestimated soil moisture during the wetting up period after high rainfall can be related to measurement problems. It is possible that water flows through preferential flow passes without being measured by the sensor. Regarding output quality it is suggested to use either the model with 'rootweighting' or model 630 with the standard parameter set.

6.6.2. Timaru

Timaru is located south of Christchurch in the Canterbury area close to the shore. Landscape is similar to that at Winchmore. Further soil texture, structure and depth is very similar. Timaru is located 74 km south of Winchmore. The shore is 5 km east of Timaru.

Profile Description

This site is also classified as Lismore stony silt loam. Maximum depth of this profile is 520 mm. Roots can penetrate the soil down to a depth of 430 mm. But penetration resistance increases with increasing depth. Roots are most abundant in the first 280 mm. Soil is strongly pedal up in that layer with up to 80 % root bounded nuts (10 mm) breaking to 3 mm nuts and finally to silt. The residual loose silt loam is apedal and pores a not visible. From 55 mm to 250 mm pedality is about 60 % with a nutty structure. The residual earth is apedal and stones (greywacke) occupy 20 to 50 % of the soil volume. Stone content increases with increasing depth. The last 250 mm of the profile has an increasing stone content with up to 80 % stones. (Ichythus, 2008)

Climate

Annual Rainfall never exceed potential evaporation with an amount of 395 mm to 705 mm. High Rainfall in summer (2005) can eliminate the pattern of an annual cycle for those particular years. Potential evapotranspiration has a ranges from 730 mm to 833 mm in the observed period. On a monthly basis standard deviation of rainfall in winter never exceeds 10 mm. In summer this can rise up to 18 mm were rainfall patterns are more variable. The relation of standard deviation of rainfall to variability in soil moisture has a gently slope. As can be shown in figure A.2 data points scatter less significant than for Winchmore. This is also true for the relation between θ_{mean} mean soil moisture and σ_θ standard deviation of soil moisture. A reason for differences between Winchmore and Timaru is probably the rainfall pattern. Standard deviation of soil moisture never exceeds 5 mm. Mean soil moisture varies between 10 and 30 %. With a noticeable distinct linear boundary at 30 %. Even maximum observed values do not exceed 37 %.

Perceptual Model

The time series is comparable to Winchmore. Though figure 6.14 is also representative for Timaru. Maximum measured values of soil moisture are between 30.9 and 37.6 %. It is assumed that field capacity is similar to that of Winchmore. It is assumed that this particular site has a maximum water storage about 160 mm to 195 mm. This is less than for Winchmore but the range of both sites is similar. Also the perceptual model of Winchmore in section 6.6.1 can transfered to Timaru. Values that are used for modeling hydrological soil response of Timaru are shown in 6.4.

Modeling Soil Response

For all used model soil moisture is over estimated after days of rainfall. Only under moderate humid conditions with days of rainfall under 20 mm there is a agreement with observed data. But also here are exceptions. The present parent rock material is similar to those one can find in a riverbed. It is possible that the sensor does not measure water after days with high rainfall. Because this water is simply passing through the soil without being measured. For further discussion refer to results of Winchmore as they are representative for this soil as well.

6.6.3. Exception: Compacted Soil, Site: Darfield

The soil at Darfield belongs to the group of recent soils. Orthic recent soils generally occur on areas of sedimentation land that is being eroded (Hewitt, 1998). A main factor that separates this site from other recent soil is the compaction which has probably been compacted under wet condition by heavy machinery (Ichythus, 2008). The similarity to other sites in the hydrological group of stony orthic brown soils with summer dryness is (1) summer dryness and (2) stone content in the lower profile > 60 %. Darfield is located in the western part of the Canterbury plains in a distance of about 30 km north west of Lincoln and about 43 km northeast of Winchmore.

Profile Description

This shallow silty loam is very stony and is suggested to belong to the Chertsey series. The modal profile is stone free for the first 45 cm. This is one of the main differences from the profile at the sensor (Ichythus, 2008). Nevertheless, in figure 6.15 is shown the platy structure is mainly developed at the top layer of the soil. This will probably effect infiltration capacity and can also cause infiltration excess surface runoff. Vegetation cover is poor with only 30 - 50 % coverage. Deeper layer of this soil are more loose and become increasingly coarser with depth, stones occupy 60 to 75 % of the soil volume from 290 mm to the C - Layer. Maximum soil depth is 490 mm. Penetration resistance is homogenous along the profile. (Ichythus, 2008) However, strong structural and textural differences of this soil profile must be considered when interpreting hydrological soil response.

Climate

Annual rainfall varies between 581 and 822 mm. Evapotranspiration exceeds rainfall every year and is between 950 mm and 1100 mm. Except for 2001 the dryness index is in every single year above one. The annual cycle in the soil moisture time series is weak developed and shows no defined sinuosity. Time series analysis on a monthly basis shown in figure A.4 shows much higher values for σ_θ standard deviation of soil moisture for particular summer month. This could be associated with water that passes the soil column through preferential flow paths to the sensor. Cracks are most likely evident after the dry period which could conduct water that then is entrapped close to the sensor. Consequently mean soil moisture increases. This evidence is supported by the relation shown in figure A.1 where this outliers can be observed at compare able low mean soil moisture.

Figure 6.15.: Shown is a (4 x 4 x 1 cm) piece of soil with a platy structure close to the measurement site at Darfield. With permission (Ichythus, 2008)

Perceptual Model

Based on the information of the soil profile the infiltration capacity of this soil is probably very low. The presence of stones decreases the water retention capacity and the maximum rooting depth implies shallow depth that is active to water exchange with the atmosphere. Plates and nuts in the soil provide a place for tension storage for water. The main amount of roots occur in the first 100 mm. Maximum rooting depth is 290 mm. The structure of soil changes from the first 100 mm to the second 290 mm of the soil column. Therefore it can be assumed that there are different tension storages that control evapotranspiration. Further it is assumed that the maximum value of soil moisture has been measured. For total storage we derive a range of 226 mm to 189 mm for the maximum water storage. Estimated field capacity from the time series is between 34 % and 38 %. The soil lies on a stony subsurface which is probably very conductive to water. The platy structure, the coarse nuts and the high stone content imply an ability to keep water only for a short time after an event. Depending on rainfall intensity surface runoff could be initiated. Finally this perceptual hypothesis will be tested with different model structures. Table 6.4 shows the results of estimated parameter used for the modeling.

Figure 6.16.: Lower graph: Model output of model 694 (gravity drainage), 630 (seperate tension storage) and 632 (cascading buckets) and observed data of the Darfield site. In addition model 630 'surface' allows surface runoff with an ARNO/VIC b exponent of 3. Upper graph: rainfall timeseries.

Modeling Soil Response

Despite the fact of some obvious differences from the other sites mentioned above it can be shown that model performance is quite similar. Considering information from the profile one can assume a lower value for the percolation exponent. This why penetration resistance is higher and homogeneous through out the profile. These factors reduce hydraulic conductivity and lead to the assumption of reduced drainage. This is consistent with observations of (Shanley et al., 2003). Model 694 shows a good agreement at recession parts. The only fitted parameter is the percolation rate. Even set to the upper bound it is not possible to fit the peaks of soil moisture response. If the parameter that defines the maximum water storage is reduced variability during the wet season is better represented (not shown). But the shape of recession parts under wet conditions (i.e. percolation process) is not sufficiently covered by the model output. The models that are shown in figure 6.16 perform good in the dry season. Ironically the model 694 with gravity drainage shows the best performance in the first dry season together with model 630 were tension storage is separated. Where in model 694 the lack of a tension storage is compensated by the percolation exponent. But the tension storage is important to keep water in the system below field capacity. As can be shown in figure 6.16 model 630 has a better performance in the wet season. The underestimated part of model 630 in the wet season can be compensated by reducing percolation from the free storage with the percolation exponent(not shown). Evapotranspiration is best represented with model 632 and also the last part of the wet season (shown in figure 6.16). But here is the percolation from the free storage reduced with the percolation exponent. This leads to an overestimation at the beginning of the wet season. A reason for that could be a portion of the soil column which is an inactive tension storage at the beginning of the wet season. Dry compacted soil with hydrophobic response to initial wetting. During the wet season this storage becomes activated by higher mean soil moisture. This can be supported with observation. It is observed that the platy structure breaks to single grain under moderate pressure (Ichythus, 2008). This indicates an imperfect binding within this structure. It is also possible that speed of percolation is reduced due to the platy structure which is horizontal to the surface (refer to 3.1). Capillary forces can be response able for the recession behaviour in the wet season. Finally all model structures fail to model a platy structure for all parts of the annual cycle. The best average performance has model 630 with only a lack of water at the end of the dry season.

6.7. Pallic soils in semi arid climate and Semiarid Soils

Pallic soils are most common in seasonally dry areas of the South Island, the eastern part of the North Island and in south east and south west of the North Island. Parent material

Table 6.5.: Estimated Parameter for soil surveys Ranfurly, Lauder, Middlemarch

Parameter	Lauder	Middlemarch	Ranfurly
$S_{1,max}$	212	222	100
θ_{tens}	0.35	0.35	0.4
k_u	10	10	10

is mostly loess or sediments derived from schist or greywacke (quartzo-feldspathic rocks). Generally pallic soil subsurface permeability is restricted. This can result in perched water table on slowly permeable layers. Further rooting depth is limited by higher bulk densities at shallow depth. Occurence of worms can be significant which leads to a distinct worm mixed A to B horizon. However, worm activity is reduced during the dry period. Soil material predominantly in the B horizon is strongly dispersive and will readily slake. It is also suggested that pallic soil occur where summers are dry and winters are moist with an annual precipitation ranging from 500 mm to 1000 mm. (Hewitt, 1998)

Semiarid Soils occur in the Otago region and southern Canterbury. As a consequence of low annual rainfall the wetting front mostly fails to penetrate lower parts of soil profile. They are based on sedimentary greywacke stone or non calcareous quartzo-feldspatic schist. Generally saturated hydraulic conductivity is slow, but drainage is moderate to good. Basically biological activity is low because of dryness. Soils in this group are also strongly dispersive and slake when wetted. (Hewitt, 1998) further suggested that mean annual precipitation that this soils experience range from 350 to 500 mm. This is consistent with observations in this study. Hewitt (1998)

To conclude observations of (Hewitt, 1998) low rainfall causes that water seldom reaches lower parts of the profile. Consequently soil development is limited to the upper part those profiles. Another feature is the strong increase in penetration resistance with depth. This boundary is associated with the maximum rooting depth. One example of how this boundary looks is shown in figure 6.17. These sites also have in common a low water storage capacity. Estimates of values for water storage and field capacity are shown in Table 6.5.

6.7.1. Lauder

Lauder is located in central Otago. The Otago region is the region in New Zealand with lowest annual rainfall. The location of Lauder is part of a valley system with gently rolling hills.

Figure 6.17.: Soil profile example for soils with a strong increase in penetration resistance that is associated with a root boundary. With permission (Ichythus, 2008).

Profile Description

The soil profile at the sensor location is classified as a sandy loam based on schistose gravel. Ichythus (2008) further suggested this soil belongs to the Matakanui series of very fine sandy loam. In contrast landcare has mapped it as one of the Becks series (Wilde, Willoughby & Hewitt, Wilde et al.). The site is not ideal for the measurement because of stones between 70 mm to 530 mm. This space could contain water instead and beside this it could cause permittivity changes that have negative effect to a accurate measurement. The soil has its maximum depth at 530 mm. The top 70 mm are covered by a dense root mat that runs along the boundary to a more stony silt loam that expanse from 70 mm to the maximum rooting depth of 190 mm. Weak and coarse blocks with low pedality break to 5 - 20 mm sub angular nuts in that layer. Approximately 45 to 60 % in aggregates that slake when wet. From 190 mm to 320 mm pedality is about 30 % and visible biopores (10 - 15 per 2mm x 2mm) occur. There is a weak development of a prismatic structure that has thin coatings of organic matter at this depth. (Ichythus, 2008)

Climate

Annual rainfall varies from 290 mm to 532 mm. Potential Evapotranspiration is between 600 mm and 750 mm per year. The calculated aridity index R is, with one exception, above 2 and even close to 3. As a consequence of low annual rainfall the mean annual soil moisture very seldom exceeds 30 %. The mean annual soil moisture varies between 10 and 24 %. The variability within years is low expect for 2004 which was a very wet year compared to the others. Variability within single month rises significant at a certain threshold of 50 mm rainfall (not shown). This is accompanied by a high positive balance of soil moisture at the end of the month (not shown). In figure A.5 the relationship between standard deviation of rainfall and standard deviation of soil moisture is shown on a monthly basis. The distribution of data points is compareable to Blenheim and Lincoln. It should be noted that all these sites have a similar grade of soil development (pedality) in the top layer. It can also be shown that variability of soil moisture depends less on mean soil moisture θ compared to Blenheim and Lincoln (refer to figure A.1 and A.2). It is observed that aggregates at Lauder are weak developed in the top 70 mm and slake when wet in the lower 70 mm to 190 mm (Ichythus, 2008). As a consequence these aggregation does not keep the water effectively as at Blenheim and Lincoln. Thus mean soil moisture has a lower effect on variability σ_θ. It should be noted that, the more weakly developed aggregate structure in the top soil, the less biological activity (Molloy, 1998). As mentioned in chapter 3.1.1 biological activity is the basis for soil development. This activity is reduced due to low availability of water and very dry summers.

Perceptual Model

Maximum measured values of soil moisture vary with a magnitude of 22 % to 50 %. This is associated with higher standard deviation in those years. Finally these values might be related to intense rainfall. For this reason the maximum water storage is to be assumed the average of oberserved values on a yearly basis. As a result we derive a value for S^1_{max} of 200 mm for the maximum water storage capacity over maximum depth of the profile. Field capacity is defined to be 35 %. The soil at this site is in the same class as that at Blenheim, but it is shallower, has a higher silt content and is much drier. The information from the pedological assessment, that water does not reach the lower part of the profile for most of the time, implies a very low rate for percolation. More important, the evapotranspiration as leading factor for soil moisture. That probably leads to a structure with upper zone control to this process. This hypothesis will be tested in the modeling part.

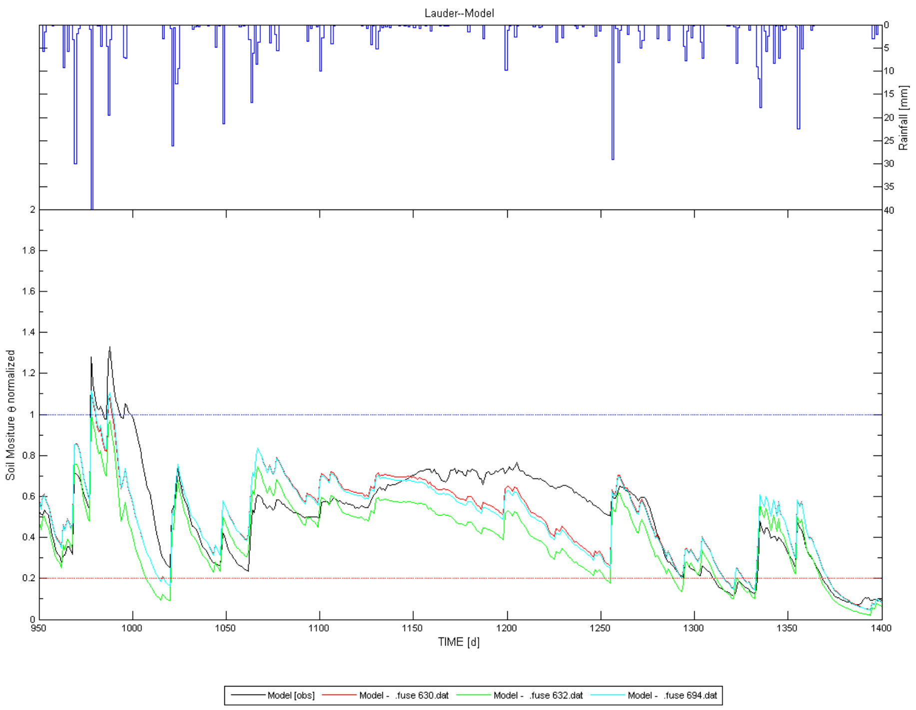

Figure 6.18.: Model results of model 694 (gravity drainage), 630 (seperate tension storage) and 632 (cascading buckets) for site Lauder. Weakness of model performance in the wet season could be related to systematical error for rainfall or soil moisture measurement.

Modeling soil Response

It is shown in figure 6.18 that model 694 (gravity drainage) and 630 (seperate tension storage) show a similar output. In contrast to modeling results of sites in section 6.4 to

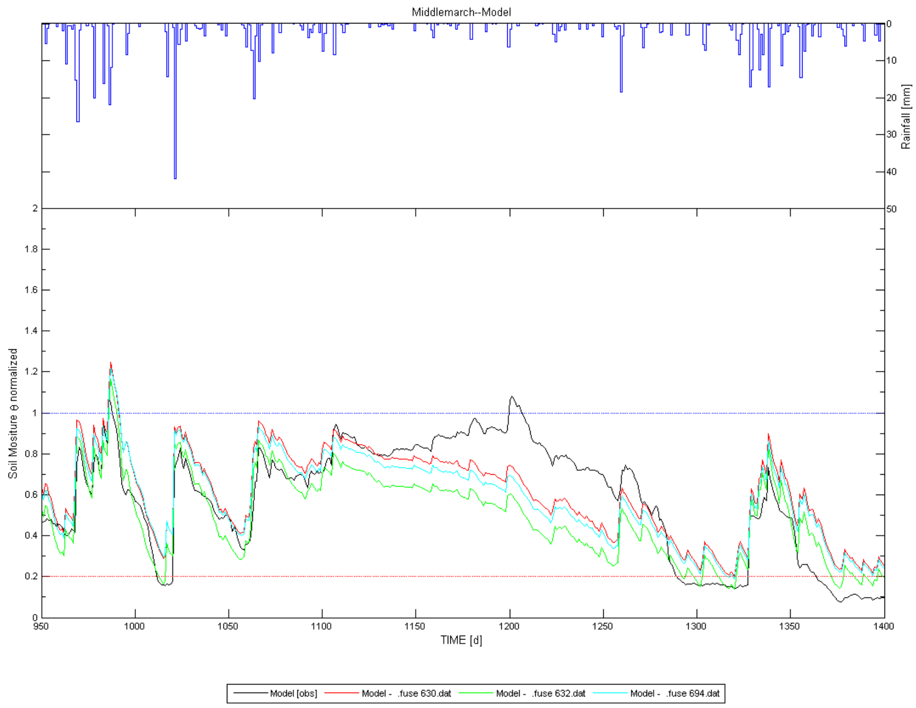

Figure 6.19.: Model results of model 694 (gravity drainage), 630 (seperate tension storage) and 632 (cascading buckets) for site Middlemarch. Weakness of model performance in the wet season could be related to systematical error for rainfall or soil moisture measurement.

6.6 the percolation exponent in model 694 is not used. Even the percolation rate is set to one. But same results can be made if percolation rate and percolation exponent are set to high values. For model 630 the percolation rate becomes insensitive above 10. Though it is reasonable to say that this process plays a minor role at this site. This is consistent with observations in section 6.7.1. Finally that means to model 694 that probably not enough recharge to the lower layer occurs. It is further observed that the usage of 'rootweighting' as evapotranspiration scheme leads to a better representation of the recession limb (not shown). But on the expense of the representation of the wetting up period. Further it is observed that roots tend to run along a boundary at 70 mm (Ichythus, 2008). Therewith it is unprobable that a 'rootweighting' concept is realistic. Model 632 does produce a worse output then the other two structures. This model is over parametrizised for this site. Further it supports the assumption that aggregates provide no space for tension storage within the matrix. It seems to be more reasonable that those aggregates slake when wet, which results conceptually in only one tension storage (i.e. the matrix) which is defined by texture. Finally the conceptual model 630 seems to represent processes most realistic. Because percolation rate becomes insensitive in contrast to model 694. Further evapotranspiration demand is provided from a defined tension storage in Model 630.

6.7.2. Middlemarch

Middlemarch is located in the Otago region 60 km south east of Lauder and 44 km south of Ranfurly (see Figure V and I). Finally this site experience a very similar climate as the other Otago sites. Further it is suggested to belong to the same subgroup as Lauder. In contrast to Lauder aggregates have a strong binding strength.

Profile Description

The sensor is installed in a Struan fine sandy loam to silt loam based on weathered schist. The sensor installation is assessed to be not ideal which highlights limitations to interpret the measurements. (more page 137) There is a very dense root mat in the first 160 mm. Also this area has a pedality from 80 to 90 %. Below 16 cm soil becomes more stony. From 210 to 320 mm the soil texture changes to silty loam with stones to a diameter of smaller than 100 mm. Furthermore this horizons are apedal. With increasing depth pedality becomes lower and a platy structure occurs together with micaceous lamellae (weathered schist). (Ichythus, 2008)

Climate

Annual rainfall is between 300 and 531 mm during the observed period. Potential evapotranspiration is between 770 mm and 924 mm per year. The calculated aridity index k is only 2004 underneath 2 for all other year it is above 2. This soil is very dry. Compared to Lauder minimum measured values are higher. This can be related to a better soil development (i.e. more effective tension storage). The relationship between σ_{prec} and σ_θ shows a similar signature as for Blenheim, Lincoln and Rangiora (refer to figure A.1 to figure A.3). But there is a obvious tendency for higher values in the summer month. The distribution of mean soil moisture to standard deviation of soil moisture shows a range were variability is high. In figure A.2 can be shown that standard deviation has higher values between 14 and 22 % of mean soil moisture. Variation is beneath 3 for mean soil moisture above 22 and beneath 14 %. The shape of the distribution is comparable with those from Martinborough, Blenheim and Lincoln for the range of 10 % to 30%. Those observation are consistent with (Brocca et al., 2007; Western et al., 2004). All these sites have a similar grade of soil development in the top layer (pedality) and a similar structure but different texture.

Perceptual Model

The maximum measured values for soil moisture during the years 2001 to 2006 range from 30 % to 43 %. The average of this percentage applied to the maximum depth of 570 mm result in a maximum storage capacity of 222 mm. Estimated field capacity is probably 35

% regarding change in slope of the recession limb of the soil moisture data (not shown). The observed good soil development (Ichythus, 2008) suggests a value of 80 % for the parameter that defines the subdivided tension storage. Percolation is assumed to be low regarding information of the soil profile description and the dry climate. It is possible that changes in the rainfall pattern result in higher recharge or surface runoff generation.

Modeling soil Response

Soil response is similar to Lauder. Apparently model 632 with cascading buckets show better performance for this site. In figure 6.19 the modeled hydrological soil response is shown for the same period as fro Lauder. This comparison illustrates similarity during the wet season. All models for both sites underesitmate observed data. But there is a response to rainfall with a similar shape. It is assumed that here systematical errors for the rainfall measurement exist.

6.7.3. Exeption: Oxyaquic Conditions, Site: Ranfurly

Ranfurly is located in central Otago 33 km east of Lauder (see Figure V and I). But this soil belongs to the Order semi-arid. It is argillic which means it occurs on land surfaces of early Holocene or late Pleistocene age (Hewitt, 1998). The sensor is located on intermediate terraces of a broad alluvial plain (Wilde, Willoughby & Hewitt, Wilde et al.). It is an exception in this group because there is a possible influence of groundwater.

Profile Description

The soil is suggested to be a Ranfurly silt loam and was pedologically found to be representative for the soil in a radius of about 200 meter. The maximum depth is 1000 mm. The top 125 mm are compacted which limits the volume of water that can be stored. Soil of this layer is to 85 % pedal rest is single grained dust. There is also a dense root mat in the first 50 mm. The Layer between 125 mm and 185 mm is more compact then above and apedal. A very weak platy structure is developed. Roots penetrate hardly and 90 % of all roots are above 160 mm. There are irregular horizontal tabular prisms (60 x 30 x 15 mm) in clusters moderately strong sub-angular nuts (3 - 11 mm) in a depth from 185 mm to 420 mm. Soil is apedal 90 % of roots are above 160 mm depth, 75 % of roots are above 90 mm. It is found that within the last 580 mm wet fine sand occurs but without traces of mottling. (Ichythus, 2008) This together with a prismatic structure was also found at Lincoln. Most probable a sign for groundwater influence also known as Oxyaquic conditions (Lin et al., 2008). If water, which is provided if the groundwater rises, is available for plants can not be told because there is no observation of the maximum rooting depth.

Climate

Ranfurly experience a very dry climate with a annual rainfall of about 350 to 548 mm. Annual evapotranspiration is quite high at 830 to 930 mm per year. As a consequence the mean soil moisture ranges from 21 % to 28 % on a yearly basis and from 10 to 50 percent on a monthly basis. The relationship between σ_{prec} and σ_θ shows a steep linear slope. Low values of $\sigma prec$ result in a very high standard deviation for soil moisture. This can be related to groundwater influence. It should be noted that the installed sensor reaches the layer where a prismatic structure (refer to figure 3.2) is developed.

Perceptual Model

Field capacity is hard to estimate because of those dry conditions soil moisture is seldom above filed capacity. By estimating field capacity one could be miss lead by high values caused by water which possibly flows into the channel were the sensor is installed. Further the influence of groundwater can effect the recession behaviour. Field capacity is identified at a soil moisture of 40 %. This is within a range suggested by (Rawls et al., 1982). It is the upper limit for a silty loam but this seems to be reasonable considering the weak platy structure in lower part of the profile. This structure increases flow path length and reduces the velocity of water movement 3.2. Measured maximum values for soil moisture are also within the range suggested by (Rawls et al., 1982). Percolation is assumed to be low because drainage is constrained by structural change and higher penetration resistance with depth. Maximum water storage is approximately 200 mm if we assume 50 % of total porosity for a active depth of 400 mm. In the case of Ranfurly it is assumed that the developed soil depth defines the water storage. Because the fine sandy texture is most likely influenced by groundwater which in turn is not available for soil water storage. This zone probably provides water to the upper part of the soil. The prismatic structure indicates forming processes by water flow.

Modeling Soil Response

Shown in figure 6.20 model results of three different model structures. The wetting up period is generally overestimated. By changing θ_{rchr} step wise from 0.1 to 0.8 the model shows a similar behaviour as for Rangiora (shown in figure 6.9). Ranfurly illustrates the importance of structural changes within the soil profile. Regarding textural information estimated values for field capacity appear to be high. When considering structural changes and its impact to hydrological processes the estimated values are more reasonable.

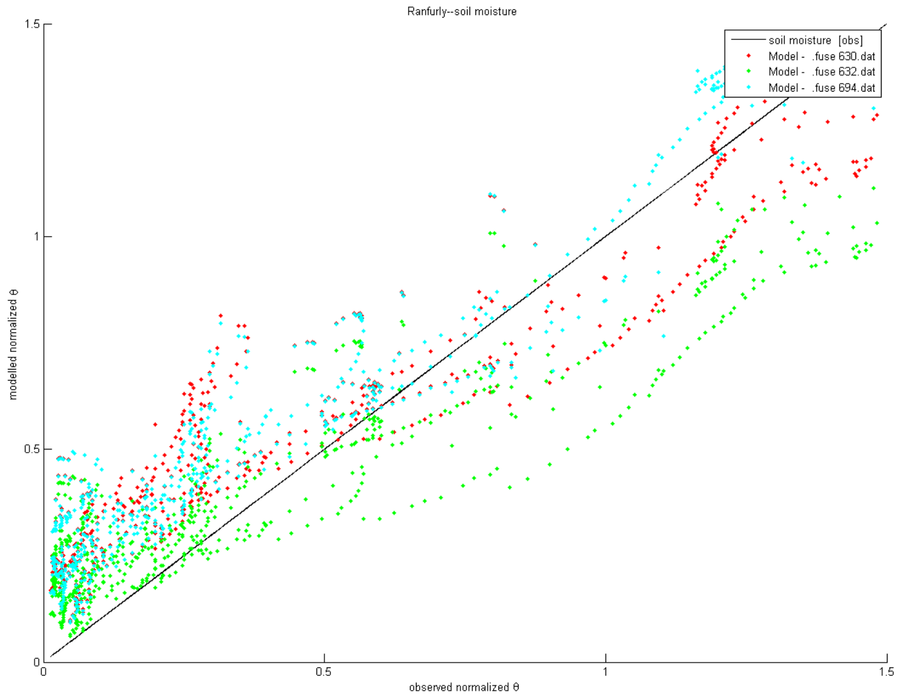

Figure 6.20.: Model output of model 694 (gravity drainage), 630 (seperate tension storage) and 632 (cascading buckets) for the Ranfurly site.

6.8. Pallic soils in a moderate climate

6.8.1. Martinborough

Martinborough is located at the very southern edge at the east of the North Island. This is shown in figure IV.

Profile Description

The fine sandy loam of this site belongs to the Tauherenikau fine sandy loam series according to the Ichythus report (2008). It has a maximum depth of 510 mm. The site is located in the Ruamahanga River Valley. Soils ability to store water is hugely variable in the Ruamahanga Valley. They are based on gravels that means that water can drain free beneath the soil layer. Also no drainage impediments were found in the first 550 mm. Roots can penetrate the soil well to a depth of 300 mm. There are many roots between aggregates (70 %). Stones are rare sizes vary from 10 mm - 30 mm and more seldom to 50 mm in diameter. The first 200 mm are strongly pedal with a nut structure dominating with 70 %. Also many fine pores are visible. The boundary is intercalated with the next layer. The sandy loam becomes more grey - brown and olive brown sand with irregular shaped fingers. With increasing depth greyisch brown colors become less frequent but spots larger. To the bottom of this layer have development of nuts with tendency to be cloddy. The bottom layer is shows many biopores (10-20 mm), but few occurrence of stones.(Ichythus, 2008)

Climate

The mean annual rainfall varies between 580 to over 1000 mm per year in the observed period. Estimated potential evaporative demand is between 900 and 1000 mm. The low values for the maximum water contents support the conclusion that the soils ability to retain water is small. Considering that water balance is in equilibrium in some years and high amounts of rainfall occur in winter. Rainfall and Evapotranspiration amounts are shown in table A.13. Dependence of mean soil moisture to their standard variation show as a similar pattern as for Blenheim and Lincoln. However, the shape of this distribution is more flat and except two outliers never exceeds 4 % of standard deviation. This implies a quite uniform distribution of rainfall through out the year.

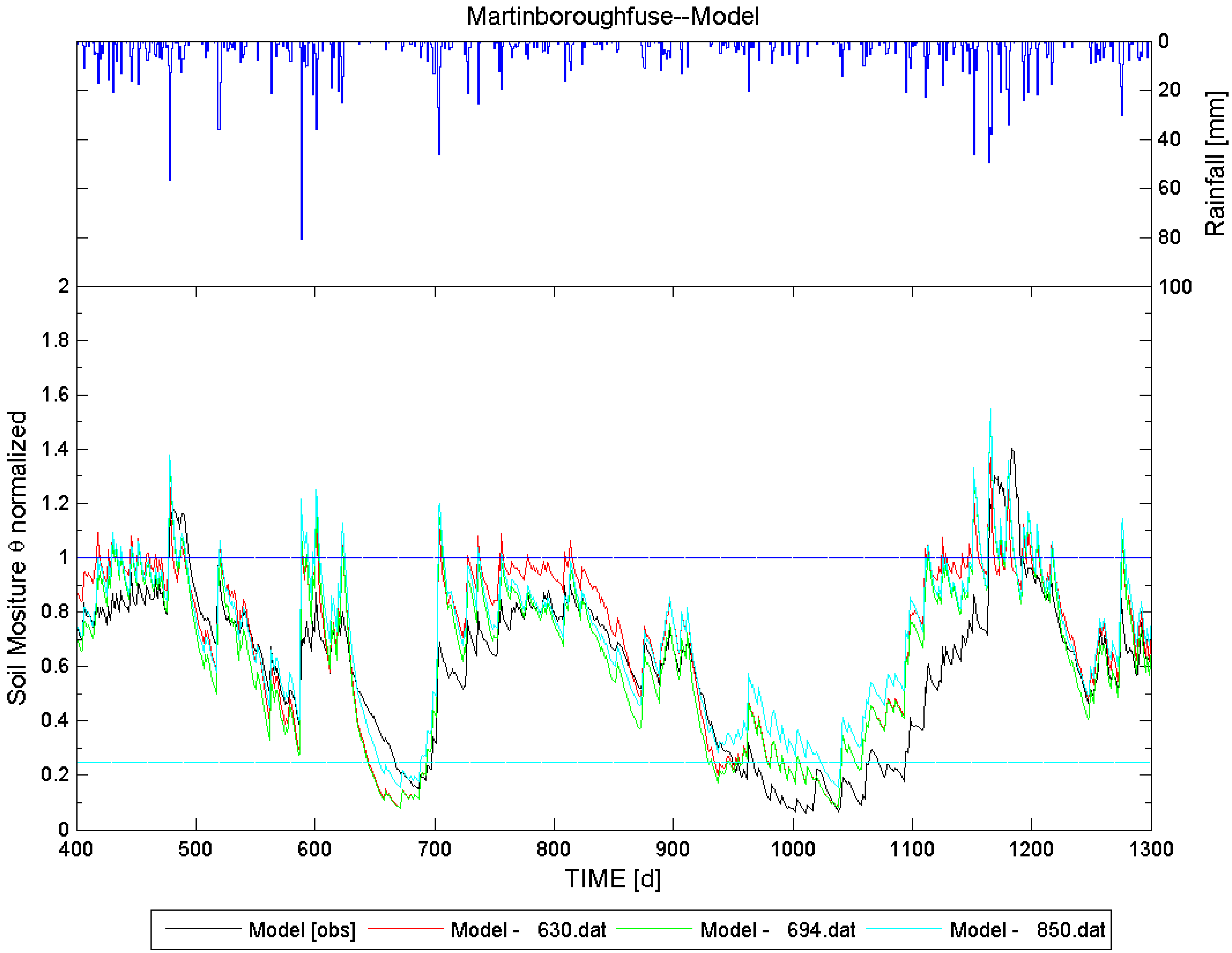

Figure 6.21.: Model output of model 694 (gravity drainage), 630 (seperate tension storage) and 630 with 'rootweighting' as evapotranspiration scheme for the Martinborough site.

Perceptual Model

The perceptual model could be as follows. Field capacity will be higher then expected because of the high pedality of the soil. I assume 42 % as field capacity derived from the time series. There is a variability in tension storage of about 25 %. The profile indicates a good drainage below the top layer. The top layer is pedologically better developed and might have a higher ability to hold water than those underneath 200 mm. We consider the maximum water capacity to be 237 mm. That is consistent with the mean of maximum values of each single year.

Modeling Soil Response

The first two model 630-694 show similar results even for same parametrization except the percolation exponent. Another evapotranspiration scheme fixes some recession parts on the expenses of peak behaviour. The root fraction parameter is aligned to the description of the soil profile and is set to 0.7. The third upper layer structure makes the errors more worse and is not shown because of that. Figure 6.21 shows model output for the visual parametrization shown in table A.10, A.11 and A.12. The 'rootweighting' evapotranspiration scheme reduces the evapotranspiration in the dry period. It is most likely that water uptake from plants is first sated by water from the upper layer. After soil moisture reaches a certain threshold, plants can easier provide water demand from the lower zone of soil. This leads to less evapotranspiration in the zone where the soil moisture sensor is located. The choice for the maximum water storage reduce variability. A higher value of S_{max} combined with a lower percolation rate leads to a much better performance. Both the 'rootweighting' and the change in parametrization of S_{max} lead to more water in the soil column but for different reasons. The 'rootweighting' shifts the evapotranspiration to another layer. The change of parametrization provides more space for water storage in the soil column, though less percolation and a higher soil moisture during the dry season.

6.9. Recent sandy soils under wet conditions

Recent sandy soils have probably a similar hydrological behaviour as pumice soils. Pumice soils are very young ranging from 700 to 3500 years in age. They occur in sandy or pumiceous volcanic ashes that can be found in the central of the North Island, particular in the volcanic Plateau. Clay contents are low. Soil strength is weak or very weak they have a apedal structure. They provide a deep rooting depth for plants except in welded flow tephras. Macroporosity is high which is associated with low matrix potential and rapid drainage. Basically the available water storage is high. Hewitt (1998)

6.9.1. Paraparaumu

Paraparaumu is located on the west coast of the North Island 53 km north west of Martinborough. This is shown on map V.

Profile Description

This sandy loam experience a relatively humid climate. It is close to the beach.Ichythus (2008) suggested this site to be pedologically useful transfered along the west coast of the Waiterere sand dunes within a radius of about 1 km excluding the airport. The maximum depth at the profile is 1000 mm. The first 100 mm of soil has low pedality; 15 % nuts and 85 % single grains. To a depth of 380 mm dune sand is present and roots to a depth of 30 mm. With increasing depth soil becomes more moist and cohesive but pedality remains low. Mottles of reddish brown and pale olive and bluish green have a similar size distribution within the matrix. Gley mottles also occur tend to be rounded, iron mottles have irregular amoeboid shapes. (Ichythus, 2008) The weak mottling at a depth of 75 mm seems to be a common feature of this soil. It is an indication of the presence of water for a long period (unoxic conditions).

Climate

Mean annual rainfall varies between 728 to 1227 mm. High amounts of rainfall in summer can lead to high mean soil moisture in this season. The variability of rainfall on a yearly basis is similar every year with one exception in 2003. This is associated with intense rainfall events during the summer month. The winter month in general are more variable then those in summer. Soil moisture drops down to under 20 % very quick if their is a lack of rainfall which indicates a good drainage and a weak developed tension storage. Even if there is a reasonable sum of rainfall every year mean soil moisture remains quite low between 7 and 15 %. On a monthly basis mean soil moisture never exceeds 26 %. Standard deviation of soil moisture increases in a linear relationship to mean soil moisture through out the entire year. The relationship between variability of soil moisture and variability of rainfall shows a similar pattern as for Martinbrough, Timaru, Winchmore and Kaitaia. This is shown for σ_{prec} to σ_{θ} in figure A.4 to figure A.6. All these sites have good drainage. Martinborough has a sandy loam texture. All other sites have a silty loam texture.

Perceptual Model

There are no drainage impediments that could constrain percolation. Also the data shows that there is a good drainage considering that soil moisture drops down after lack of rain. The low values of mean soil moisture but the high amounts of yearly rainfall indicate that tension storage is weak. Field capacity is very low by 22 to 24 % derives from the time series. Variation in tension storage is between 20 and 30 %. Maximum water retention is probably high because of a high total porosity of sand. The value is set to 500 mm. These assumptions for a sandy loam are consistent with values of (Rawls et al., 1982). Low pedality in the top layer within a sand matrix of single grains causes a fast drainage and a weak tension storage.

Modeling Soil Response

Model result show that neither model 694 nor 630 perform sufficiently for this enclosure. By adding a negative multiplicative rainfall error the summer can be better represented for both models (not shown). The site characteristic is probably represented with the perceptual model. But quality of forcing data is assumed not to be reliable. It is possible to fit the recession after the wet season but on the expense of the rest of the model results This is valid for all model structures. Model 694 (gravity drainage) needs to be adjusted either for the percolation exponent or for a lower percolation rate. The other two models need to be adjusted for the percolation rate. It is also possible that the conceptual model are not able to represent processes that occur in sand texture. The stepwise adjustment of the percolation rate from 20 to 200 shifts the output. As a consequence different parts of the wet season show a good agreement with observed data (not shown). Low values of c result in a good fit at the end of the wet season. In contrast high values show a good agreement at the beginning of the wet season. Finally this leads to the assumption that high percolation rates at the beginning of the wet season are related to higher infiltration rates because of unsaturated soil at higher depth. Once the lower part of the soil is saturated the percolation rate in the model has to be reduced. Models that are used here are not able to capture this process. The use of a model structure were the lower layer demand controls percolation improves this behaviour. The negative trend during the wet season is reduced. This supports the assumption of a lower zone control at this location.

6.10. Allophanic Soil, Volcanic Ash

Allophanic soils most common feature is weak strength, sensitivity and low bulk density. They can be found in volcanic parent materials. This means ash and basaltic scoria. It is also possible to find these soils in quartzo-feldspathic and greywacke stone. In New Zealand they can be found mostly on the North Island on volcanic ash or weathering products of volcanic rocks. As weathering products of greywacke they can be found on the South Island. (Hewitt, 1998)

6.10.1. Stratford

Stratford is located at the east site of Mt. Taranaki. It is the most humid location in the experimental setup. It is a orthic allophanic soil. Their common feature is a high rooting depth because of low bulk density and a good drainage.

Profile Description

The sandy loam at this site located on the North Island this enclosure experience hight intense rainfall because of the orographic effect of Mt. Taranaki. Maximum depth of this profile is 100 mm. Penetration resistance is low (800 kPa) and decreases down to the lower horizons (675 kPa). First 160 mm of this profile contain a nut (25%) and crumb (75%) matrix. Sub-angular nuts (25-30 mm) break into smaller nuts (5 mm) then to crumb. There is a dense root mat that makes this horizon stable. Next 100 mm is moist but no free water. There are pumice inclusions with a diameter of 15 to 35 mm that penetrate the ground surface from 170 to 230 mm. Then rounded punmice fragments follow surrounded by subangular nuts and crumb in a silty sand loam. At a depth of 340 mm silt and clay content rises but soil is apedal and moist. The last 400 mm are much moister then above. Blocks break to individual grains (unusual for this depth). At a depth of 780 grey flakes of weathered andestic or rhyolitic material appears that is easy to break. Finally clay content rises with increasing depth. Boundaries between horizons are diffuse but linear. (Ichythus, 2008)

Climate

Mean annual rainfall is very high (1400 mm - 2624 mm) compared to potential evapotranspiration (792 mm - 809 mm). The time series shows a weak annual cycle. Rainfall is slightly higher in Winter. Despite the fact of those high yearly rainfall amounts mean soil moisture remains under 34 %. A maximum value of 50 % can be observed which does not correspond to the highest annaul rainfall in 2006. This is probably correlated with intense rainfall during a certain day or week. On a monthly basis mean soil moisture is clustering between 20 and 40 % with slighty higher variability in summer. This indicates that during the dry season more drying and wetting occurs. Values for standard deviation of soil moisture does not exceed 6 %. The relationship between standard deviation of rainfall and standrd deviation of soil moisture is parallel to the x-axis. This indicates that even strongly variable rainfall does not affect soil moisture very much. There are exceptions between 12% and 15 %. This compared with higher values of σ_θ in figure A.3 shows that there is more variabilty in month with a mean soil moisture under 30 %.

Perceptual Model

This site shows probably the same behaviour as Paraparaumu. The main difference is the higher silt and clay content in the lower part of the soil profile. Therewith percolation rate will lower then for Paraparaumu. Regarding observation of soil moisture time series maximum water storage is probably 427 mm. Field capacity is around 35 %. There are possibilites for preferential flow paths because of pumice inclusions and clustering of aggregates because of the compareable high clay content. There are also pumcie inclusions that can cause a particular behaviour of water flow and storage (preferential flow path).

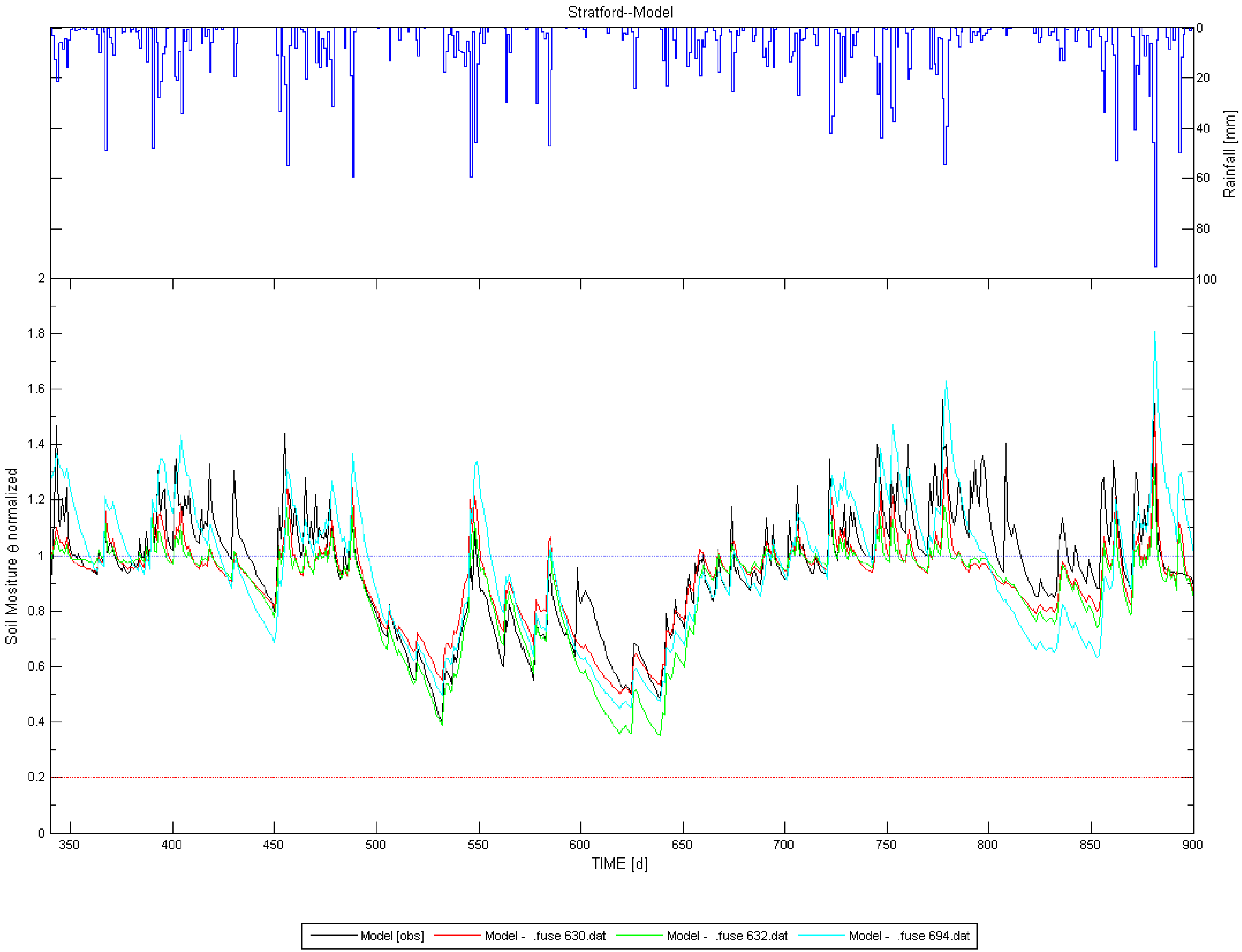

Figure 6.22.: Model results of model 694 (gravity drainage), 630 (seperate tension storage) and 632 (cascading buckets) for site Straford.

Modeling Soil Response

All model results show a qualitative good representation for the hydrological soil response of the annual cycle as can be shown in figure 6.22. There are three obvious parts which are underestimated. This is probably related to missing rainfall data. No model is capable to explain spikes of the observed data during the wet season. It is observed that there is a dense root mat and pumice inclusion in the soil (Ichythus, 2008). These inclusions provide space for preferential water flow. Thus water can reach the sensor through those flow path. As a result there is a steep recession in the time series because of these fast flow paths. Between days 500 and 600 it can be shown that model 632 shows the best performance for the evapotranspiration. The value for the second tension storage can again be related to the percentage of soil development. But only to the portion of nutty aggregates.

Finally the conceptual models that are used here are able to capture the annual cycle and also recession after the wet season. The variability during the wet season can not be represented by conceptual models used here. Probably because of preferential flow paths. These process is not implemented in conceptual models used here. Further it can be shown that there is a link between evapotranspiration and aggregation in the soil because of a better representation with model 632 (cascading buckets).

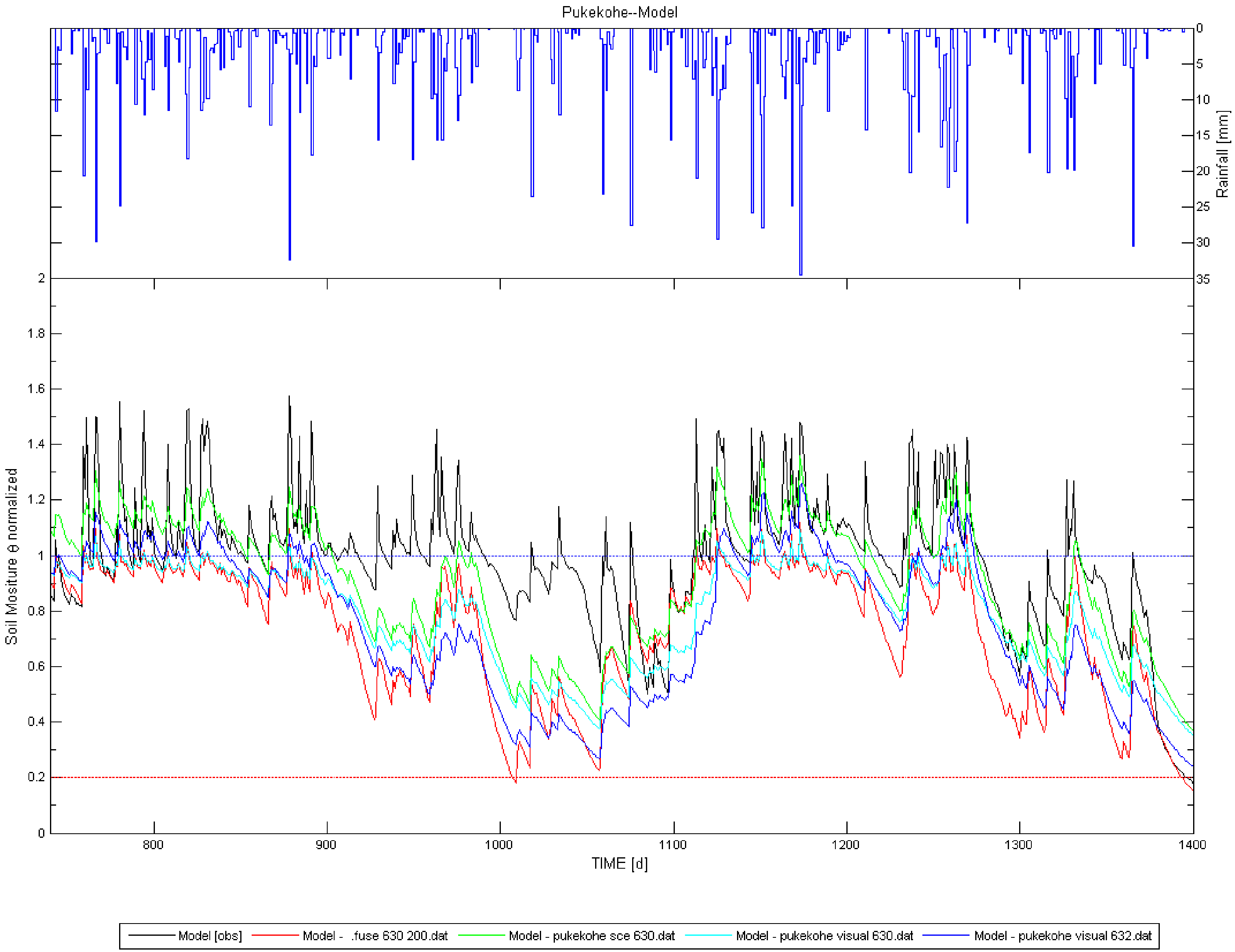

Figure 6.23.: Model results of model 694 (gravity drainage), 630 (seperate tension storage) and 632 (cascading buckets) for site Pukekohe. Spikes in the time series are probably induced by water flow through cracks. This process can be represented by those structures.

6.11. Granular Soils

Granular soils occur in the South Auckland region and in the Waikato lowlands. Saturated hydraulic conductivity is slow which can result in periods with a perched water table. Rooting depth can be restricted either by high penetrations resistance, wetness or aluminum toxicity. This group of soils are derived predominantly from strongly weathered tephras mostly older than 50 000 years. Further they occur also on basaltic and andesitic rocks. (Hewitt, 1998)

6.11.1. Pukekohe

Orthic Granular soils are well, moderately or imperfectly drained soils. Because they are very plastic and can be sticky after heavy rain.

Profile Description

Far in the north of the north island the silty loam of Pukekohe experience a humid climate. (Ichythus, 2008) suggested that this site is representative for the Patumahoe clay loam. The soil originates from volcanic ash. At a maximum depth of 800 mm water table appears. The profile is strongly pedal 50 to 80 % of the matrix has nuts (9-12mm) that break to smaller nuts (3-5mm) under moderate pressure. Some nuts occur with a size up to 25 mm. Nuts are well developed and loosely packed. Also worms are present. Roots penetrate the soil between and within aggregates to a depth of 120 mm. At a depth of 100 to 220 mm soil has less pedality. There are few worms and stones with diameter up to (10 - 20 mm). With increasing depth pedality decreases nuts become coarser and blocks occur (e.g 65 x 45 x 35 mm) breaking to nuts then to crumb. Also size of stones and clay content increases. From 220 to 500 mm worms disappear stones are larger and more frequent. Soil is apedal and cloddy. The lower part of the profile is wet because of the close water table. (Ichythus, 2008)

Climate

The mean annual rainfall exceeds every year in the observed period potential evaporative demand. On that basis there is no significant annual cycle at this site. Mean annual rainfall varies between 823 mm and 1262 mm. Evapotranspiration is quite consistent with a mean of 841 mm to 872 mm. On a monthly basis there is square in which standard deviation of rainfall and standard deviation of soil moisture are present (see figure A.5). Rainfall is consistent during the entire year. There are a few outliers that indicate that with rising variability of rainfall also soil moisture respond with more variability. Mean soil moisture is dominating between 30 and 40 %. Where the highest standard deviation is reached at 30 % of mean soil moisture. Mean soil moisture never drops down under 15 %.

Perceptual Model

The soil profile provide information that lead to assumption of macro pore flow generation. Because of the high clay content cracks are generated during drying periods because clay soils tend to shrink and expand depended on water content. If a rain event occurs first macro pores are filled then tension storage is sated with residual water. Clay soils have a strong developed tension storage. In contrast porosity is lower dominated by mentioned cracks. Finally field capacity is defined with a value of 37 %. Maximum water storage is probably between 400 and 500 mm regarding estimates of Rawls et al 1982 and also measurements show that this values are feasible. Regarding model structure it is assumed that a separation in tension and free storage is the best available model structure.

Modeling Soil Response

As shown in figure 6.23 no model is able to capture the observed time series.Obviously peaks caused by macro pore flow are not captured. Macropores at this particular site are pores with a very low ability to hold water against gravity. Clay tend to absorb water very slowly. A model without implementation of macro pore flow and its interaction with aggregated can not represent soil response. Because after rainfall the soils tension storage is not active. Thus soils tensions storage is low. Variability can be better represented by reduction of the maximum water storage of 200 mm (not shown) on the expense of the annual cycle representation. To conclude observation it is not possible to model soil response adequate at this site with structures that are implemented in FUSE. As can be shown in figure 6.23 it is not possible fitting the model rather visual nor by using other optimization methods. Using the bucket concept improvement could mean there is a need of a bucket representing those macro pores. They should interact with the tension storage and allow percolation or fast runoff generation.

6.11.2. Windsor

Windsor is located north east of in the Otago region. It belongs to mottled immature pallic soils.

Profile Description

Soil type is classified as a silt loam at the enclosure. Pedologically it is suggested that this soil is similar to Wakanui clay loam. There is possibility that overlandflow occur upslope of the sensor. Maximum depth of the soil profile is 970 mm. Rooting depth down to 375 mm where 75 % of roots occur in the first 200 mm. Soil has a moderate pedality in the first 240 mm. Nuts make 75 % of this layer with different grade of firmness and size. Biggest are 200 - 300 mm of blocks. Penetration resistance increases with increasing depth (1210 kPa to 1590 kPa). All layers below have a penetration resistance of over 5700 kPa. The following layer has lower pedality with a weak fine nut structure sizes are equal to the smallest nuts in the upper layer. Redish brown mottling and gley occurs. At a depth of 37.5 there is a perched water table visible. At this depth clay content rises, extensive olive mottles are visible which have a high contrast to rest of the matrix. With increasing depth mottles become more frequent and pedality decreases. Soil crumbles under moderate pressure in the last 200 mm and gley mottles are reduced. (Ichythus, 2008)

Climate

The climate is similar to Winchmore but a little bit dryer. The variability of rain is higher then for those sites in central Otago (Lauder, Ranfurly), but mean annual rainfall is also comparable low between 396 mm and 614 mm. Mean potential evapotranspiration exceeds mean annual rainfall every year with 716 mm and 941 mm. Mean annual soil moisture is for every year below 30 %. Maximum values for soil moisture are between 33 and 39 %. It can be shown that between 20 and 30 % of mean soil moisture on a monthly basis, standard deviation of soil moisture increases significant compared to lower and higher values of θ_{mean}. See therefore figure A.3. Standard deviation of precipitation compared to standard deviation of soil moisture shows that Summer, and spring response is related to higher values of standard deviation.

Perceptual Model

Regarding the perched water table percolation is restricted at a depth of 370 mm. This could lead to higher values for field capacity and also to low values for percolation rate. However, the maximum storage of water is probably between 320 mm and 370 mm. Rawls suggested for silt loam values for field capacity between 25 % and 40 %. From the soil profile it can also be concluded that most of the roots occur in the top 200 mm of the soil. Based on that information the root weighting scheme for evapotranspiration will be tested.

Modeling Soil Response

It can be noted that model 694 and model 630 show the same performance. Ichythus (2008) observed a perched watertable within the soil profile. This suggests a low percolation rate. Percolation rate is set to 6 which is very low. With the model 'rootweighting' it is also possible to reduce the portion of roots in the upper layer which leads to a lower evapotranspiration. By adding surface runoff, this result in a similar output of soil moisture response. Ichythus (2008) observed that there is a possibility of surface runoff generation at this gently slope. Thus it is suggested to use the parametrisation with surface runoff because it fit better to the perceptual model. Further the soil profile shows a high penetration resistance which will reduce percolation. This is consistant with observation of Shanley et al. (2003).

6.12. Soil Group: Podzols

Podzol soils occur most often in areas in the northland on the north island with high amounts of precipitation. Soils of this group can also be found in North Islands high country on the West Coast and in the high country of the South Island. Occurrence of this soils is in most cases associated with precipitation above 1400 mm per year. Another feature is a low biological activity. This is also associated with low rates of mineralization. Humus is weakly decomposed and minimal incorporated with the upper mineral soil which leads to low level of pedality. Rooting depth is often constraint by low pH or even aluminum toxity or high water table. Parent underlying rock material are often silica-rich rocks such as granite, greywacke, schist or rhyolite (Hewitt, 1998).

6.12.1. Kaitaia

Kaitaia is located at the northern edge of the North Island.

Profile Description

This silty loam soil of the Te Kopuru series that is a very shallow sandy loam. Also groundwater level could reach the surface as ponding at the location indicates. Ichythus classified this enclosure as representative for soil within a radius of 200 metre. In addition its suggested to use information from this site for others that experience similar climate and have similar texture as this site. The water table is close to the ground water table. In the first 14 cm are many intra- and interpedal roots. Dark grey loam dominates the first to the same depth. Silty sand inclusions are found between 8 to 14 cm. Bewtween 14 and 19 cm texture changes to 50 % dark grey silt loam, 30 % yellow silt loam and 20 % grey sand. This layer is apedal and very moist. At a depth of 19 to 25 cm free water is visible. Structure is friable in hand. Last 10 cm have a platy morphology and clay content rises. (Ichythus, 2008)

Climate

The climate at this site classified as humid regarding figure . In table That is shown in figure and table **??** Dryness R seldom exceeds 1 like at Invercargill. However both rainfall and evapotranspiration is higher. The relation between rainfall and soil moisture behaviour seems to be much more random then for the dryer sides. Furthermore the annual cylce is much weaker and because of the wet climate higher soil moisture averages are dominating. The variability of soil moisture is highest at an intermediate level between 20 and 40 %. In summer soil moisture is still quite high accompanied with low standard deviation. Soil moisture beneath 30 % is accompanied with with a stronger response to rainfall that causes a higher standard deviation in those month.

Perceptual Model

Regarding the high groundwater level the maximum water retention is probably varying with groundwater level. Drainage ability can rise between 14 - 19 cm of the profile because sand content. The color change at this depth could indicate vertical drainage. Also it has take into account that the location is located in a basin similar to Appelby. Choosing the same structure could lead to same performance. Because he water table is a drainage impediment. The wet soil in the lower layer of this profile is probably the result of capillary forces sucking water upwards to the surface. Therewith percolation is probably very low at this site Because of the high water table and also high rainfall in this area it is assumed that saturation excess surface runoff will be produced. Two different surface runoff possibilities are implemented in FUSE and are tested here. Values derived from the statistic shows us that there is a variation in tension storage between 25 and 30 %. Field capacity is identified by 50 %. Considering the shallow soil layer we get a value for maximum water capacity of about 150 to 180 mm. Recession analysis of soil moisture data gives a range for the percolation exponent.

Modeling soil Response

Model results show that there is enough variability in the upper storage. Therewith field capacity and the dimension of water storage are sufficiently aligned to the soil at this site. It is observed, without surface runoff peaks are extremely over estimated. There are some exceptions for small amounts of rainfall. In the case of a high value of surface runoff the increase is much better represented, but the recession at the end of the wet season is worse represented. Both surface runoff implementations show quite similar results for soil moisture response. Objective values differ slightly.

7. Discussion

This study focused on hydrological soil response. Soil characteristic is discussed for every of the 17 locations based on statistical methods (Brocca et al., 2007; Western et al., 2004).

Field capacity and maximum water retention for these sites were estimated analysing the timeseries. These values were compared to literature values of Rawls et al. (1982). On the basis of pedological knowledge (Ichythus, 2008) hypothesis about suitable model structure were considered (Lin et al., 2008). Finally these assumptions were transfered into common conceptual lumped models (Clark et al., 2008). The conceptual models were provided with parameters derived from the timeseries analysis or calibrated against observed data. The calibration has been conducted either visually and automatically. The aim was to define a model structure and parameter based on knowledge of pedological information. Further the performance of different conceptual models provided with similar parameters was compared. Finally findings can be used for regionalisation purposes in rainfall - runoff -models on the basis of pedological information.

7.1. Main findings

Main findings of this study comprise statistical relationships of soil genesis to hydroloical behaviour. It could be shown that there are similarities between sites with a similar structure regarding evapotranspiration. This is true for the statistical part as well as it is for the modeling part. Further sensitivity of parameters of simple conceptual models for the soil layer can be used to indentify processes within the soil. Finally possibilities to transfer information to other locations are discussed. It can also be shown that automatic optimization and parameter sampling result in high values for the objective measure on the expense of realistic parameters.

7.1.1. Statistical Analysis

The statistical analysis brought qualitative insights into hydrological soil response at 17 different location in New Zealand. The relationship for all these sites are illustrated in Figure A.1 to Figure A.3 . There are different patterns that can be interpreted on a hydro-pedological basis. For some sites there is a decrease of variability of soil moisture either with an increase and an decrease in mean soil moisture on a monthly basis. In this cases intermediate values of mean soil moisture is related to higher values of variability. For the experimental sites here was found, the relationship between mean soil moisture and standard deviation of soil moisture is not explicitly related to texture. In this regard Blenheim, Lincoln, Martinborough, Middlemarch and Musselburgh show a similar pattern of the mentioned relationship. Where Martinborough and Musselburgh show lower values of variability of soil moisture for intermediate values of mean soil moisture.

Blenheim, Martinborough and Middlemarch share a similar texture (fine sandy loam). In contrast Lincoln, and Musselburgh have a silty loam texture. However, all of these sites share a high grade of soil development of the upper layer (pedality). Finally it is assumed, the shape of data points Figure A.1 to Figure A.3 for these sites is related to soil structural similarities (peds). The evidence of a relationship between hydrological soil response and pedality is quantified in the modeling part.

Soil development is also high in the toplayer of Lauder, Ranfurly, Rangiora and Pukekohe, but they do not show a increase of σ_θ at intermediate soil moisture. The Pukekohe site is an exception in this listing because of a high clay content. Finally soil of this site has a much stronger aggregation and a tendency of flow within shrinking cracks which leads to a flashy behaviour from a hydrological point of view. The other sites have a similar texture.

For Lauder behavioral differences to similar soil such as Middlemarch can be related to soil genesis. They both experience a similar climate. The main difference of these two sites is the genesis of the soil and the underlying parent rock. At Lauder parent material is schistose gravel without traces of weathering. Soil genesis at his site is related to fluvialmorpholgical processes (refer to section 6.7.1). In contrast Middlemarch is located on weathered schist which result in a mineral composition that provides better binding ability between particles. It is observed that aggregates at Lauder have a low strength and slake when wettet 6.18. In contrast Middlemarch has stronger developed peds. Finally it is assumed that qualitative differences shown of the relationship between mean soil moisture and standard deviation of soil moisture are related to soil structural differences. This can be shown in more detail in the following modeling comparison part.

Ranfurly shows the mentioned relationship with a lower magnitude. A reason for that can be that it has a strong increase in penetration resistance at a depth of 125 mm to 185 mm. This is not the case for the other sites. Another reason for these differences can be the influence of groundwater.

7.1.2. Model comparison

In addition to a statistical analysis of timeseries of rainfall, evapotranspiration and soil moisture different conceptual models were compared. On the basis of the statistical time series analysis and pedological knowledge simple assumption about processes were made. These, so called perceptual models, where then transfered into conceptual models. The performance of these models for every single site are discussed in the sections 'Modeling Soil Response'. Model parameters of all modeling approaches are illustrated in Figure A.10 to Figure A.12 . According to this Figure A.7 to A.9 show Nash-Sutcliffe scores for the different models and the different calibration methods. Finally relationships between observations, parameters and model structures brought more insights into hydro-pedological processes.

Calibration

The models were calibrated with four different methods. The visual calibration was combined with knowledge a prior (soft data) where available. Parameters that could not be estimated by the data or pedological information were calibrated against the observed data. This brought further incites into the hydrological behaviour of the 17 different soils. This will be discussed in section 'Parameter Sensitivity'. Based on the knowledge derived by experiments with different conceptual models a standard parameter set were derived that shows reasonable output for most of the sites. The standard parameter sets are shown in table A.19.

All other parameter sets are shown in Figure A.10 to Figure A.12. It can be shown that automatic methods used to calibrate model 694 (gravity drainage) have a tendency to over compensate the lack of a tension storage with the percolation exponent (figure A.10 PERCEXP). In comparison the percolation exponent of the model with a separate tension storage (model 630) is in ten cases calibrated to unity with values derived by MCMC and SCE.

Exceptions are found for nine sites. All of these nine sites have a particular pattern as discussed in section 'Performance Measure'. The visual optimization found for every site a value of 1 for model 630. SCE was not able to find an optimum after 3 days with starting point for $c = 1$ for model 694. The optimization was canceled and started again with a value of $c = 5$ which leaded to a successful optimization. For the other two models the starting point was one.

Performance Measure

In Figure A.7 to A.9 Nash-Sutcliffe scores of a the different calibration methods for every single site are shown. Model performance varies between sites. It can be shown, if the global optimum result in a high value for the Nash-Sutcliff score then values for the other methods are also high. In contrast the lower the Nash-Sutcliff of the global optimum, the lower it is for the other methods. This in general can be related to weakness of the model formulation. Generally, the model 630 (seperate tension storage) shows the best performance with regard to the mean Nash-Sutcliffe-score of 0.71 . This is true for the automatic methods as well as for the visual calibration.

The worse performance is found for Pukekohe with a Nash-Sutcliffe of under 0.5 for all models. This site has a high clay content and it is assumed that macropore flow within cracks is a leading process which is not implemented in the conceptual models that are used here.

There are several sites with a Nash-Sutcliff of 0.6 to 0.8 for a global optimum. These sites are Lauder, Middlemarch, Musselburgh, Paraparaumu, Ranfurly and Stratford. Lauder, Middlemarch and Ranfurly share a similar climate which is semi-arid. Apparently, the conceptual models do not cover processes of soils that experience such a climate. Further Lauder, Middlemarch and Musselburgh share a dense root mat within the first 100 mm of the soil profile. Processes that occur in this layer are not covered by the model. It is also possible that there are uncertainties related to the soil moisture measurement. There is a possibility of evaporation or water storage in this layer which is not measured.

Both Stratford and Paraparaumu experience a annual rainfall that is close to 1000 mm or higher. Also the composition of these soils is different to the others. Stratford has pumice inclusions which is related to parent material. This means volcanic ash or weathering products of volcanic rocks. As a consequence water flow and storage within this soil is controlled by features of this inclusions. The Paraparaumu site has a deep soil profile and a sand matrix. It was found that percolation or infiltration to deeper parts of this soil is most likely controlled by the water content in the lower layer during the wet season. With different values for the percolation rate it could be shown that other parts during the wet season fit to the observation data. This is an indication that the percolation rate changes during this season. Further a model structure that provides the possibility of a lower zone control was tested (not shown). This model structure reduced the underestimation compared to the other models at the end of the wet season.

7.1.3. Parameter Sensitivity

The results of the MCMC simulation illustrated that there are general features regarding parameter sensitivity and interrelations. This is discussed in the next sections.

Field capacity and Maximum Water Retention

In most cases $S_{1,max}$ and θ_{tens} show a strong relationship to each other for model 694 (gravity drainage). This is shown in Figure 6.1. Exception are found for Appelby, Kaitaia, Paraparaumu, Pukekohe and Stratford. All of these sites show a similar pattern as shown in Figure A.13. This relationship between $S_{1,max}$ and θ_{tens} shown in Figure 6.2 of model 630 (seperate tension storage) was found for most of the sites. Exception were found for Appelby, Kaitaia, Pukekohe, Stratford and Windsor. The relationship between $S_{1,max}$ and θ_{tens} of these exception is similar to that in Figure A.13. This interrelation can be related to water flux induced by evapotranspiration. The parameter θ_{tens} in model defines the size of the bucket from which evapotranspiration demand is provided. A low value of θ_{tens} can be compensated by an high value of $S_{1,max}$. For the exceptions that are found for model 694 a lack of this interrelation can be associated with the aridity index

R that is one or lower. Appelby has an higher value of R, but the particular situation of this sites result in a good water availability through out the year. It was found for model 694, the higher the aridity index the stronger the interrelation between these two parameter (not shown). The same was found for model 630 but here this interrelation is stronger developed. In general model 632 shows a similar behaviour as model 630. However, Model 632 does not show a linear relationship for six sites (Kaitaia, Lauder, Musselburgh, Pukekohe, Stratford, Windsor). Parameters derived by parameter sampling or automatic optimization show in all cases unrealistic values within the boundaries.

Percolation

The percolation rate defines the amount of water that can flow from the upper layer as recharge to the lower layer reservoir. With regard to results of the MCMC simulations it should be noted that this parameter becomes insensitive at a certain threshold. This is especially true for model 630 and 632. For the model with gravity drainage (694) the percolation in catchment (Lauder, Lincoln, Middlemarch, Ranfurly ,Rangiora, Windsor) is close to zero. This is true for the global optimum as well as for the visual interpretation. Except for Lincoln and Rangiora the Nash-Sutcliff is lower 0.8 for the global optimum. For the sites Lauder, Lincoln and Middlemarch this can be related to the semi-arid climate. Most likely percolation does not influence the soil moisture behaviour because of a lack of water input. The dominating process at this sites that affect soil moisture is evapotranspiration.

The low value at Windsor can be related to the increase of penetration resistance with depth. Low values were also found for Appelby and Blenheim. Appelby is a gley soil with an impeding layer at a depth of about 650 mm. A similar pattern is found at Blenheim where visually calibrated a slightly higher value for percolation was found (refer to section 6.4.1). However, the percolation exponent is used at this sites to reduce the rate of percolation from the tension storage.

For the Paraparaumu site was found, percolation is probably controlled by the water demand of lower parts of the profile. Sensitivity to the parameter defining the percolation rate implied, the rate of water flux to the lower layer decreases during the end of the wet season. With a model structure that covers the feature of a lower zone control the underestimation of the end of the wet season could be reduced.

The percolation exponent was found to be most sensitive for model structure 694 (gravity drainage). On the basis of the the visual calibration it was found, for every site the percolation exponent is set to unity for models with tension storage. The approach to relate the parameter k to the percolation exponent c for the model 694 could not be explicitly defined. In table A.1 to table A.18 values of k were calculated for the years 2000 to 2006. It is found that the relationship between k of the simple water balance equation

4.4 and the percolation exponent of model 694 for some years can be defined with the following equation:

$$c = k * 10^2 \tag{7.1}$$

However, this relationship can not be related to soil properties or climate pattern. Further this relationship appears in a random pattern. The water balance equation 4.4 describes a linear relationship between rainfall and antecent moisture content. In contrast equation 5.7 describes a exponential relationship between the relative soil moisture content and the percolation exponent. Maybe a particular combination of soil moisture and rainfall pattern result in a similar behaviour of these two equations. Another reason for the failing attempt to represent soil response with a linear equation is that there is no evapotranspiration considered. A sinus function was fitted to the soil moisture data to erase the annual cycle. Another approach was to use a moving mean over 30 days. Both approaches have not been successful in producing reasonable results for k. In conclusion, the relationship of evapotranspiration and percolation is very complex and can not adequate represented with a linear equation. As mentioned above, the models with tension storage are provided with a percolation exponent set to unity. In these models percolation and evapotranspiration are treated in two different domains. There is one bucket for percolation and another for evapotranspiration. Percolation from the free storage is represented with a linear equation. But evapotranspiration processes are represented within a separate tension storage. For the model with gravity drainage there is a need of a exponential function to account for processes related to the tension storage. This illustrates how improvement of conceptual models lead to a better process representation in a system of complex interactions.

Evapotranspiration

Evapotranspiration has a strong influence on soil moisture. Effects of plant root uptake are very complex and interrelated to soil properties. In contrast model structures that are used here consider simple assumption to mimic interactions between soil water and evapotranspiration (refer to section 5). However, the analysis of hydrological soil response to rainfall and evapotranspiration with different conceptual models brought more insights into processes. It was found, interpretation of parameter sensitivity can be usefull to identify possible interaction between soil properties and hydrological soil response.

As discussed in section 7.1.1 a relationship was found between hydrological soil response and soil development. The evidence of this relationship can be shown in more detail with the model 632 (cascading buckets). It is possible to relate the parameter θ_{rchr} to the percentage of soil development. The adjustment of this parameter improved agreement with the observed data mainly in the dry seasons for sites with a pedality in the toplayer higher 50 %. This observation is consistent with a concept of Braudeau & Mohtar (2009).

The example of the Rangiora site illustrates that there is also a relationship between the overestimated wetting-up period and the parameter θ_{rchr} (refer to Figure 6.9). Water distribution within the soil matrix could be underestimated by the measurement if water distributes only the first centimeters of the soil column. Further, interaction between matrix and soil aggregation regarding water distribution and evapotranspiration and their representation in rainfall runoff models needs more detailed investigation.

7.1.4. Regionalisation

Soil orders integrate information about soil genesis and climate. The groups in section 6.3 illustrate that there are similarities between soil genesis, climate and hydrological soil response. Information of soil type genesis and climate patterns can be transfered to soil locations with similar history. This information brings more insides into the choice of parameters and the choice of model structure. For all model structures that were used here a general trend exist regarding model performance. As can be shown in Figure A.7 to Figure A.9 there are sites with a Nash-Sutcliffe score which reaches a similar value for all model structures. Further this trend exist for all of the four different parameters. Thus performance of these models is related to soil properties. It is interesting to note that each model shows a similar performance when calibrated to a global optimum.

Derived parameters of $S_{1,max}$ and θ_{tens} can be useful transfered to parameters of conceptual models. These values are consistent with observations made in other studies (Rawls et al., 1982). If there is no time series available than parameter ranges could be defined by the use of literature values or a random parameter set can be used for sites that have similarities with those discussed later. It was found that knowledge a priori of a pedological survey could be useful transfered into a conceptual idea of hydrological processes within the soil column. Further quantitative parameter estimates based on soil information can be made for $S_{1,max}$, θ_{tens} and θ_{rchr}. It was found that percolation rate can only be estimated qualitative. Further this value, for models with tension storage, shows a threshold behavior as discussed earlier.

A default parameter set was defined on a basis of virtual experiments with the visual interface of FUSE. It was found, 11 of 17 sites modeled with model 630 (separated tension storage) provided with a random parameter set result in an output with an Nash-Sutcliffe above 0.6 . At least seven sites with the same configuration have a Nash-Sutcliffe above 0.7 . This illustrates that equifinality in some cases can be used to account for heterogenity in soil properties on the catchment scale.

8. Conclusion

This study introduced a new methodology to evaluate model structure performance of rainfall-runoff model in more detail. The evaluation of internal states of different rainfall runoff models against observation brought more insights of model structure deficits. It is shown that pedological knowledge can be used to provide these conceptual models with parameters on a physical basis. Automatic optimization methods showed no reasonable parameter sets. This methods produce a good agreement with the data based in the objective measure. In this regard interpretation of parameters would bring no insights into process understanding.

Common used methods to calibrate models showed that there is a general trend regarding model performance. An improved understanding about uncertainties that arise from model structural differences and parameter uncertainty can be achieved by usage of visual calibration via an suitable interface. It was found that a more detailed evaluation of single structures in rainfall runoff models brings more insights to parameter uncertainty and model structural deficits.

Similarities of hydrological soil response on a temporal basis were found for sites with similar structure but different texture. Further evaluations with more complex model structures are needed. The Framework for Understanding Structural Errors should be expanded with more conceptual models. Based on the findings in this study it seems to be reasonable linking soil hydraulic properties with their genetic history.

Conceptual ideas of various hydrological processes such as preferential flow could be added to consider these process in the context of different conceptual model structures. Further it would be useful to collect findings of different experts in a central hydrological database. This relational database should be organized in an order of hydrological features. Further there should be relationships between hydrological features and conceptual models.

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Bibliography

Allen, T., Allen, P., & Wixon, D. (2009). Hierarchy theory in hydropedology. *Hydrology and Earth System Sciences Discussions*, *6*, 2931–2959.

Bai, Z., Wagener, T., & Reed, P. (2009). A top-down framework for watershed model evaluation and selection under uncertainty. *Environmental Modelling & Software*, *24(8)*, 901 – 916.

Beven, K. (2002). Towards an alternative blueprint for a physically based digitally simulated hydrologic response modelling system. *Hydrological processes*, *16*(2), 189–206.

Beven, K. (2005). *Rainfall-Runoff Modelling*. Wiley.

Beven, K. (2006). A manifesto for the equifinality thesis. *Journal of Hydrology*, *320*(1-2), 18–36.

Beven, K. & Freer, J. (2001). Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of Hydrology*, *249*(1-4), 11–29.

Braudeau, E. & Mohtar, R. (2009). Modeling the soil system: Bridging the gap between pedology and soil-water physics. *Global and Planetary Change*, *67*(1-2), 51–61.

Brocca, L., Melone, T., Moramarco, T., & Morbidelli, R. (2009). Soil moisture temporal stability over experimental areas in Central Italy. *Geoderma*, *148*, 364–374.

Brocca, L., Melone, T., Moramarco, T., & Singh, V. (2009). Assimilation of Observed Soil Moisture in Storm Rainfall-Runoff Modelling. *Journal of Hydrologic Engineering*, 153–165.

Brocca, L., Morbidelli, R., Melone, F., & Moramarco, T. (2007). Soil moisture spatial variability in experimental areas of central Italy. *Journal of Hydrology*, *333*(2-4), 356–373.

Buytaert, W. & Beven, K. (2009). Regionalization as a learning process. *Water Resources Research*, *45*(11), W11419.

Carpenter, T. & Georgakakos, K. (2006). Intercomparison of lumped versus distributed hydrologic model ensemble simulations on operational forecast scales. *Journal of Hydrology*, *329*(1-2), 174–185.

Choi, H. & Beven, K. (2007). Multi-period and multi-criteria model conditioning to reduce prediction uncertainty in an application of TOPMODEL within the GLUE framework. *Journal of Hydrology*, *332*(3-4), 316–336.

Clark, M. & Kavetski, D. (revised March 2010). The acient numerical daemons of conceptual hydrological models part 1: Fidelity and efficiency of time stepping schemes. *Water Resources Research*.

Clark, M., McMillan, H., Collins, D., Kavetski, D., & Woods, R. (submitted March 2010). Hydrological field data from a modellers perspective part 2. process-based model evaluation. *Hydrological Processes*.

Clark, M., Slater, A., Rupp, D., Woods, R., Vrugt, J., Gupta, H., Wagener, T., & Hay, L. (2008). Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models. *Water Resources Research*, *44*, W00B02.

Dalton, F. & Van Genuchten, M. (1986). The time-domain reflectometry method for measuring soil water content and salinity. *Geoderma*, *38*(1-4), 237–250.

Greenberg, S. (1995). Understanding the Metropolis-Hastings Algorithm. *The American Statistician*, *49*(4), 327–335.

Hallikainen, M., Ulaby, F., Dobson, M., El-Rayes, M., & Wu, L. (1985). Microwave dielectric behavior of wet soil-part 1: empirical models and experimental observations. *IEEE Transactions on Geoscience and Remote Sensing*, 25–34.

Hewitt, A. (1998). *New Zealand Soil Classification*. Manaaki Whenua Press.

Ichythus (2008). Representativeness of NIWA Soil Moisture Sensors: Eastern Sites. Technical report, Confidential to NIWA.

Kavetski, D. & Clark, M. (revised March 2010). The acient numerical daemons of conceptual hydrological models part 2: Impact of time stepping schemes on model analysis and prediction. *Water Resources Research*.

Kavetski, D., Kuczera, G., & Franks, S. (2003). Semidistributed hydrological modeling: A saturation path perspective on TOPMODEL and VIC. *Water resources research*, *39*(9), 1246.

Kavetski, D., Kuczera, G., & Franks, S. (2006). Bayesian analysis of input uncertainty in hydrological modeling: 1. Theory. *Water Resources Research*, *42*(3), W03407.

Kopmann, G. (2009). Diplomarbeit ueber die beurteilung der datenqualitaet des neuseelaendischen bodenfeuchtigkeitssensornetzwerkes und deren nutzung fr die simulation der bodenfeuchtigkeit mit der wasserhaushaltsgleichung.

Laio, F., Porporato, A., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress:: II. Probabilistic soil moisture dynamics. *Advances in Water Resources*, *24*(7), 707–723.

Lawrence, J. & Hornberger, G. (2007). Soil moisture variability across climate zones. *Geophys. Res. Lett*, *34*, L20402–L20402.

Lin, H. (2009). Earths Critical Zone and hydropedology: concepts, characteristics, and advances. *Earth*, *6*, 3417–3481.

Lin, H., Brooks, E., McDaniel, P., & Boll, J. (2008). Hydropedology and Surface/Subsurface Runoff Processes. *Encyclopedia of Hydrologic Sciences. edited by: Anderson, MG, John Wiley & Sons, Ltd., doi*, *10*(0470848944), 1–25.

Liu, Y. & Gupta, H. (2007). Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. *Water Resources Research*, *43*, W07401.

McDonnell, J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M., et al. (2007). Moving beyond heterogeneity and process complexity: a new vision for watershed hydrology. *Water Resources Research*, *43*(7), W07301.

McKerchar, A. & Henderson, R. (2003). Shifts in flood and low-flow regimes in New Zealand due to interdecadal climate variations/Variations dans les régimes de crue et de basses eaux en Nouvelle-Zélande dues à des variations climatiques inter-décennales. *Hydrological Sciences Journal*, *48*(4), 637–654.

McMillan, H., Clark, M., Bowden, W., Duncan, M., & Woods, R. (submitted March 2010). Hydrological field data from a modellers perspective part1. diagnostic tests for model structure. *Hydrological Processes*.

Merz, R. & Bloeschl, G. (2004). Regionalisation of catchment model parameters. *Journal of Hydrology*, *287*(1-4), 95–123.

Milly, P. (1994). Climate, soil water storage, and the average annual water balance. *Water Resources Research*, *30*(7), 2143–2156.

Molloy, L. (1998). *The living mantel* (second ed.). Mallinson Rendal Publisher Ltd., Wellington.

Mosley, M. (2000). Regional differences in the effects of El Niño and La Niña on low flows and floods/Variabilité régionale des effets de El Niño et de La Niña sur les crues et les étiages. *Hydrological Sciences Journal*, *45*(2), 249–267.

Mullan, A. (1998). Southern hemisphere sea-surface temperatures and their contemporary and lag association with New Zealand temperature and precipitation. *International journal of climatology*, *18*(8), 817–840.

Pauwels, V., Hoeben, R., Verhoest, N., & De Troch, F. (2001). The importance of the spatial patterns of remotely sensed soil moisture in the improvement of discharge predictions for small-scale basins through data assimilation. *Journal of Hydrology*, *251*(1-2), 88–102.

Porporato, A., Laio, F., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress:: III. Vegetation water stress. *Advances in Water Resources*, *24*(7), 725–744.

Qiu, Y., Fu, B., Wang, J., & Chen, L. (2001). Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. *Journal of Arid environments*, *49*(4), 723–750.

Rawls, W., Brakensiek, D., & Saxton, K. (1982). Estimation of soil water properties. *Trans. Asae*, *25*(5), 1316–1320.

Rodriguez-Iturbe, I., Porporato, A., Laio, F., & Ridolfi, L. (2001). Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress:: I. Scope and general outline. *Advances in Water Resources*, *24*(7), 695–705.

Salinger, M. (1980). New Zealand climate: I. Precipitation patterns. *Monthly weather review*, *108*(11), 1892–1904.

Salinger, M., Renwick, J., & Mullan, A. (2001). Interdecadal Pacific oscillation and south Pacific climate. *International Journal of Climatology*, *21*(14), 1705–1721.

Seibert, J. (1999). Regionalisation of parameters for a conceptual rainfall-runoff model. *Agricultural and Forest Meteorology*, *98*(1), 279–293.

Seibert, J. (2000). Multi-criteria calibration of a conceptual runoff model using a genetic algorithm. *Hydrology and Earth System Sciences*, *4*, 215–224.

Seibert, J. & Beven, K. (2009). Gauging the ungauged basin: how many discharge measurements are needed? *Hydrol. Earth Syst. Sci*, *13*, 883–892.

Seibert, J. & McDonnell, J. (2002). On the dialog between experimentalist and modeler in catchment hydrology: use of soft data for multicriteria model calibration. *Water Resources Research*, *38*(11), 1241.

Shanley, J., Hjerdt, K., McDonnell, J., & Kendall, C. (2003). Shallow water table fluctuations in relation to soil penetration resistance. *Ground Water*, *41*(7), 964–972.

Starks, J., C.G., H., Jackson, T., & Cosh, M. (2006). Temporal stability of soil moisture profile. *Journal of Hydrology*, *324*, 400 – 411.

Svetlitchnyi, A., Plotnitskiy, S., & Stepovaya, O. (2003). Spatial distribution of soil moisture content within catchments and its modelling on the basis of topographic data. *Journal of Hydrology*, *277*(1-2), 50–60.

Tait, A., Henderson, R., Turner, R., & Zheng, X. (2006). Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology*, *26*(14), 2097–2115.

Thornthwaite, C. (1948). An approach toward a rational classification of climate. *Geographical review*, *38*(1), 55–94.

Uhlenbrook, S., Seibert, J., Leibundgut, C., & Rodhe, A. (1999). Prediction uncertainty of conceptual rainfall-runoff models caused by problems in identifying model parameters and structure/Incertitude de prevision d'un modèle conceptuel pluie-débit due à l'identification des paramètres et de la structure du modèle. *Hydrological Sciences Journal*, *44*(5), 779–797.

Wagener, T., McIntyre, N., Lees, M., Wheater, H., & Gupta, H. (2003). Towards reduced uncertainty in conceptual rainfall-runoff modelling: Dynamic identifiability analysis. *Hydrological Processes*, *17*(2), 455–476.

Wagener, T., Sivapalan, M., Troch, P., & Woods, R. (2007). Catchment classification and hydrologic similarity. *Geography Compass*, *1*(4), 901–931.

Warrik, A. (2002). *Soil physics companion.*

Weiler, M. (2003). An experimental tracer study of the role of macropores in infiltration in grassland soils. *Hydrological Processes*, *17*, 477 – 493.

Weiler, M. (2005). An infiltration model based on flow variabiltty in macropores: development, sensitivity analysis and applications. *Journal of Hydrology*, *310*, 294 – 315.

Weiler, M. & McDonnell, J. (2004). Virtual experiments: a new approach for improving process conceptualization in hillslope hydrology. *Journal of Hydrology*, *285*, 3 – 18.

Weiler, M. & McDonnell, J. (2007). Conceptualizing lateral preferential flow and flow networks and simulating the effects on gauged and ungauged hillslopes. *Water Resources Research*, *43*(3), W03403.

Western, A., Grayson, R., Bl
"oschl, G., Willgoose, G., & McMahon, T. (1999). Observed spatial organization of soil moisture and its relation to terrain indices. *Water Resources Research*, *35*(3), 797–810.

Western, A., Zhou, S., Grayson, R., McMahon, T., Bl
"oschl, G., & Wilson, D. (2004). Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. *Journal of Hydrology*, *286*(1-4), 113–134.

Wilde, R., Willoughby, E., & Hewitt, A. National soils database.

Woods, R. (2003). The relative roles of climate, soil, vegetation and topography in determining seaonal and long-term catchment dynamics. *Advances in Water Resources*, *26*, 295 – 309.

Woods, R., Hendrikx, J., Henderson, R., & Tait, A. (2006). Estimating mean flow of New Zealand rivers. *Journal of Hydrology(New Zealand)*, *45*(2), 95–110.

Yatheendradas, S., Wagener, T., Gupta, H., Unkrich, C., Goodrich, D., Schaffner, M., & Stewart, A. (2008). Understanding uncertainty in distributed flash flood forecasting for semiarid regions. *Water Resources Research*, *44*(5).

Zolezzi, G., Bellin, A., Bruno, M., Maiolini, B., Siviglia, A., Balistrocchi, M., Grossi, G., Bacchi, B., Chen, C., Minear, J., et al. (2009). On the calibration of hydrological models in ungauged basins: A framework for integrating hard and soft hydrological information. *Water Resour. Res*, *45*(12), W12422.

A. Annex

A.1. Figures

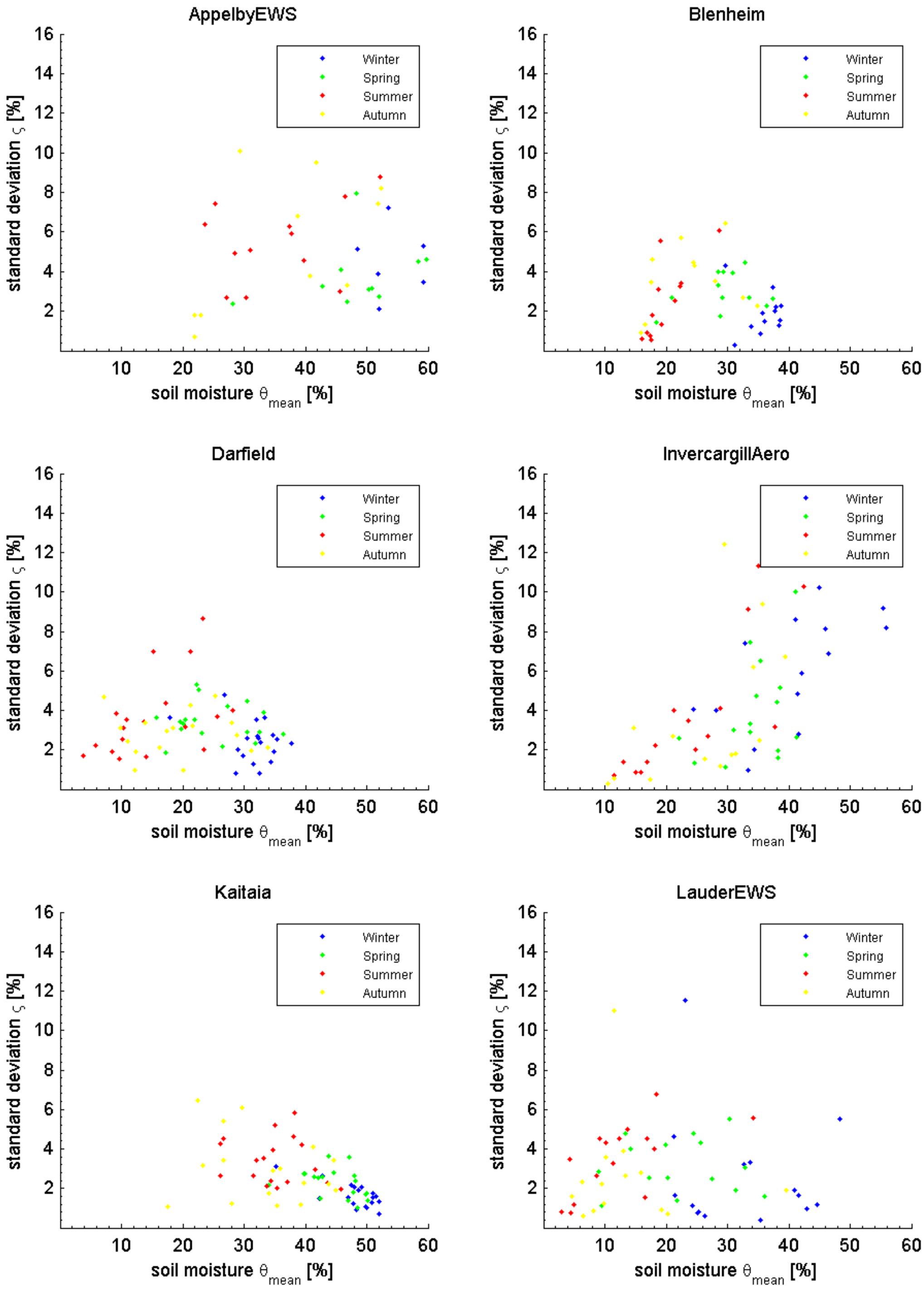

Figure A.1.: Mean soil moisture θ against standard deviation ς for the sites 1 to 6 on a monthly basis. Site Invercargill is a artificial soil and groundwater can reach the sensor. Kaitaia is also influences by water table fluctuation.

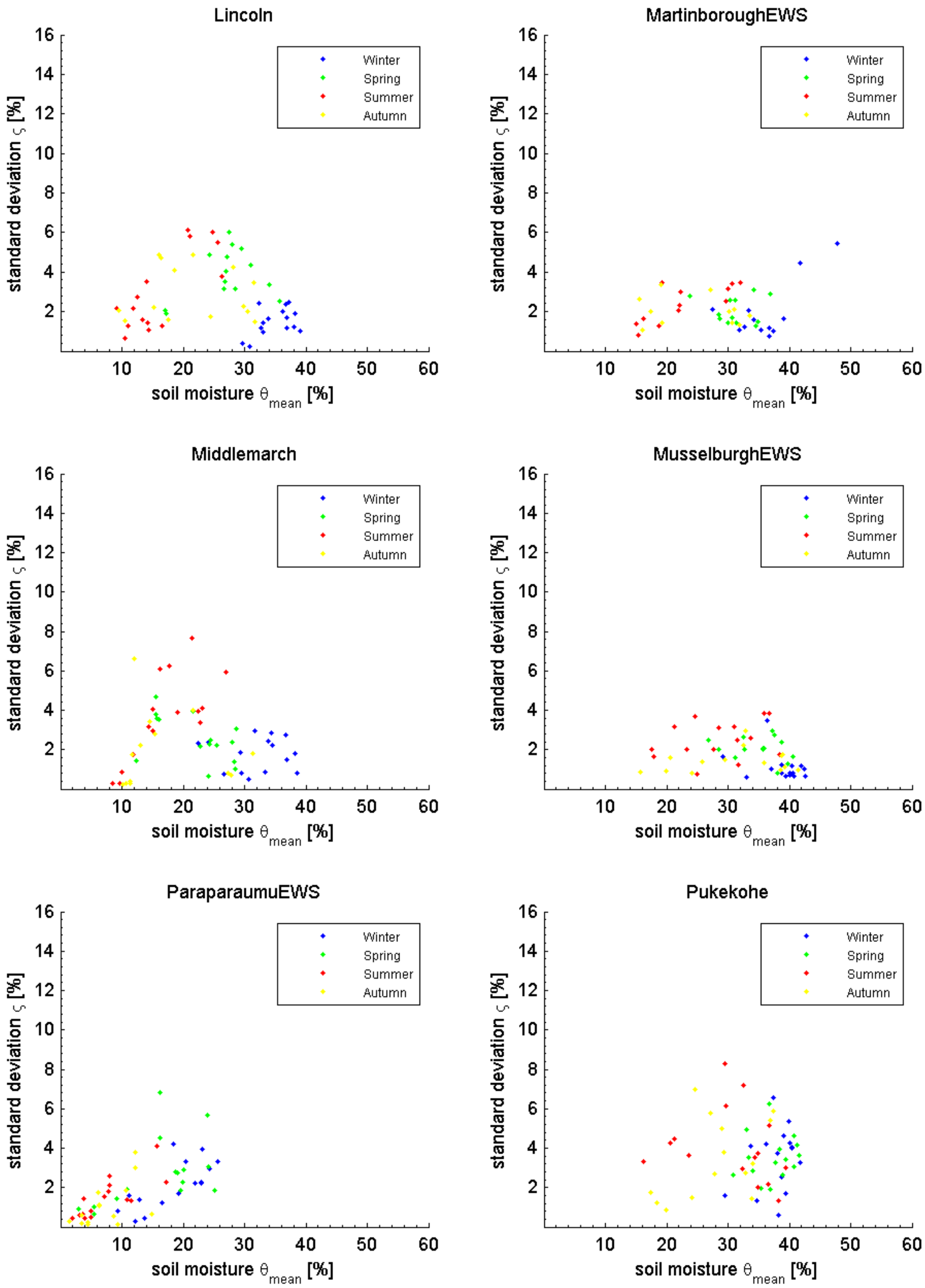

Figure A.2.: Mean soil moisture θ against standard deviation ς for the sites 7 to 12 on a monthly basis.

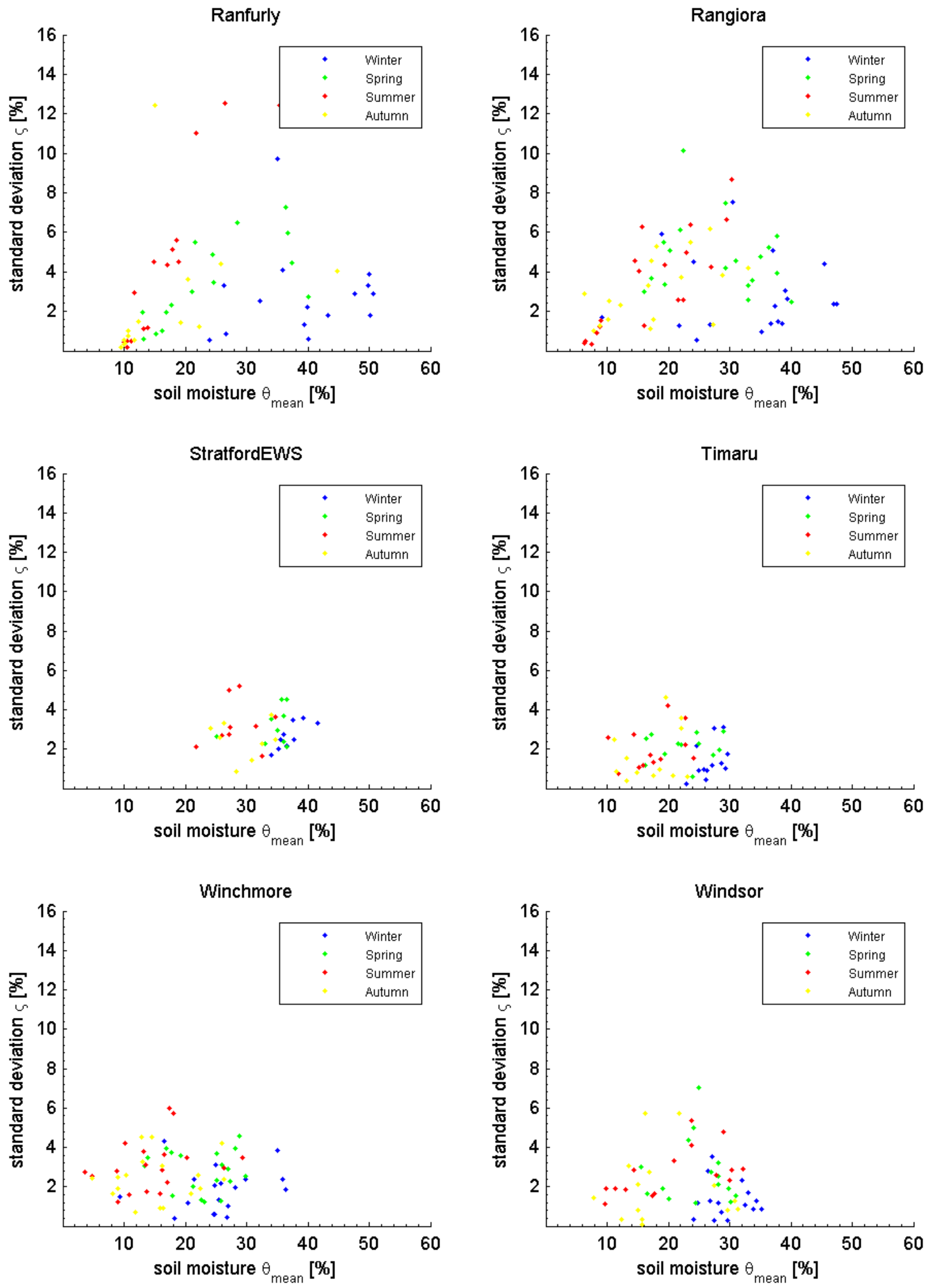

Figure A.3.: Mean soil moisture θ against standard deviation ς for the sites 13 to 18 on a monthly basis.

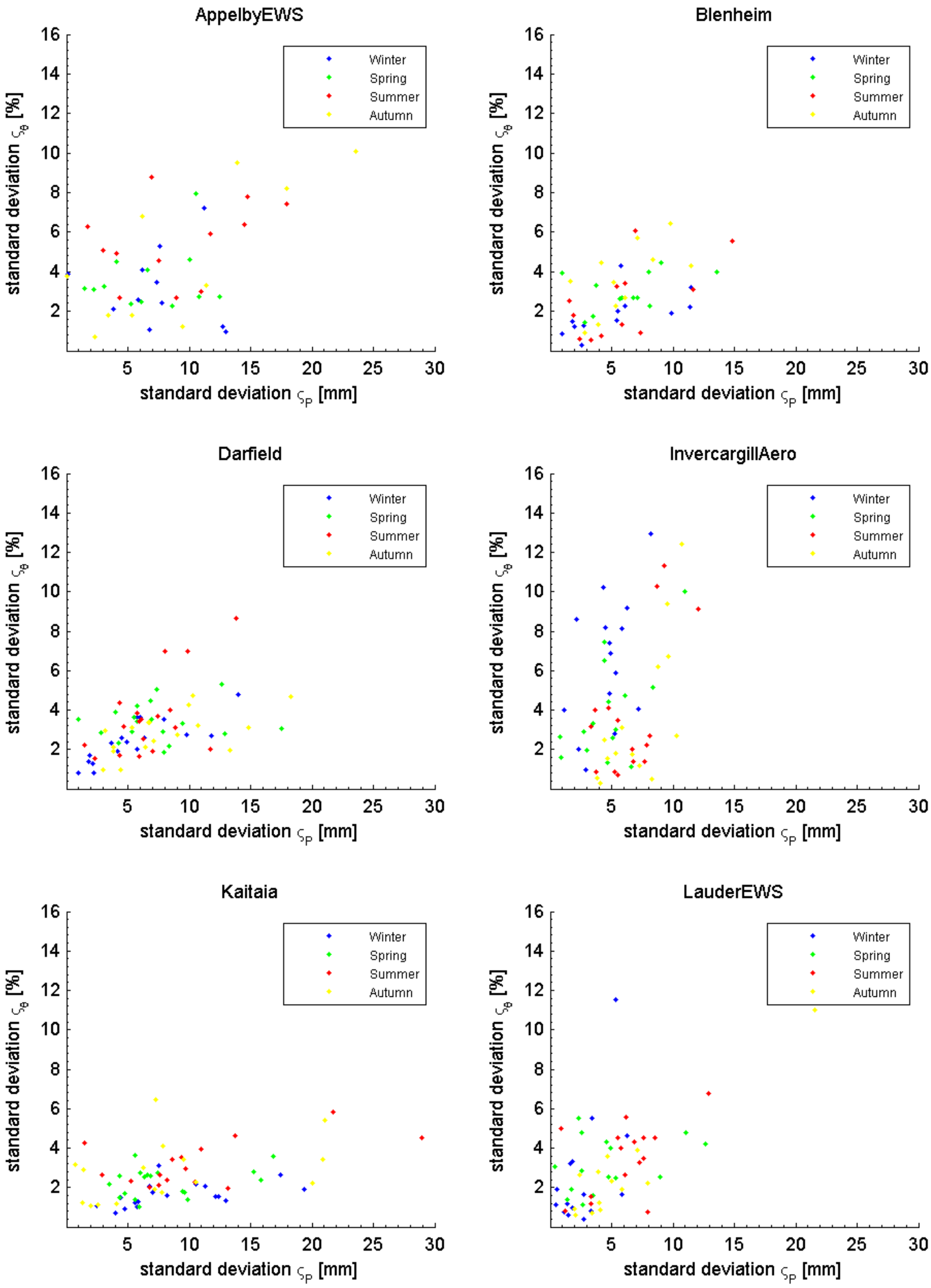

Figure A.4.: Variability of Soil moisture (ς_{soil}) against variability of Rainfall (ς_{prec}) for the sites 1 to 6 on a monthly basis.

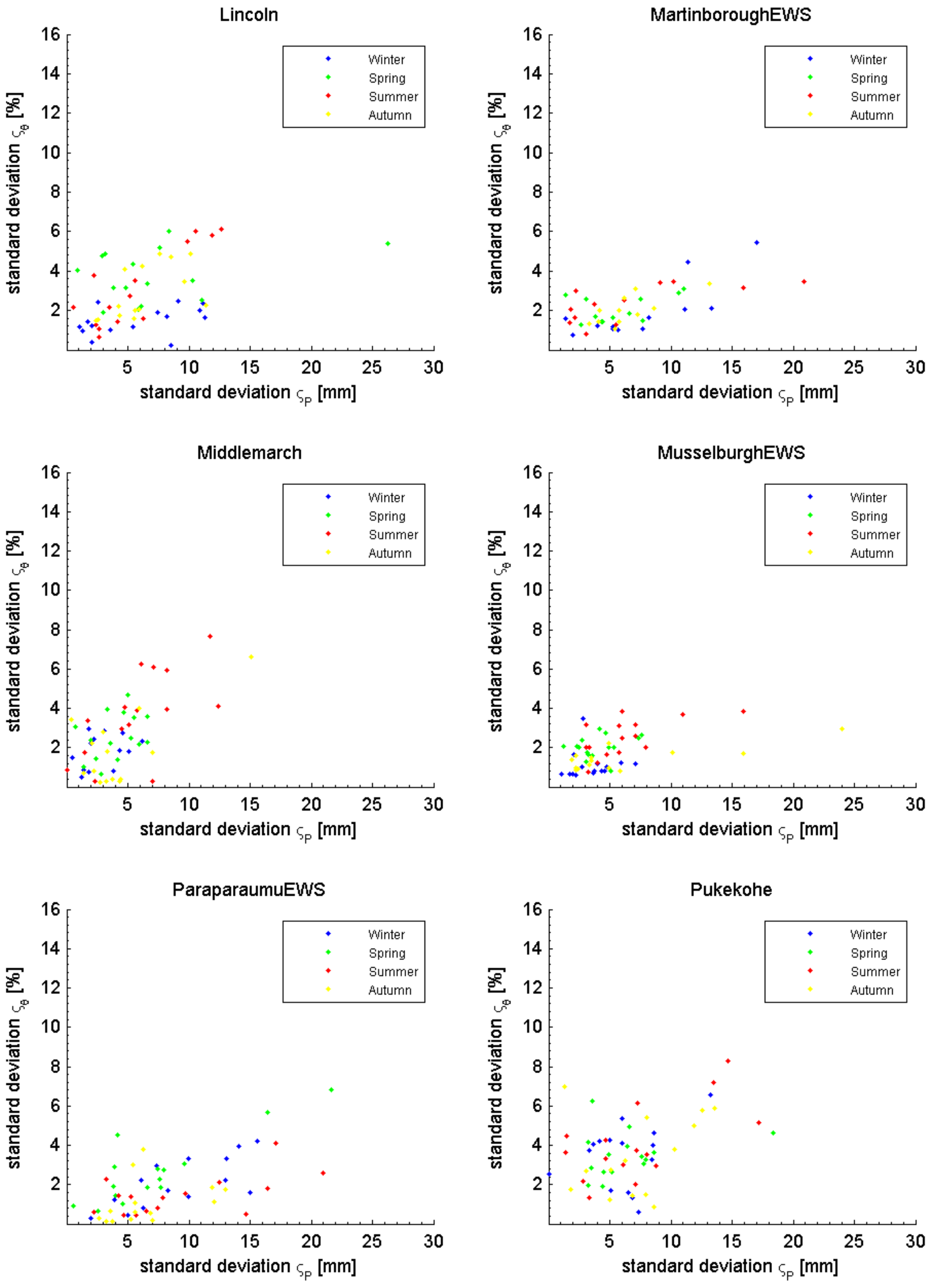

Figure A.5.: Variability of Soil moisture (ς_{soil}) against variability of Rainfall (ς_{prec}) for the sites 7 to 12 on a monthly basis.

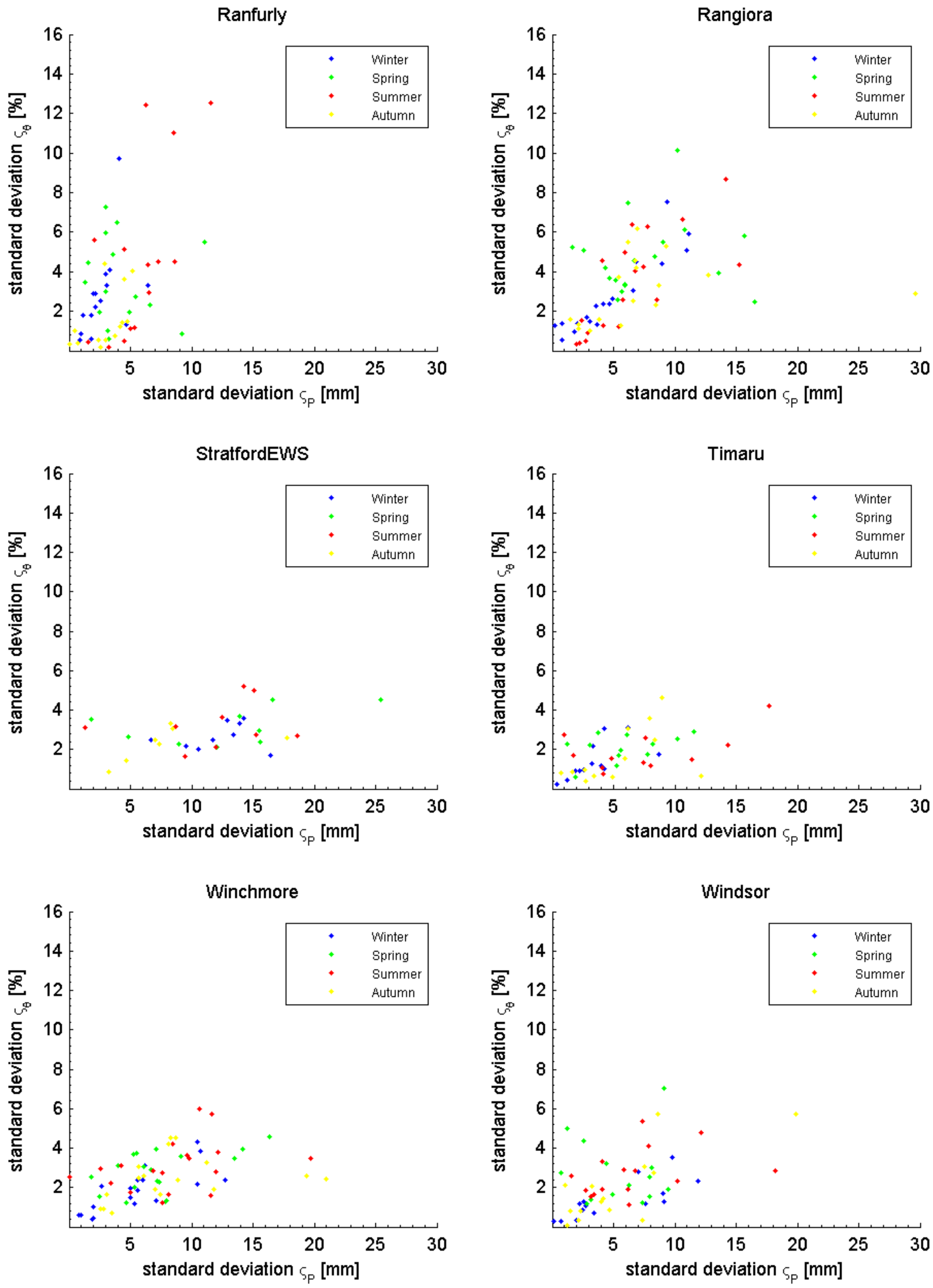

Figure A.6.: Variability of Soil moisture (ς_{soil}) against variability of Rainfall (ς_{prec}) for the sites 13 to 18 on a monthly basis.

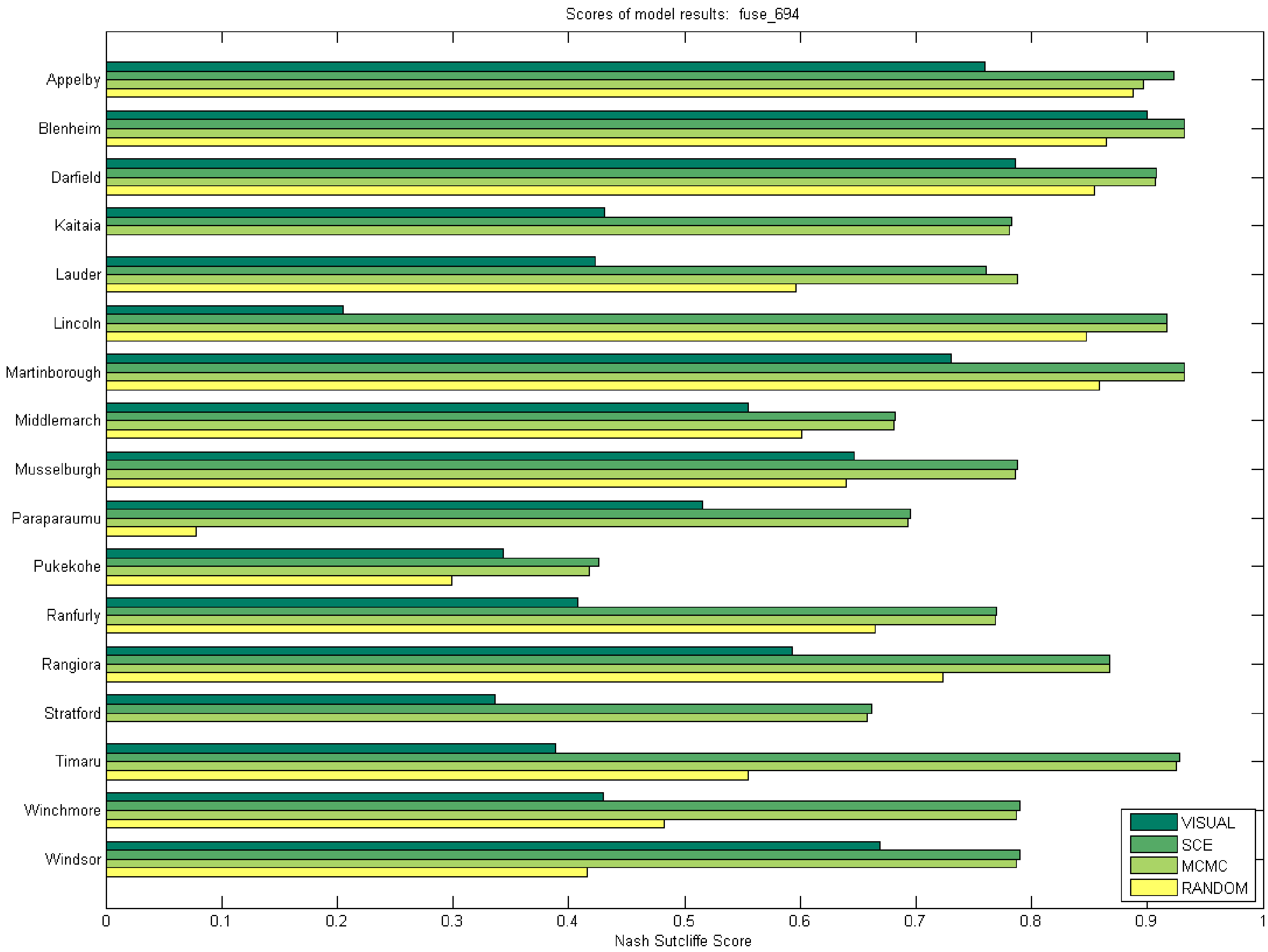

Figure A.7.: Comparison of results of model performance for all sites derived by four different methods.

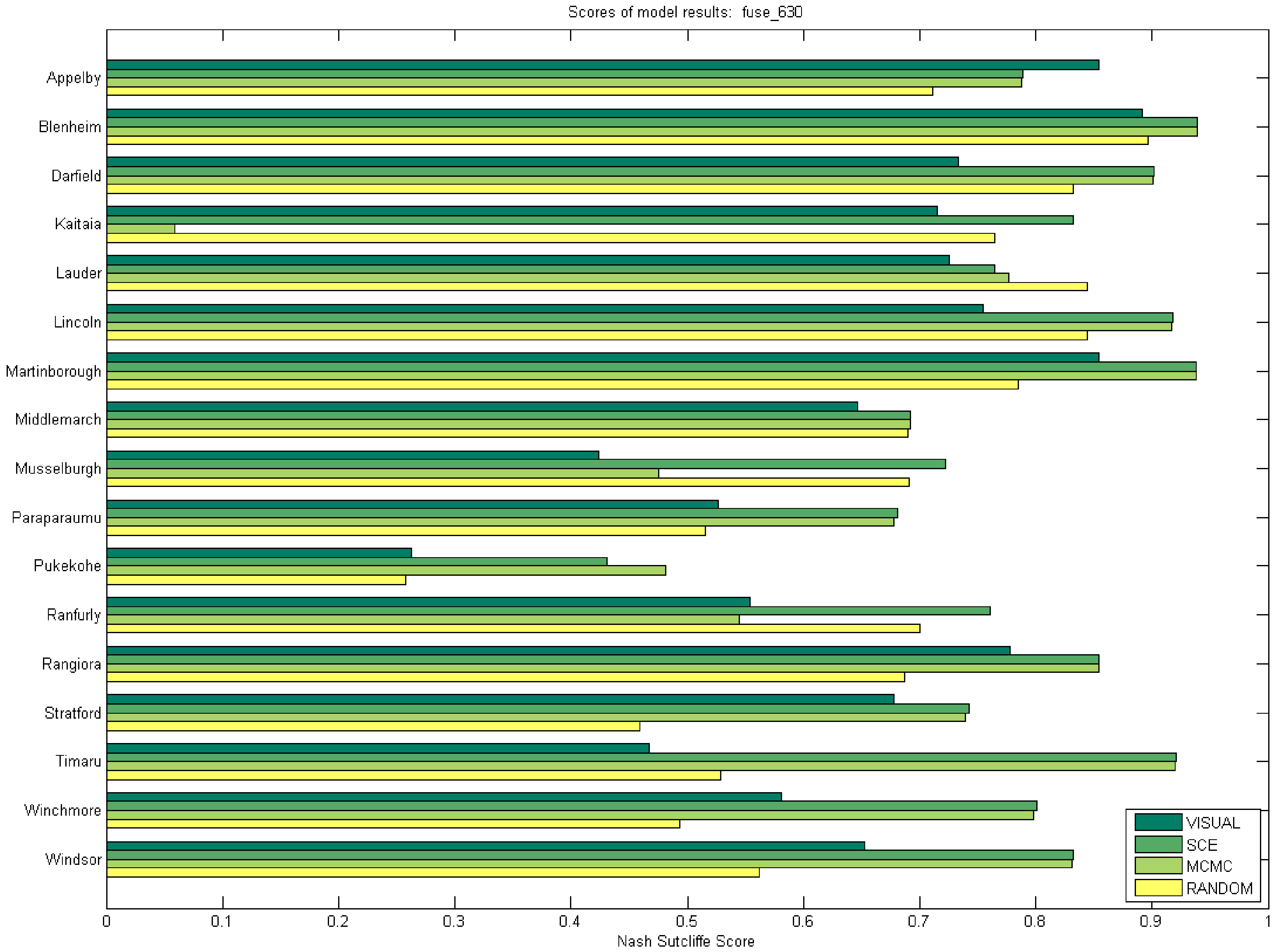

Figure A.8.: Comparison of results of model performance for all sites derived by four different methods.

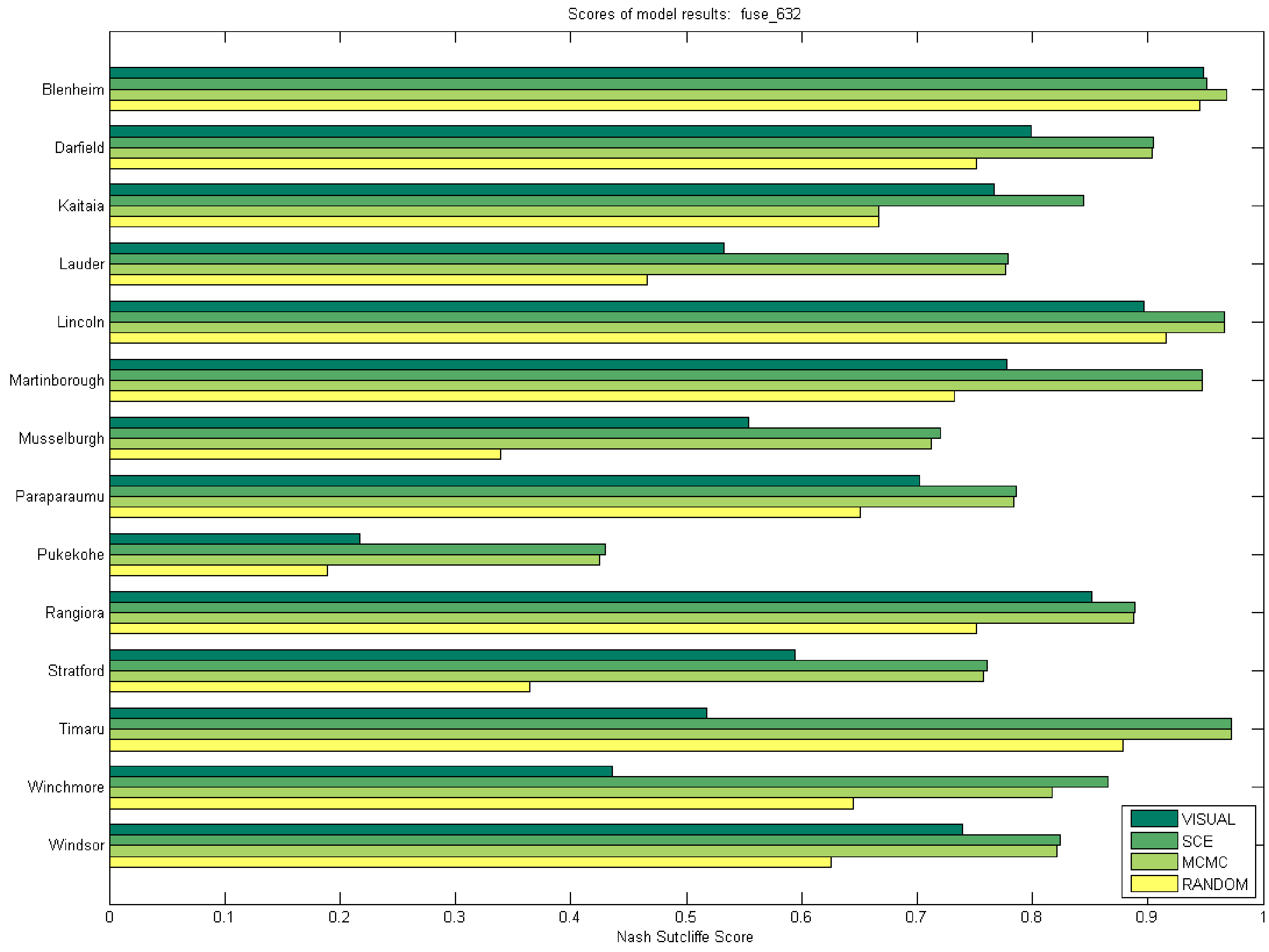

Figure A.9.: Comparison of results of model performance for all sites derived by four different methods.

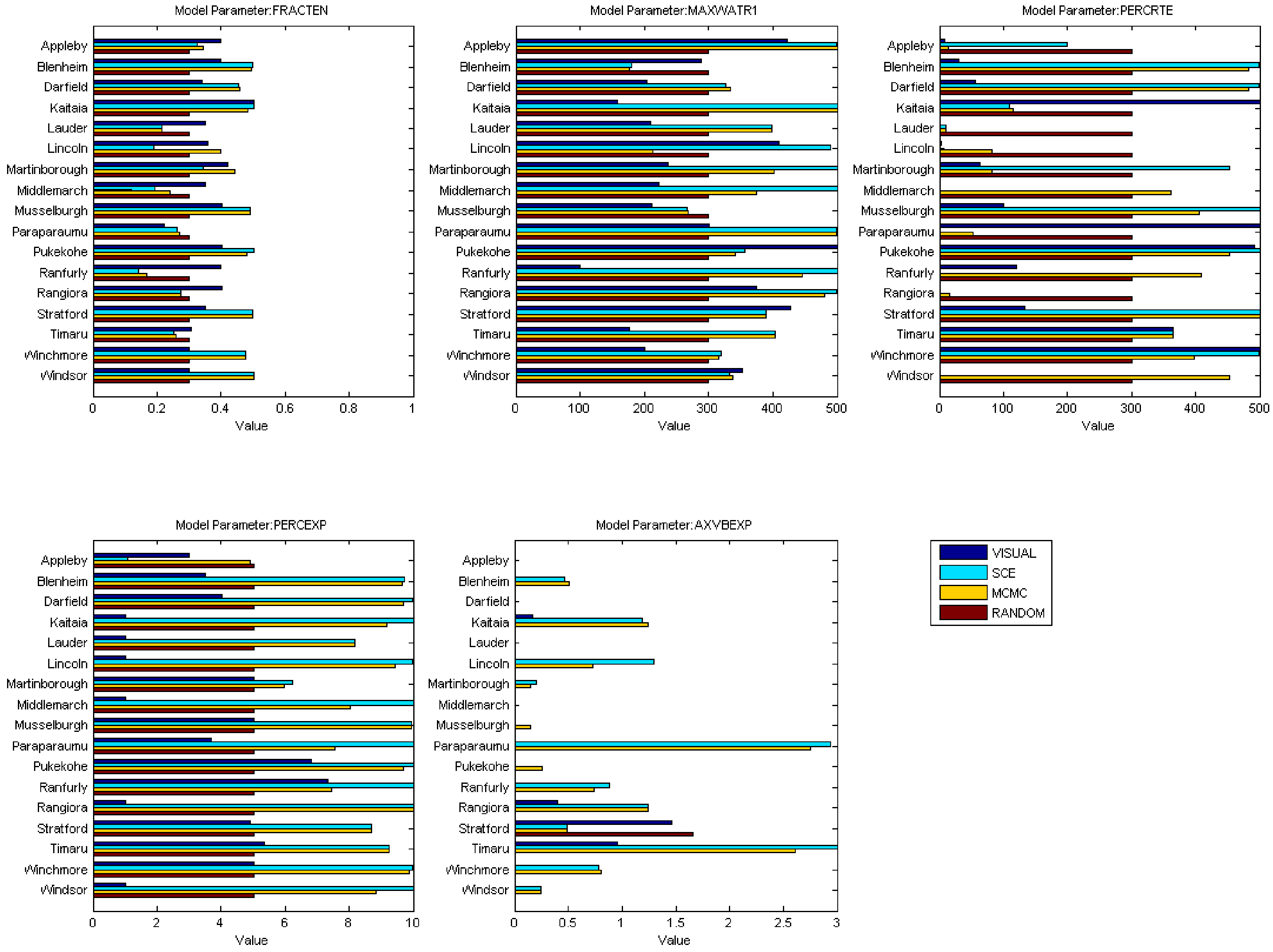

Figure A.10.: Model parameter 694

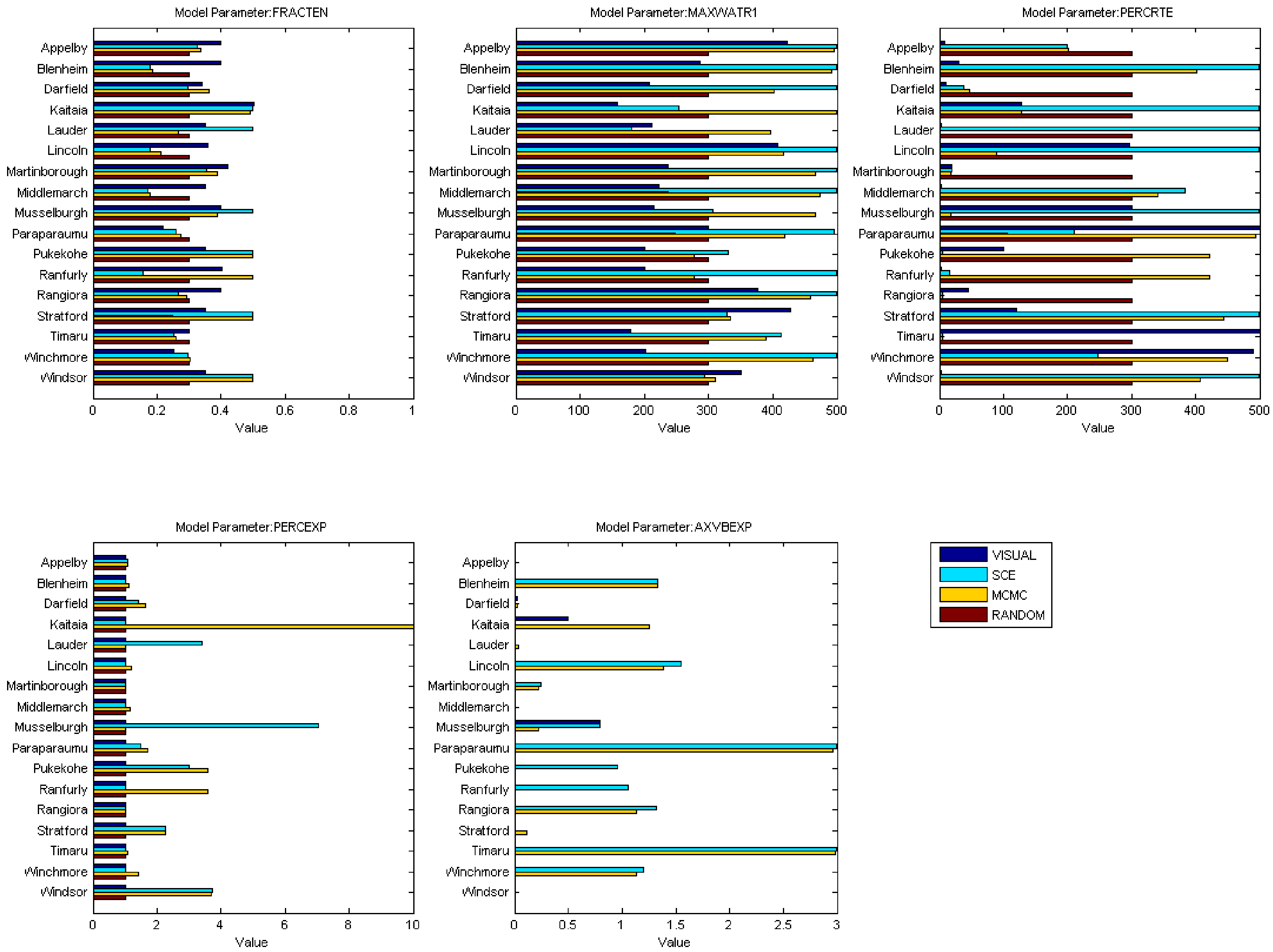

Figure A.11.: Model parameter 630

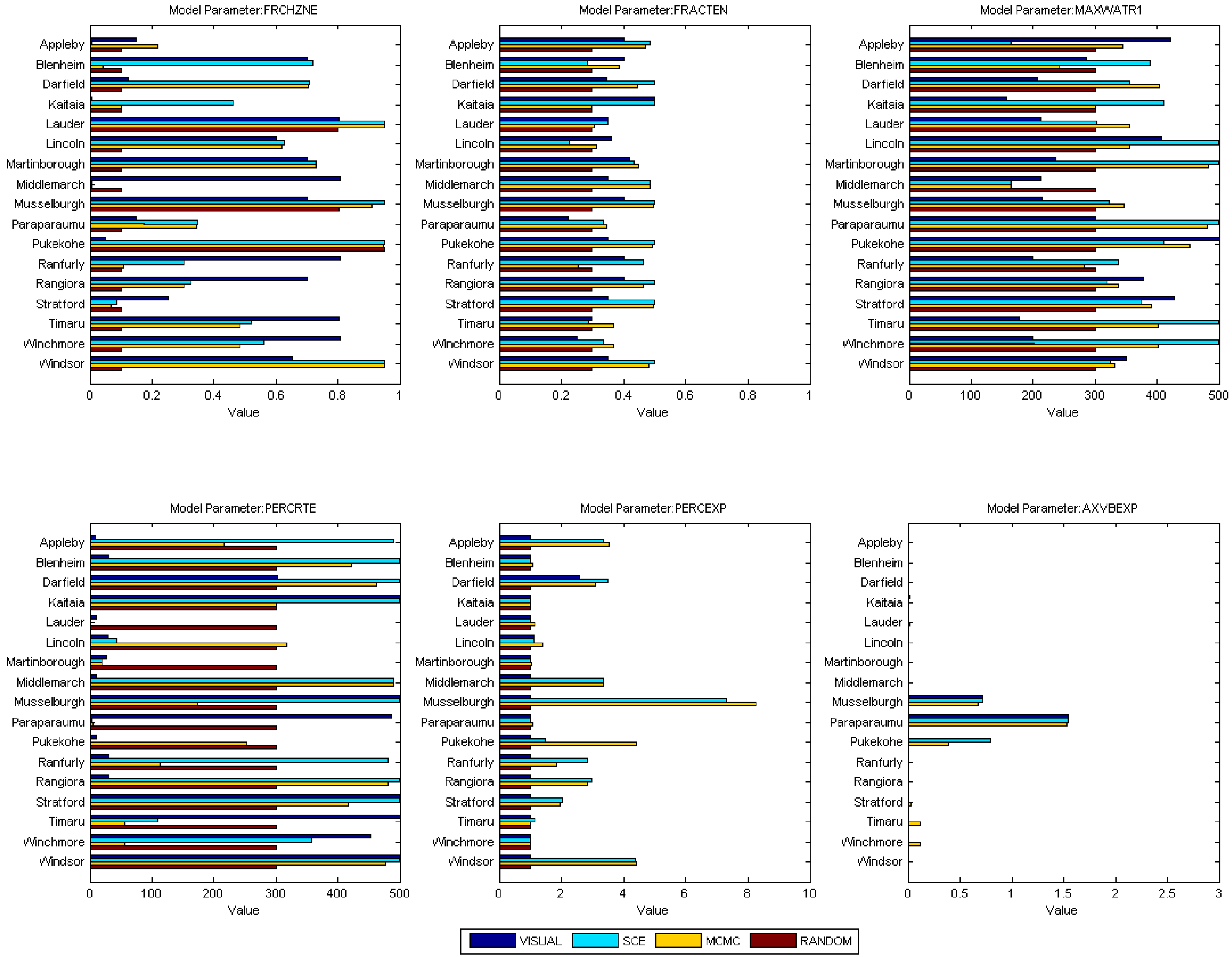

Figure A.12.: Model parameter 632

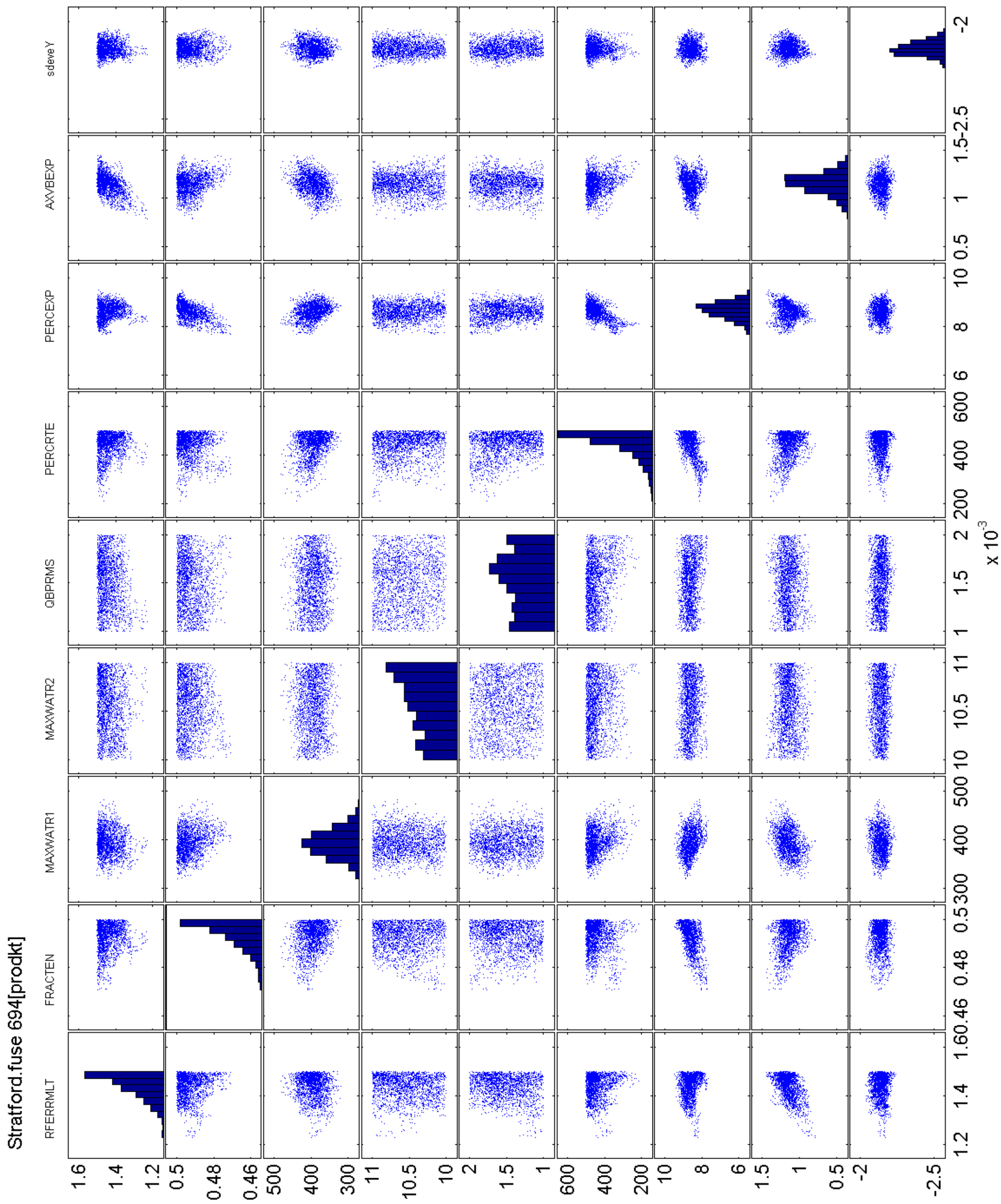

Figure A.13.: 5000 MCMC simulations of model 694 for the Stratford site

A.2. Tables

Table A.1.: Site AppelbyEWS:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	44.03	45.73	52.74	40.75	44.29
$\theta_{max}[\%]$	65.30	64.90	65.60	65.50	65.43
$\theta_{min}[\%]$	17.70	19.60	22.00	19.80	20.80
$\delta_{\theta}[\%]$	14.96	12.20	13.36	13.94	14.16
$FK[\%]$	65.30	64.80	65.49	65.30	65.39

Climate Attributes

Year	2002	2003	2004	2005	2006
$\sum P[mm]$	667.40	1073.20	958.20	735.90	666.60
$\sum pet[mm]$	1049.70	1030.10	990.40	1062.90	1008.20
$P_{max}[mm]$	44.40	93.40	78.10	50.40	51.20
$pet_{max}[mm]$	7.90	7.40	8.70	10.30	8.70
$\delta_P[mm]$	7.77	15.27	11.93	9.25	8.38
$\delta_{pet}[mm]$	1.78	1.91	1.88	2.05	1.84
$P - pet[mm]$	-382.30	43.10	-32.20	-327.00	-341.60
$\theta_{flux}[mm]$	-150.00	305.00	-232.00	150.00	-203.00

Further Indices

Year	2002	2003	2004	2005	2006
R [-]	1.57	0.96	1.03	1.44	1.51
S[-]	0.67	0.71	0.45	2.01	1.28
$k_{*}10^3[d]$	32.87	34.05	97.16	47.04	29.37
$\rho_{spear}[-]$	0.67	0.64	0.53	0.41	0.63

Table A.2.: Site Blenheim:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	27.91	25.11	30.18	26.12	27.57
$\theta_{max}[\%]$	52.30	42.80	44.70	44.80	43.30
$\theta_{min}[\%]$	14.50	15.30	15.30	14.70	14.60
$\delta_{\theta}[\%]$	10.77	7.35	7.88	8.06	8.99
$FK[\%]$	49.46	38.97	42.19	41.75	41.99

Climate Attributes

Year	2002	2003	2004	2005	2006
$\sum P[mm]$	449.60	578.20	713.60	534.30	502.30
$\sum pet[mm]$	1162.50	1131.90	1067.60	1123.10	1100.50
$P_{max}[mm]$	52.00	41.00	41.80	36.80	48.40
$pet_{max}[mm]$	9.60	8.90	8.70	9.10	9.30
$\delta_P[mm]$	8.17	7.20	7.32	7.13	6.48
$\delta_{pet}[mm]$	2.08	2.13	2.03	2.11	2.03
$P - pet[mm]$	-712.90	-553.70	-354.00	-588.80	-598.20
$\theta_{flux}[mm]$	-12.00	50.50	-20.00	71.00	-75.50

Further Indices

Year	2002	2003	2004	2005	2006
R [-]	2.59	1.96	1.50	2.10	2.19
S[-]	1.14	0.66	0.80	0.41	0.82
$k_{*}10^3[d]$	35.76	63.82	99.43	29.58	95.36
$\rho_{spear}[-]$	0.70	0.52	0.62	0.61	0.54

Table A.3.: Site Darfield:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	20.39	21.48	23.93	23.61	24.73	20.95	21.43
$\theta_{max}[\%]$	46.20	38.60	40.20	46.20	43.10	39.90	39.80
$\theta_{min}[\%]$	2.70	4.10	3.90	2.70	5.70	5.50	5.50
$\delta_\theta[\%]$	12.53	6.36	11.05	12.36	8.01	9.03	8.24
$FK[\%]$	39.53	36.21	38.46	42.69	38.59	37.27	38.87

Climate Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	581.30	822.90	678.20	613.80	684.00	517.80	820.60
$\sum pet[mm]$	947.10	877.90	1095.30	1080.70	1013.30	1024.10	987.90
$P_{max}[mm]$	89.00	46.60	48.80	44.20	38.60	28.80	58.00
$pet_{max}[mm]$	10.10	8.20	9.80	10.30	10.60	10.00	8.30
$\delta_P[mm]$	10.46	9.44	8.99	7.48	7.09	6.17	8.75
$\delta_{pet}[mm]$	1.86	1.77	2.21	2.22	2.07	2.14	1.94
$P - pet[mm]$	-365.80	-55.00	-417.10	-466.90	-329.30	-506.30	-167.30
$\theta_{flux}[mm]$	-116.00	144.50	2.00	-62.50	14.00	-29.00	-9.00

Further Indices

Year	2000	2001	2002	2003	2004	2005	2006
R [-]	1.63	1.07	1.62	1.76	1.48	1.98	1.20
S[-]	3.01	0.64	1.43	0.60	1.58	0.19	1.58
$k_* 10^3[d]$	98.32	46.63	99.96	86.00	64.35	99.85	34.93
$\rho_{spear}[-]$	0.53	0.70	0.31	0.43	0.37	-0.01	0.78

Table A.4.: Site InvercargillAero:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	24.44	27.49	24.45	34.47	36.02	35.38
$\theta_{max}[\%]$	60.40	60.40	65.20	65.30	65.30	65.30
$\theta_{min}[\%]$	9.60	10.00	12.10	18.80	14.90	17.10
$\delta_{\theta}[\%]$	12.02	13.98	8.67	9.16	12.59	9.33
$FK[\%]$	60.40	60.20	51.69	65.20	65.30	65.15

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	1036.90	1087.40	1112.10	1185.20	1122.60	812.10
$\sum pet[mm]$	763.20	806.00	827.70	734.80	794.90	761.10
$P_{max}[mm]$	52.20	45.20	42.40	59.40	34.40	36.30
$pet_{max}[mm]$	6.00	7.40	8.10	6.60	6.60	7.00
$\delta_P[mm]$	6.83	5.95	6.26	7.25	6.95	5.72
$\delta_{pet}[mm]$	1.49	1.57	1.66	1.47	1.51	1.48
$P - pet[mm]$	273.70	281.40	284.40	450.40	327.70	51.00
$\theta_{flux}[mm]$	-20.50	-57.50	86.00	20.50	-9.00	-22.00

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	0.74	0.74	0.74	0.62	0.71	0.94
S[-]	0.71	2.46	0.87	0.18	0.86	0.84
$k_{*}10^3[d]$	99.43	83.90	36.29	96.08	100.00	99.71
$\rho_{spear}[-]$	0.12	0.63	0.27	0.40	0.26	-0.00

Table A.5.: Site Kaitaia:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	43.79	45.04	42.19	41.42	40.11	34.89	40.42
$\theta_{max}[\%]$	54.70	55.40	55.20	55.40	53.30	48.70	54.70
$\theta_{min}[\%]$	26.90	30.40	22.80	21.50	16.00	15.70	23.53
$\delta_\theta[\%]$	5.98	6.89	8.59	8.53	10.41	7.50	7.44
$FK[\%]$	53.90	53.79	54.09	53.40	51.69	46.57	52.06

Climate Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	1363.50	1489.40	1543.40	1443.70	1006.50	1233.50	1148.10
$\sum pet[mm]$	1079.10	1027.90	1051.80	999.80	1009.90	1055.90	967.20
$P_{max}[mm]$	77.80	52.60	151.00	100.80	54.80	56.40	98.50
$pet_{max}[mm]$	6.50	7.00	6.40	7.20	6.60	7.50	6.40
$\delta_P[mm]$	13.45	9.86	14.61	14.91	8.15	10.33	12.12
$\delta_{pet}[mm]$	1.52	1.47	1.46	1.51	1.48	1.60	1.72
$P-pet[mm]$	284.40	461.50	491.60	443.90	-3.40	177.60	180.90
$\theta_{flux}[mm]$	26.50	-5.00	-20.50	-57.00	-70.00	136.00	-32.50

Further Indices

Year	2000	2001	2002	2003	2004	2005	2006
R [-]	0.79	0.69	0.68	0.69	1.00	0.86	0.84
S[-]	0.57	0.72	0.78	0.69	0.96	0.67	3.72
$k_{*}10^3[d]$	23.38	63.16	27.12	99.99	54.78	21.65	99.81
$\rho_{spear}[-]$	0.67	0.45	0.71	0.54	0.59	0.81	0.44

Table A.6.: Site LauderEWS:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	12.23	20.70	17.90	23.17	15.94	23.80
$\theta_{max}[\%]$	24.10	55.20	36.50	46.10	39.00	56.00
$\theta_{min}[\%]$	2.20	2.80	1.30	8.30	3.70	3.30
$\delta_{\theta}[\%]$	6.47	13.21	11.45	7.85	8.05	16.14
$FK[\%]$	23.89	44.68	36.40	42.62	27.01	55.23

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	389.60	332.60	290.00	531.30	378.70	343.70
$\sum pet[mm]$	889.90	1013.60	1059.50	914.30	995.30	1002.40
$P_{max}[mm]$	27.20	24.00	23.60	40.00	59.40	37.00
$pet_{max}[mm]$	6.60	8.50	10.50	8.70	8.30	8.80
$\delta_P[mm]$	4.89	5.07	3.96	7.20	7.51	5.31
$\delta_{pet}[mm]$	1.77	1.97	2.22	1.91	1.99	1.95
$P-pet[mm]$	-500.30	-681.00	-769.50	-383.00	-616.60	-658.70
$\theta_{flux}[mm]$	79.00	-49.50	-2.00	48.50	93.00	-145.10

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	2.28	3.05	3.65	1.72	2.63	2.92
S[-]	0.78	0.40	0.11	0.50	2.66	0.30
$k_{*}10^3[d]$	95.58	99.58	33.82	99.96	100.00	93.42
$\rho_{spear}[-]$	0.21	0.17	0.36	0.08	-0.15	0.07

Table A.7.: Site Lincoln:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	25.58	27.28	24.50	23.03	22.80	27.96
$\theta_{max}[\%]$	39.70	44.00	45.50	38.20	35.72	46.00
$\theta_{min}[\%]$	8.40	8.70	7.90	8.90	8.40	13.40
$\delta_{\theta}[\%]$	7.41	10.86	10.44	8.39	8.54	7.36
$FK[\%]$	38.09	41.51	39.66	35.73	35.27	43.25

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	654.00	543.20	460.60	624.20	442.40	778.80
$\sum pet[mm]$	862.00	1020.00	986.70	954.60	947.80	893.00
$P_{max}[mm]$	36.80	33.20	34.20	36.60	28.60	73.60
$pet_{max}[mm]$	7.70	9.80	8.60	8.30	9.20	7.80
$\delta_P[mm]$	7.24	7.59	6.65	7.67	5.42	10.03
$\delta_{pet}[mm]$	1.66	1.95	1.98	1.77	1.88	1.73
$P - pet[mm]$	-208.00	-476.80	-526.10	-330.40	-505.40	-114.20
$\theta_{flux}[mm]$	146.00	-35.60	-40.50	23.50	9.50	-19.50

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	1.32	1.88	2.14	1.53	2.14	1.15
S[-]	0.52	0.61	0.52	0.67	0.30	2.22
$k_{*}10^3[d]$	83.90	94.33	88.93	93.47	99.93	39.16
$\rho_{spear}[-]$	0.49	0.32	0.44	0.48	0.02	0.81

Table A.8.: Site MartinboroughEWS:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	27.04	28.69	31.77	26.18	28.29
$\theta_{max}[\%]$	40.80	39.80	47.30	39.10	54.00
$\theta_{min}[\%]$	16.00	15.40	16.60	14.00	12.20
$\delta_{\theta}[\%]$	6.50	5.37	6.66	8.30	9.75
$FK[\%]$	38.20	38.00	46.79	38.49	51.61

Climate Attributes

Year	2002	2003	2004	2005	2006
$\sum P[mm]$	580.60	903.70	1021.40	540.10	938.90
$\sum pet[mm]$	1011.00	974.40	995.40	1030.00	963.10
$P_{max}[mm]$	46.00	66.20	80.60	25.80	49.40
$pet_{max}[mm]$	9.00	7.90	8.00	8.30	7.30
$\delta_P[mm]$	6.13	9.42	10.03	4.46	8.84
$\delta_{pet}[mm]$	1.87	1.84	1.86	1.99	1.88
$P - pet[mm]$	-430.40	-70.70	26.00	-489.90	-24.20
$\theta_{flux}[mm]$	-38.50	44.50	14.00	-49.50	-30.00

Further Indices

Year	2002	2003	2004	2005	2006
R [-]	1.74	1.08	0.97	1.91	1.03
S[-]	4.93	0.10	0.74	0.41	3.82
$k_{*}10^3[d]$	52.61	81.87	99.93	50.12	48.15
$\rho_{spear}[-]$	0.74	0.59	0.60	0.40	0.92

Table A.9.: Site Middlemarch:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	16.63	24.24	18.50	23.55	21.66	22.74
$\theta_{max}[\%]$	30.10	43.60	34.40	38.00	38.40	38.60
$\theta_{min}[\%]$	8.60	10.50	8.00	11.00	8.90	8.90
$\delta_{\theta}[\%]$	6.82	10.01	7.78	6.21	9.76	9.44
$FK[\%]$	29.42	41.99	32.79	35.49	37.52	38.49

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	386.80	373.00	308.00	531.00	387.70	364.40
$\sum pet[mm]$	777.30	893.90	924.80	793.50	851.80	879.10
$P_{max}[mm]$	28.00	21.60	21.80	41.80	44.20	45.00
$pet_{max}[mm]$	6.00	7.40	8.70	7.90	9.30	10.90
$\delta_P[mm]$	4.39	4.41	4.36	6.25	5.35	6.02
$\delta_{pet}[mm]$	1.48	1.69	1.97	1.63	1.70	1.80
$P - pet[mm]$	-390.50	-520.90	-616.80	-262.50	-464.10	-514.70
$\theta_{flux}[mm]$	78.00	-69.00	-1.00	83.00	-4.50	-78.00

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	2.01	2.40	3.00	1.49	2.20	2.41
S[-]	0.28	0.52	0.26	0.58	4.43	0.35
$k_{*}10^3[d]$	59.78	99.76	99.18	14.39	99.63	99.97
$\rho_{spear}[-]$	0.26	0.27	0.26	0.14	-0.27	-0.16

Table A.10.: Site MusselburghEWS:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	27.74	29.10	31.02	38.28	36.11	32.67
$\theta_{max}[\%]$	37.20	42.00	41.70	44.00	44.30	43.50
$\theta_{min}[\%]$	14.40	14.60	18.70	26.00	23.70	23.00
$\delta_{\theta}[\%]$	3.50	9.27	6.16	3.15	5.76	6.17
$FK[\%]$	34.37	40.67	41.07	43.87	44.10	42.49

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	674.20	543.40	572.80	837.40	646.10	487.40
$\sum pet[mm]$	819.20	976.80	933.40	839.20	889.00	830.20
$P_{max}[mm]$	34.40	25.20	38.80	65.80	82.00	25.60
$pet_{max}[mm]$	6.10	7.80	7.40	6.80	6.70	7.80
$\delta_P[mm]$	5.24	4.66	4.76	8.45	7.72	4.40
$\delta_{pet}[mm]$	1.49	1.65	1.71	1.49	1.61	1.47
$P-pet[mm]$	-145.00	-433.40	-360.60	-1.80	-242.90	-342.80
$\theta_{flux}[mm]$	109.00	-76.50	84.50	24.50	-5.50	-47.50

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	1.22	1.80	1.63	1.00	1.38	1.70
S[-]	0.71	0.70	0.72	0.75	3.07	0.65
$k_{*}10^3[d]$	98.69	43.75	99.99	99.90	99.95	98.97
$\rho_{spear}[-]$	0.28	0.44	0.39	0.29	-0.03	0.08

Table A.11.: Site ParaparaumuEWS:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	13.01	11.07	11.76	14.96	7.16	16.70
$\theta_{max}[\%]$	30.70	37.20	31.30	36.30	16.80	43.30
$\theta_{min}[\%]$	2.80	1.10	3.60	2.30	1.70	7.80
$\delta_\theta[\%]$	5.89	8.50	5.53	8.74	3.33	6.24
$FK[\%]$	27.31	27.21	25.90	30.28	13.77	32.66

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	1173.70	828.40	1224.60	1009.30	728.00	1028.00
$\sum pet[mm]$	892.90	982.30	905.70	956.60	983.10	905.90
$P_{max}[mm]$	56.60	64.80	68.40	66.20	55.80	62.50
$pet_{max}[mm]$	7.10	7.10	6.60	6.80	6.90	6.40
$\delta_P[mm]$	9.18	9.49	11.86	9.74	8.41	9.54
$\delta_{pet}[mm]$	1.59	1.72	1.56	1.67	1.70	1.56
$P - pet[mm]$	280.80	-153.90	318.90	52.70	-255.10	122.10
$\theta_{flux}[mm]$	-3.00	-14.00	38.50	-40.00	18.00	6.00

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	0.76	1.19	0.74	0.95	1.35	0.88
S[-]	0.83	4.60	0.89	1.06	0.56	3.53
$k_* 10^3[d]$	97.35	58.46	79.23	85.29	30.90	45.96
$\rho_{spear}[-]$	0.71	0.84	0.51	0.65	0.49	0.86

Table A.12.: Site Pukekohe:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	29.47	31.22	32.57	37.30	33.17	33.65
$\theta_{max}[\%]$	50.90	51.20	52.70	51.00	49.00	54.80
$\theta_{min}[\%]$	14.00	12.60	14.70	24.80	16.50	19.60
$\delta_{\theta}[\%]$	8.03	7.20	8.81	4.65	8.87	6.57
$FK[\%]$	50.54	49.84	49.69	49.70	48.19	47.97

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	1262.00	1092.00	823.40	904.40	1020.00	1166.90
$\sum pet[mm]$	847.10	872.40	841.90	870.20	889.20	858.10
$P_{max}[mm]$	58.00	43.40	61.00	53.00	40.00	79.40
$pet_{max}[mm]$	5.80	5.70	6.00	6.30	6.30	5.90
$\delta_P[mm]$	8.52	8.45	7.95	7.05	7.47	9.44
$\delta_{pet}[mm]$	1.37	1.43	1.37	1.42	1.49	1.42
$P - pet[mm]$	414.90	219.60	-18.50	34.20	130.80	308.80
$\theta_{flux}[mm]$	31.50	2.50	-28.35	27.00	-19.44	78.06

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	0.67	0.80	1.02	0.96	0.87	0.74
S[-]	0.86	1.01	0.11	2.18	3.25	0.24
$k_{*}10^3[d]$	51.09	99.87	99.71	41.03	49.10	12.88
$\rho_{spear}[-]$	0.78	0.58	0.22	0.60	0.65	0.90

Table A.13.: Site Ranfurly:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	21.79	24.70	21.87	28.75	19.53	27.91
$\theta_{max}[\%]$	43.90	55.74	41.90	54.40	45.50	56.20
$\theta_{min}[\%]$	9.20	9.40	9.40	11.30	9.20	9.30
$\delta_\theta[\%]$	11.06	14.49	11.61	11.71	8.22	16.81
$FK[\%]$	42.78	54.66	41.90	53.57	40.84	55.86

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	479.60	349.40	403.00	548.80	392.60	368.60
$\sum pet[mm]$	838.30	914.90	925.60	843.50	903.50	869.30
	35.20	19.00	23.80	37.00	58.00	29.00
$P_{max}[mm]$						
$pet_{max}[mm]$	6.30	7.90	8.80	7.50	8.20	9.20
$\delta_P[mm]$	5.35	3.96	4.16	6.10	7.25	5.32
$\delta_{pet}[mm]$	1.65	1.82	1.95	1.74	1.79	1.75
$P-$	-358.70	-565.50	-522.60	-294.70	-510.90	-500.70
$pet[mm]$						
$\theta_{flux}[mm]$	127.50	-117.00	54.00	-17.50	114.00	-149.00

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	1.75	2.62	2.30	1.54	2.30	2.36
S[-]	0.42	0.38	0.57	0.48	1.58	0.42
$k_* 10^3[d]$	48.20	99.93	84.10	99.79	99.98	99.85
$\rho_{spear}[-]$	0.43	0.15	0.22	0.03	0.04	0.21

Table A.14.: Site Rangiora:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	24.38	18.24	23.10	22.46	20.78	26.68	33.06
$\theta_{max}[\%]$	45.06	45.00	46.03	45.55	49.00	44.52	51.00
$\theta_{min}[\%]$	5.60	5.70	5.20	6.00	6.70	13.90	15.40
$\delta_\theta[\%]$	15.35	8.12	12.12	13.16	10.39	9.37	10.53
$FK[\%]$	44.68	42.45	42.76	44.49	45.34	43.16	50.65

Climate Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	540.20	704.60	594.60	520.50	567.10	555.40	736.20
$\sum pet[mm]$	881.50	782.40	903.00	886.20	814.90	813.60	829.30
$P_{max}[mm]$	79.00	45.60	63.20	59.00	35.40	54.50	53.40
$pet_{max}[mm]$	9.50	7.50	7.50	8.20	7.50	7.70	6.90
$\delta_P[mm]$	8.63	8.51	9.02	8.25	6.59	7.11	7.72
$\delta_{pet}[mm]$	1.70	1.52	1.76	1.80	1.49	1.62	1.53
$P-pet[mm]$	-341.30	-77.80	-308.40	-365.70	-247.80	-258.20	-93.10
$\theta_{flux}[mm]$	-137.00	109.50	18.50	-84.50	17.00	63.62	28.84

Further Indices

Year	2000	2001	2002	2003	2004	2005	2006
R [-]	1.63	1.11	1.52	1.70	1.44	1.46	1.13
S[-]	2.97	0.56	0.83	0.56	0.71	0.50	0.79
$k_* 10^3[d]$	56.11	47.10	96.97	96.46	47.91	99.95	67.62
$\rho_{spear}[-]$	0.68	0.73	0.47	0.33	0.63	0.11	0.36

Table A.15.: Site StratfordEWS:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2003	2004	2005	2006
$\theta_{mean}[\%]$	24.74	31.86	31.55	33.98
$\theta_{max}[\%]$	34.30	44.90	48.40	51.20
$\theta_{min}[\%]$	18.20	17.40	17.60	20.50
$\delta_{\theta}[\%]$	3.14	5.09	5.86	5.46
$FK[\%]$	33.03	42.62	44.41	46.50

Climate Attributes

Year	2003	2004	2005	2006
$\sum P[mm]$	2623.20	1894.00	1770.30	1673.40
$\sum pet[mm]$	792.40	806.50	809.50	804.40
$P_{max}[mm]$	121.20	70.20	128.20	95.40
$pet_{max}[mm]$	5.90	5.90	6.90	6.30
$\delta_{P}[mm]$	21.63	12.54	14.86	13.75
$\delta_{pet}[mm]$	1.39	1.46	1.48	1.51
$P - pet[mm]$	1830.80	1087.50	960.80	869.00
$\theta_{flux}[mm]$	75.50	-13.00	5.00	3.00

Further Indices

Year	2003	2004	2005	2006
R [-]	0.30	0.43	0.46	0.48
S[-]	0.90	1.59	0.89	2.29
$k_{*}10^{3}[d]$	4.44	29.20	66.94	73.45
$\rho_{spear}[-]$	0.74	0.64	0.61	0.62

Table A.16.: Site Timaru:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	19.61	21.41	23.40	20.05	19.92
$\theta_{max}[\%]$	35.70	37.60	33.70	30.90	36.40
$\theta_{min}[\%]$	8.50	8.50	13.40	9.15	10.20
$\delta_{\theta}[\%]$	7.28	6.22	4.43	5.48	6.33
$FK[\%]$	33.66	32.60	31.87	29.00	32.33

Climate Attributes

Year	2002	2003	2004	2005	2006
$\sum P[mm]$	395.60	486.20	705.00	466.20	570.60
$\sum pet[mm]$	823.10	833.40	744.10	730.50	761.60
$P_{max}[mm]$	27.80	35.40	59.20	36.00	37.60
$pet_{max}[mm]$	8.30	7.60	8.00	8.10	7.30
$\delta_P[mm]$	5.32	6.47	8.89	5.69	5.74
$\delta_{pet}[mm]$	1.63	1.77	1.51	1.54	1.48
$P - pet[mm]$	-427.50	-347.20	-39.10	-264.30	-191.00
$\theta_{flux}[mm]$	-49.75	-14.75	34.50	-14.50	-20.50

Further Indices

Year	2002	2003	2004	2005	2006
R [-]	2.08	1.71	1.06	1.57	1.33
S[-]	0.55	0.51	0.70	0.38	0.73
$k_{*}10^3[d]$	47.63	99.99	99.90	99.70	53.74
$\rho_{spear}[-]$	0.13	0.29	0.08	0.06	0.19

Table A.17.: Site Winchmore:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	15.93	14.64	18.93	17.92	17.80	20.17	27.09
$\theta_{max}[\%]$	56.10	26.91	30.40	49.80	32.30	32.80	47.70
$\theta_{min}[\%]$	0.00	0.70	2.40	1.00	4.80	9.50	11.80
$\delta_\theta[\%]$	11.60	5.50	7.98	10.18	5.80	5.83	7.50
$FK[\%]$	33.51	26.35	29.28	34.70	28.54	30.29	42.69

Climate Attributes

Year	2000	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	708.20	755.80	695.20	670.60	774.70	561.00	851.20
$\sum pet[mm]$	901.90	791.50	898.60	920.40	834.20	828.50	807.80
$P_{max}[mm]$	97.40	42.70	56.20	46.40	41.80	31.40	63.40
$pet_{max}[mm]$	10.00	7.00	7.90	7.90	8.40	8.00	7.90
$\delta_P[mm]$	11.90	7.64	9.37	8.86	8.28	6.46	9.62
$\delta_{pet}[mm]$	1.78	1.55	1.76	1.86	1.62	1.68	1.59
$P-pet[mm]$	-193.70	-35.70	-203.40	-249.80	-59.50	-267.50	43.40
$\theta_{flux}[mm]$	-110.00	130.50	8.50	-67.50	37.00	32.00	-23.00

Further Indices

Year	2000	2001	2002	2003	2004	2005	2006
R [-]	1.27	1.05	1.29	1.37	1.08	1.48	0.95
S[-]	3.52	0.75	4.16	1.07	0.70	0.17	1.54
$k_* 10^3[d]$	55.49	45.78	99.94	99.78	90.90	99.76	43.06
$\rho_{spear}[-]$	0.65	0.71	0.18	0.36	0.42	0.11	0.67

Table A.18.: Site Windsor:
Main characteristic of soil moisture, rainfall and evapotranspiration measurements from the 01-05-2002 to 30-04-2006 (first and second table). Undermost table shows the result of the indices dryness R and climate S. Also the recession coefficient k derived from the simple water balance model (equation 4.4) is shown in the context of the objektive function (equation).

Soil Attributes

Year	2001	2002	2003	2004	2005	2006
$\theta_{mean}[\%]$	20.25	19.19	20.71	28.75	23.97	26.13
$\theta_{max}[\%]$	38.80	37.60	34.80	36.50	33.00	37.70
$\theta_{min}[\%]$	4.80	6.30	9.70	11.60	13.10	15.00
$\delta_{\theta}[\%]$	5.98	8.92	6.92	3.82	6.00	7.48
$FK[\%]$	32.97	35.17	32.97	35.50	32.42	36.49

Climate Attributes

Year	2001	2002	2003	2004	2005	2006
$\sum P[mm]$	593.10	396.70	378.40	614.40	423.20	475.40
$\sum pet[mm]$	716.80	988.90	941.00	744.50	758.30	804.70
$P_{max}[mm]$	45.00	38.60	20.80	40.40	58.80	32.40
$pet_{max}[mm]$	6.40	10.70	9.70	6.80	7.10	8.00
$\delta_P[mm]$	7.12	6.80	5.23	7.48	7.56	6.89
$\delta_{pet}[mm]$	1.35	1.95	1.82	1.42	1.43	1.52
$P - pet[mm]$	-123.70	-592.20	-562.60	-130.10	-335.10	-329.30
$\theta_{flux}[mm]$	120.00	-73.00	-5.50	86.50	-1.00	-67.75

Further Indices

Year	2001	2002	2003	2004	2005	2006
R [-]	1.21	2.49	2.49	1.21	1.79	1.69
S[-]	0.72	0.45	0.57	0.70	2.84	0.57
$k_{*}10^3[d]$	48.39	98.70	83.98	56.72	99.66	74.25
$\rho_{spear}[-]$	0.63	0.04	0.46	0.66	0.01	0.24

Table A.19.: Standard parameter for evaluated model structures derived from visual experiments with the three different model structure. 694 (gravity drainage), 630 (separated tension storage), 632 (cascading buckets)

Parameter	**694**	**630**	**632**
P_{multi}	1.0	1.0	1.0
$S_{1,max}$	300.0	300.0	300.0
θ_{rchr}	-	-	0.15
θ_{tens}	0.3	0.3	0.3
k_u	300.0	300.0	300.0
c	5.0	1.0	1.0