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Simulation of the Upper Waimakariri River Catchment by Observed Rain & Radar Reflectivity

A dissertation submitted in partial fulfilment of the requirements for the Degree of Master of Applied Science

at

Lincoln University

by

Xiao Feng Lu

Lincoln University

2009
Abstract of a dissertation submitted in partial fulfilment of the requirements for the Degree of Masters of Applied Science

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Xiao Feng Lu

ModClark and Clark’s Unit Hydrograph (Clark’s UH) within HEC-HMS software are distributed and lumped models, respectively. Clark’s UH simulates the transformation and attenuation of excess precipitation, and requires time of concentration (Tc) and Storage Coefficient (R) parameters. ModClark transformation accounts for variations in travel time to catchment outlet from all regions of a catchment, and it additionally requires gridded representation of a catchment and Gridded cell-based input files. Four cases (three from observed rain, and one from radar reflectivity) of three chosen events were specifically chosen and examined for the comparison of simulation results with the same estimated initial parameters apart from different rainfall inputs.

The Upper Waimakariri River Catchment was divided into ten subcatchments, and the HEC-HMS basin model parameters were estimated by using the physical/hydrological characteristics. However, ModClark transformation was unavailable because of an output error from converting ASCII to gridded Soil Conservation Service Curve Number (SCS CN) format by the conversion tool – ai2dssgrid.exe. Therefore, Mean Aerial Precipitation (MAP) for each subcatchment was calculated by Thiessen polygon method combined with an overlay analysis for grid-cell-based rainfall estimation from radar with geographic information system (GIS) tools. The automated calibration/optimisation procedure included in HEC-HMS package was applied to the cases which showed a deviation between simulation and observed flows. The purpose is to ‘optimise’ the initial estimates of parameters only in a mathematical-fit manner based on the observed flows from the only discharge gauge at Old Highway Bridge (OHB).

The Tc values calculated from the five equations vary in a relatively narrow range apart from the one from Bransby-Williams equation. Therefore, the values from all the other four equations were averaged and used as the initial Tc input. The simulation results showed that there was a notable difference between observed and simulated hydrographs for some case studies even though Tc, R, CN, and lag time were calibrated/optimised separately. Also, radar estimated rainfall and grid-based data storage system (DSS) need more investigations.

Key Words – Waimakariri River, HEC-HMS, ModClark, Clark’s UH, DSS, Radar reflectivity, ai2dssgrid
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1. Introduction

An accurate estimation of precipitation is critical for hydrologists to predict direct runoff, and thus make better decision on surface water management. For many years, engineers and hydrologists have been estimating rainfall distributions by relating a spatial geometry to point rain gauge observations using Thiessen polygon, inverse distance squared weighting, or geostatistical Kriging techniques. However, unfortunately, the spatial distributions deduced from these mathematical-based methods have little connection with how rain actually falls (Brian & David, 2002).

In recent years, radar has been considered as a powerful tool which provides a high resolution view of the variability of rain falling over a region. This brings an idea of comparing radar precipitation with those mathematical-based methods on estimating the mean aerial precipitation (MAP) for a study area. ModClark, as one of the distributed models, is a suitable transformation which has the ability of accounting for both radar precipitation and grid-cell-based losses.

With computer-based modelling system developed, HEC-HMS package which includes Clark’s UH, ModClark and many other methods, created by US Army Corps of Engineers, is one of these efficient modelling systems.

This study applied both distributed model ‘ModClark’ with grid-cell-based precipitation input and one of the lumped models (see Table 2.1), Clark’s Unit Hydrograph (Clark’s UH) method, with the rainfall input from Thiessen polygon method.

1.1 Objectives

- Set up the initial input parameters for both ModClark and Clark’s UH surface direct-runoff models
- Investigate time of concentration \((T_c)\) methods, and compare the simulation results using these \(T_c\) values as inputs each time
- Apply the simulation runs from both surface direct-runoff models with four cases of three chosen events, and calibrate/optimise the output runoff (if necessary) by the reference flows
- Compare both MAPs, the one derived from radar grid cells and the one from point gauges by Thiessen polygon method, with the observed flows at Waimak Gorge
2. Literature Review

Chapter 2 provides the literature review during the course of this study, which includes three previous studies of the Waimakariri River Catchment, hydrologic modelling review on model definitions and classifications, radar background information and its application in Meteorology, and brief description of the study area.

2.1 Previous Studies

2.1.1 Rainfall-Runoff Routing in the Waimakariri Basin, New Zealand (Griffiths, et al., 1989)

The non-linear network model - RORB, was used to compute outflow hygrographs from measured storms within the large and steep Waimakariri catchment by Griffiths, Pearson, and Horrell (1989). The purpose of utilising this model was to make better preparation for a floodplain management plan for the Waimakariri River (NCCB, 1986).

The RORB model itself is a computer-based model where rainfall excess is routed through a network of concentrated non-linear storages arranged to represent river topology (Griffiths, et al., 1989). After applying a loss submodel, the rainfall excess was derived from the gross rainfall, then it was converted to a direct runoff hydrograph for each pre-delineated subcatchment. This hydrograph could be routed through a non-linear storage representing the effects of overland and subsurface flow and channel reaches. Therefore, the final hydrograph could be derived by superimposing those from the upper reaches, and this sequence was repeated until the catchment outlet (sink) was reached and the complete outflow hydrograph could be obtained by adding baseflow (Griffiths, et al., 1989).

Eight rainfall data and flow datasets recorded at nine automatic rain gauges and a single outflow station were used to calibrate and test the model (Griffiths, et al., 1989).

2.1.2 Combining GIS ArcHydro Tools with a Distributed HEC-HMS Model for the Upper Waimakariri River Basin (Brookland, 2004)

This study was carried out by Brookland in 2004, and it was the first attempt to apply distributed hydrologic modelling method – ModClark (see section 3.1.5) within HEC-HMS software (see sections 2.2, 3.2, and 4.1) on the Upper Waimakariri River Catchment of New Zealand, with the assistance of ArcHydro package as an extension for one of the geographic information system (GIS) platforms – ArcGIS Desktop series.
ArcHydro, developed by David Maidment (1993), is based on geographic information system (GIS) software. It is a set of powerful tools for terrain and watershed processing, hydrological network generation and attributes assignment for the ArcHydro data model. Brookland (2004) used this tool for drainage analysis and watershed delineation, created an ArcHydro geodatabase for the Upper Waimakariri River Catchment, and made an estimation of a set of input parameters [time of concentration (Tc), Soil Conservation Service Curve Number (SCS CN), reach lag time, and storage coefficient (R)] required by HEC-HMS.

Rainfall from point gauges and radar reflectivity were obtained from Environmental Canterbury (ECan) and National Institute of Water & Atmospheric Research (NIWA), respectively. Gridded SCS CN and gridded precipitation, created by ArcGIS Desktop and edited by Microsoft Excel, were considered as two main characteristic input parameters required by the only distributed surface direct-runoff model, namely ModClark in HEC-HMS. The simulated flows were then compared to those at Waimakariri Gorge (WG) estimated from the observed flows at Old Highway Bridge (OHB) without calibration/optimisation. By examining the simulation results, the SCS curve numbers were generally too low and required modification.

Brookland’s (2004) study has shown that a data input set for the HEC-HMS ModClark model can be developed with several GIS tools.

2.1.3 Sensitivity Analysis and Calibration of a Distributed HEC-HMS Hydrologic Model for the Upper Waimakariri River Catchment (Witham, 2006)

In 2006, Witham expanded Brookland’s research by more exploration of optimising/calibrating the relationship between radar reflectivity and gauged precipitation based on the same rainfall datasets obtained from Brookland’s research. To continue Brookland’s research, some of the physical catchment characters, like subcatchment boundaries, flows length etc., were retained for the study area. The sensitivity of model parameter was determined in two stage sensitivity analysis. In stage one, parameters were perturbed about the base by nominated increases and decreases and subsequently ranked in terms of sensitivity. This information was used to undertake stage two of the analysis where parameters were simultaneously perturbed in order to obtain the best fit between observed and calculated flow hydrographs.

Witham (2006) considered that the values for parameters which were determined though the sensitivity analysis and calibration/optimisation processes are correct. However, the sensitivity of the model to changes in rainfall inputs was unable to be explored due to the core
DSS problem. Also, overall the use of the software requires user support from the US Army Corps if it is to be applied in New Zealand. It is not recommended that HEC-HMS be pursued as an effective means of calculating rainfall runoff in New Zealand with the use of radar precipitation.

2.2 Hydrologic Modelling Classifications and HEC-HMS Components

A model relates something unknown (the output) to something known (the input). In the case of excess rainfall-runoff models included in HEC-HMS, the known input is precipitation and the unknown output is runoff (Feldman, 2000).

2.2.1 Hydrologic Modelling Classifications

Models take several forms. In hydrologic modelling field, models can be categorised as physical models which are reduced-dimension representations of real world systems (Feldman, 2000), such as using sprinklers to simulate rainfall in laboratories.

Analog models also have been developed by researchers, and they represent the flow of water with the flow of electricity in a circuit. Historically, analog models have been used to calculate subsurface flow (Feldman, 2000).

The models included in HEC-HMS are in a third category – mathematical models. There are several definitions of this category, one of them was defined by Diskin (1970) as “…simplified systems that are used to represent real-life systems and may be substitutes of the real systems for certain purposes. The models express formalized concepts of the real systems.” Mathematical models, including those that are included in HEC-HMS, can be classified and summarised in Table 2.1 (Ford and Hamilton, 1996).

2.2.2 HEC-HMS Components

HEC-HMS uses a separate model to represent each component of the runoff process, and it includes:

- Models that compute runoff volume; (Table 2.2)

The runoff-volume models can calculate the volume of precipitation that falls on the watershed, the volume of infiltration on pervious surface, the volume of runoff on pervious and imperious surfaces, and the time when runoff starts (Feldman, 2000).
• Models of direct runoff (Table 2.3);

The direct-runoff models describe what happens as water that has not infiltrated or been stored on the watershed moves over or just beneath the watershed surface (Feldman, 2000).

• Models of baseflow (Table 2.4);

These models simulate the slow subsurface drainage of water from the system into the channels (Feldman, 2000).

• Models of channel flow (Table 2.5).

These routing models simulate one-dimensional open channel flow.

Table 2.1 Categorization of mathematical models (Ford and Hamilton, 1996)

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>event or continuous</td>
<td>An event model simulates a single storm with a typical duration of a few hours to a few days. A continuous model simulates a longer period and accounts for watershed response during and between precipitation events.</td>
</tr>
<tr>
<td>lumped or distributed</td>
<td>A distributed model accounts for the spatial variation of characteristics and hydrologic processes. Lumped models average or ignore the spatial variation of these characteristics.</td>
</tr>
<tr>
<td>empirical or conceptual</td>
<td>A conceptual model is based on knowledge of the pertinent physical, chemical, and biological processes that act on the input to produce the output. An empirical model is based upon observations of input and output without explicitly representing the conversion process.</td>
</tr>
<tr>
<td>deterministic or stochastic</td>
<td>If all inputs, parameters, and processes are considered free from random variation and known with certainty, a model is deterministic. A stochastic model describes these random variations and includes the effects of uncertainty in the output.</td>
</tr>
<tr>
<td>measured parameter or fitted parameter</td>
<td>In a measured parameter model, model parameters can be directly or indirectly measured from system properties. A fitted parameter model includes parameters that cannot be measured and instead must be found through empirical calibration or optimization techniques.</td>
</tr>
</tbody>
</table>
Table 2.2 Runoff-volume models (Feldman, 2000)

<table>
<thead>
<tr>
<th>Model</th>
<th>Categorisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial and constant-rate</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>SCS curve number (CN)</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Gridded SCS CN</td>
<td>event, distributed, empirical, fitted parameter</td>
</tr>
<tr>
<td>Green and Ampt</td>
<td>event, distributed, empirical, fitted parameter</td>
</tr>
<tr>
<td>Deficit and constant rate</td>
<td>continuous, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Soil moisture accounting (SMA)</td>
<td>continuous, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Gridded SMA</td>
<td>continuous, distributed, empirical, fitted parameter</td>
</tr>
</tbody>
</table>

Table 2.3 Direct-runoff models (Feldman, 2000)

<table>
<thead>
<tr>
<th>Model</th>
<th>Categorisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>User-specified unit hydrograph (UH)</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Clark's UH</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Snyder's UH</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>SCS UH</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>ModClark</td>
<td>event, distributed, empirical, fitted parameter</td>
</tr>
<tr>
<td>Kinematic wave</td>
<td>event, lumped, conceptual, measured parameter</td>
</tr>
</tbody>
</table>

Table 2.4 Baseflow models (Feldman, 2000)

<table>
<thead>
<tr>
<th>Model</th>
<th>Categorisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant monthly</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Exponential recession</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Linear reservoir</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
</tbody>
</table>

Table 2.5 Routing models (Feldman, 2000)

<table>
<thead>
<tr>
<th>Model</th>
<th>Categorisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic wave</td>
<td>event, lumped, conceptual, measured parameter</td>
</tr>
<tr>
<td>Lag</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Modified Puls</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Muskingum</td>
<td>event, lumped, empirical, fitted parameter</td>
</tr>
<tr>
<td>Muskingum-Cunge Standard Section</td>
<td>event, lumped, quasi-conceptual, measured parameter</td>
</tr>
<tr>
<td>Muskingum-Cunge 8-point Section</td>
<td>event, lumped, quasi-conceptual, measured parameter</td>
</tr>
<tr>
<td>Confluence</td>
<td>continuous, conceptual, measured parameter</td>
</tr>
<tr>
<td>Bifurcation</td>
<td>continuous, conceptual, measured parameter</td>
</tr>
</tbody>
</table>
2.3 Radar Background Information

Traditionally, point rain gauges have been applied to estimate rainfall distribution by assuming a spatial geometry tied to their observations using, for example, Thiessen polygons, inverse distance squared weighting, or statistical Kriging techniques (Brian & David, 2002). Unfortunately, spatial distributions estimated from these techniques have almost no correlation with the spatial variability of how the rain actually falls and leads to wrong rainfall for wrong time and location (Young-Hye et al., 2008). This in turn will have its negative impact when this rainfall is used in watershed modelling or flood forecast.

RADAR (RA dio Detection And R anging), as equipment used to detect and measure the distance to a target through radio wave, has been improved in technology so as to make it a viable tool to enhance the estimation of rainfall between the rain gauges. Essentially, radar provides a high resolution image for the spatial distribution of rainfall as an aerial template (Brian & David, 2002), and it gives a measure of rainfall variability and measures rainfall in grids of 1km by 1km or greater, which enables radar to extend information on rainfall with considerably greater spatial density than regular rain gauges (Young-Hye et al., 2008). Historically, radar had not estimated rainfall distributions accurately until the 1980s, during which the National Weather Service planned to deploy the WSR-88D radars (Hudlow et al., 1991) in the United States.

MetService in New Zealand operates rain radar at Mount Tamahunga (near Warworth), New Plymouth Airport, Outlook Hill (Wellington South Coast), Rakaia (southwest of Christchurch) (see the map in Figure 2.1) and Invercargill Airport1.

2.3.1 Types of Radar

Radar can be classified by the type of radio waves used and the information that can be obtained. Conventional radars measure only the amplitude information of the radio waves which have back-scattered from raindrops and returned to the radar (reflectivity factor), from which rain rates can be estimated. Doppler radars, in operation as airport radars, measure frequency information (Doppler frequency) in addition to the amplitude information, from which the radial velocity (Doppler velocity) of raindrops to the radar can be measured. Multi-parameter radars enable the transmission of two types of radio waves; vertical and horizontal polarization, while conventional and Doppler radars can transmit only a single type. Various parameters can be obtained from the signals that are reflected from raindrops. The use of

multi-parameter radar enables accurate rainfall estimates, as polarization parameters are closely related to raindrop shape and their drop-size distribution. Further, distinctions can be made such as that between rain and snow (NIED, 2005). Radar types are illustrated in Figure 2.2

![Figure 2.1 Location of the radar in Canterbury region (Rakaia)](image)

**Figure 2.1 Location of the radar in Canterbury region (Rakaia)**

### 2.3.2 Rain Gauge vs. Radar

Fortunately, hydrologists now have two ways built on very different fundamental theories, namely rain gauge estimated rainfall and radar estimated rainfall. However, it cannot be easy to say that one is better than the other (Brian & David, 2002), because both methods have their own advantages and disadvantages.

For rain gauge estimated rainfall, one of the most criticized limitations is that people can not actually know what is happening between each rain gauge location during a rainfall event, especially in the case of a large catchment (Brian & David, 2002). However, accurate measurement of rainfall at its point location is one of its advantages. As for radar estimated rainfall, one of its strengths makes up for the other's deficiency in estimation of spatial variability of rainfall, and its weakness is its relative inability to consistently describe the absolute depth of rainfall at a specific location.
However, rain gauges and radar data are hard to compare directly as they measure the same physical process in two fundamentally different ways. Radar determines the average rainfall over an area described as a radar pixel, e.g., 1km by 1km or greater. Rain gauges mainly measure rainfall at a point which is usually less than 0.00000028 sq mi (0.07251967 sq m) for a 12 in (304.8 mm) diameter rain gauge (Brian & David, 2002). More importantly, the rain gauge observation is a function of its location within the radar pixel, and the rain gauge data are used to scale the areal template provided by radar measurement (Brian & David, 2002). However, radar does not directly measure the rainfall but measures reflectance within air and uses an assumed distribution of reflectance and rainfall intensity to estimate the rainfall. That is to say, radar does not estimate accurate rainfall in a certain region, but rather
estimates the relative rainfall in each region to derive a spatial variability (Young-Hye et al., 2008).

### 2.3.3 Limitations of Radar

There is no guarantee that precipitation detected by the radar will reach the earth's surface. In some circumstances, precipitation may partially or completely evaporate as it falls. A lot of precipitation begins its life in the cloud as hail or snow and melts before it reaches the earth's surface. Ice and water-coated ice scatter the radar beam in different ways from water droplets. When interpreting radar images, it should be noted that echoes from frozen precipitation are very likely to be present and how these might change as the precipitation falls need to be considered.

Mountains block the radar beam very effectively. This effect is seen often on images from the Canterbury radar, where there can be strong boundaries - caused by the Southern Alps - between where precipitation appears to be and not to be. Also, very heavy precipitation scatters the radar beam so effectively that it can block echoes from precipitation that is further away from the radar, in much the same way that mountains do. This attenuation of the radar beam can lead to radar images which display precipitation over a far smaller area than it actually covers.

### 2.4 Description of Study Area

The Waimakariri River Catchment was defined by surface catchment boundaries of the Waimakariri River and its tributaries. The total area of the Waimakariri Catchment is 3560 km², of which 2406 km² are westward of the plains which is the study area of this dissertation (see Figure 2.3). Seventy (70%) percent of the catchment is steeplands with slopes of more than 15 degrees. The altitude, ranges from 250 metres at the Gorge Bridge to 2,400 metres at Mt Murchison (Douglas and Harvey, 1975).

#### 2.4.1 Climate

The average rainfall ranges from 890mm to 5,100mm, and rainfall increases westward and with altitude. Sixty percent (60%) of the total rainfall falls on about 30% of the catchment in close proximity to the main divide (Douglas and Harvey, 1975).

---

The Alps create a rain shadow effect which is shown by the precipitous drop between 4,570mm annual precipitation at Arthurs Pass and 1,500mm annual precipitation at Bealey, 10km eastwards (Douglas and Harvey, 1975).

For the whole Waimakariri River Catchment, the moderate and high rainfall intensities are seldom related to convention storms. Snow precipitation is about 30% of the precipitation above 1,500m on the Craigieburn Range and below this the importance of snowfall diminishes. Snow cover above 1,500m is usually continuous from May to November. The warm weather of spring and north-west wind induces quick spring thaws (Douglas and Harvey, 1975).

![Figure 2.3 Upper Waimakariri Catchment – the study area](image)

2.4.2 Waimakariri River

The Waimakariri River is one of the most iconic features of Canterbury and is one of the largest and best examples of braided river habitat in New Zealand. It connects the Southern Alps to the Pacific Ocean. Not only is the river of great ecological importance for the region,

---

but it is also of economic and recreational significance. The river and its landscape are highly
sought by many people for a vast range of recreational activities.\(^5\)

The Waimakariri River is also the source of water for major agricultural activities and
Christchurch’s pristine untreated drinking water. To the west and north of Christchurch is a
groundwater recharge area for a series of aquifers under the city – underground water fed
from the Waimakariri River.\(^6\)

The most significant flooding threat to the Christchurch urban area is posed by the
Waimakariri River, which has frequently changed course, sometimes shifting as far south as
Lake Ellesmere. Much of the city of Christchurch is built on the old Waimakariri floodplain
and it is protected from future floods by a series of stopbanks, and regular riverbed gravel
extraction, which is necessary to counteract the build-up of gravel in the lower reaches of the
river where its slope flattens.\(^7\)

2.4.3 Hydrology

The upper catchment has a low storage and much of the flow comes from surface runoff and
rapid subsurface flow (Douglas and Harvey, 1975). From the historical river hydrographs, the
peak flow in the lower Waimakariri River happened in 1957; 130,000 cusecs\(^8\) with 330 mm of
rainfall fell at Arthurs Pass in 24 hours (Douglas and Harvey, 1975). The most reliable
gauging site on the Waimakariri River is near its mouth, though measured flows are affected
by losses to the Canterbury Plains. Mean annual runoff from the catchment above the gorge is
about 1,600mm with a coefficient of variation of 0.21; monthly flows are more changeable
with coefficients of variation from 0.33 to 0.55 (NCCBRWB, 1986).

One peak flow usually occurs during the spring months which coincides with the seasonal
peak in precipitation along the main divide, but is believed to be increased by snowmelt. A
secondary peak coincides with the autumn precipitation maximum in the western part of the
catchment. Low flows occur in February, when precipitation is low and evaportranspiration
loss is high, and in July, when part of precipitation is stored as snow (Bowden, 1977).

---

\(^5\) \(^6\) \(^7\) Waimakariri River - An important asset to the region, retrieved from
http://www.ecan.govt.nz/Our+Environment/Land/Parks+and+Reserves/Waimakariri+River.htm on 5\(^{\text{th}}\)

\(^8\) A measure of flow rate and a shorthand for cubic foot per second (28.317 litres per second).
Floods can happen at any time of the year, but approximately sixty percent (60%) of all floods occur from October through February (Hayward, 1967). Most floods are associated with northwesterly storms (NCCBRWB, 1986).

2.4.4 Soil

The predominant soils of the catchment are upland and high country yellow-brown earths, which have poor supplies of the essential plant nutrients and are naturally infertile. An important characteristic is the abrupt decrease in nutrient status down the soil profile (Cowie et al., 1986).

Nearly fifty percent (50%) of the catchment is from severely to extremely eroded. There are five broad forms of erosion – wind, sheet, gully, slip, and debris avalanche (Douglas and Harvey, 1975).

2.4.5 Land Use and Vegetation Cover

Only fifty-five percent (55%) of the catchment is used for agriculture or grazing. The vegetation of the catchment has been much influenced and modified by human activities (Johnston, 1969). The present day vegetation cover of the waimakariri Catchment consists of Grasslands, Scrubland, Forest Land, and other land (Cowie et al., 1986).
3. Materials and Available Data

This chapter briefly describes the tools used and the data available for this study.

3.1 GIS Software

The GIS packages used in this study are ArcGIS Desktop 9.2 and Spatial Analyst extension with ArcInfo license. The purpose of using this GIS package is to prepare several input files for running models within HEC-HMS. The main tools used in this study are:

- Conversion Tools – ASCII to Raster, Raster to Point, and Raster to polygon in ArcToolbox
- Math – Int (which converts each cell value of a raster to an integer by truncation) in ArcToolbox
- Analysis Tools – Identity, and Create Thiessen Polygons
- Spatial Analyst Tools – Sink, Fill, Flow Direction, and Flow Length
- Data Management Tools – Mosaic

As the gridded catchment characteristic input file is required by the ModClark transformation, this gridded file must be created before setting up a simulation run (the registration of this gridded file is shown in Figure 4.7). The detailed procedure will be illustrated in Figure 4.8 in section 4.3.2 of chapter 4.

3.2 HEC-HMS Software

As described in section 2.2, the Hydrologic Modelling System (HEC-HMS) was designed by Hydrologic Engineering Centre of US Army Corps, for the purpose of simulating the precipitation–runoff process of dendritic\(^9\) watershed systems. The package features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. Data Storage System (DSS) is specially designed to store precipitation inputs and simulation results in this package.

3.3 DSS Conversion Tools

ASC2DSSGrid and DSS2ASCGrid are the programs to convert between ASCII grid files and DSS format mutually for the purpose of creating grid-cell-based inputs (see section 4.3.4 and 4.3.5) for ModClark transformation within HEC-HMS. ASC2DSSGrid is mainly used in this

\(^9\) [Hydrology] Irregular stream branching with tributaries joining the main stream at all angles (http://www.answers.com/topic/dendritic-drainage on 5th July, 2009).
study, for converting ASCII radar precipitation into DSS file as an input precipitation for ModClark within HEC-HMS.

3.4 Available Data

Data used in this study were obtained from several sources. Table 3.1 lists the available data and their source.

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar estimated hourly rainfall ASCII datasets</td>
<td>For the rainfall event from 0:00 on 8th January to 19:00 on 9th January in 2004</td>
</tr>
<tr>
<td>SCS CN shapefile</td>
<td>Polygon feature class with SCS CN attached as attributes</td>
</tr>
<tr>
<td>Observed flow at Old Highway Bridge</td>
<td>Flow rates with the same period and time resolution as that for Rain gauge precipitation</td>
</tr>
<tr>
<td>Digital Elevation Model (DEM)</td>
<td>Raster feature class for Upper Waimakariri Catchment</td>
</tr>
<tr>
<td>Subcatchment boundaries and rivers feature class</td>
<td>Subcatchments of the Upper Waimakariri Catchment</td>
</tr>
</tbody>
</table>

3.4.1 Details on ASCII Grid File Format

ASCII Grid File Format (Brian, 2003).

The ASCII file must consist of header information containing a set of keywords, followed by cell values in row-major order. The file format is

```
<ncols xxx>
<nrows xxx>
<xllcenter xxx | xllcorner xxx>
```
Rows [1] and [2] indicate how many grid cells in each column and row, respectively. In this case, there are 73 grid cells in each column and 72 grid cells in each row.

Theoretically, rows [3] and [4] give the coordinates of the bottom-left cell’s bottom-left corner in the extent of ncols by nrows.

Row [5] shows the cell size in the unit of metres, in this example; the size for each grid is 1000 metres by 1000 metres.

Row [6] contains the value (-9999) in the ASCII file to be assigned to those cells whose true value is unknown. In the grid they will be assigned the keyword NODATA.

There are specific cell values from row [7] on, and they should be delimited by spaces and no carriage returns are necessary at the end of each row in the grid. The number of columns in the header is used to determine when a new row begins. The values except those indicating NODATA are the incremental rainfall within the chosen temporal resolution (hourly step datasets were chosen for the above example and this study) in the unit of millimetres.

It should be noted that the number of cell values must be equal to the number of rows times the number of columns; otherwise, an error will be returned.
4. Methodology – GIS and Modelling Techniques

This chapter describes the methods used to achieve the objectives in Chapter 1.

4.1 HEC-HMS Model Components and Required Inputs

As described in the previous chapters, the Hydrologic Modelling System (HEC-HMS) is designed by US Army Corps of Engineers, for the purpose of simulating the precipitation–runoff process of dendritic watershed systems. The package features a completely integrated work environment including a database, data entry utilities, computation engine, parameter calibration/optimisation and results reporting tools (Scharffenberg and Fleming, 2006). Data Storage System (HEC-DSS) is specially designed to store data for this package.

4.1.1 Basin Model

The basin model in HEC-HMS is responsible for describing the physical properties of a watershed\(^{10}\) and the topology of the stream network. The modelling components that describe infiltration, surface runoff, baseflow, channel routing, and lakes are contained in the basin model. Usually, a basin model contains hydrologic elements, namely subcatchment, reach, reservoir, junction, diversion, source and sink, which represent physical process.

4.1.2 Meteorologic Model

The meteorologic model in HEC-HMS is responsible for preparing the boundary conditions that act on the watershed during a simulation. One meteorologic model can be used with one or more basin model. However, results computed by the meteorologic model will be matched with the subcatchments in the basin models using the name of subcatchment (Scharffenberg and Fleming, 2006).

Gridded precipitation must be used with a grid based, distributed basin model. As no method exists to temporally interpolate gridded precipitation data, the time step of the HEC-HMS model is limited to the time step of the gridded precipitation data (section 4.3.2).

To use gridded precipitation and a gridded basin model, the cell size and the locations (coordinates) for precipitation grids and catchment physical characteristics grids must match exactly.

\(^{10}\) Watershed is referred to as catchment in this study.
4.1.3 Control Specifications

Control specifications are required as one of the main components in a simulation, and they control when a simulation starts and stops, and what temporal resolution is applied in the simulation (see Figure 4.1).

![Control Specifications](image1.png)

Figure 4.1: Control specifications requirements

4.1.4 Simulation Runs

Simulation runs (See Figure 4.2) contain one basin model, one meteorologic model, and one control specifications. Outputs can be visualised as graphs, summary tables, and time-series tables through HEC-HMS interface.

![Simulation Run](image2.png)

Figure 4.2: HEC-HMS simulation requirements

4.1.5 Clark’s UH / ModClark Surface Runoff Transformation

The Clark’s UH and ModClark methods account for the storage and attenuation properties of a catchment by lagging rainfall excess based on catchment travel time and routing rainfall excess through a linear reservoir. Required parameters for Clark’s UH and ModClark are the time of concentration ($T_c$) and the storage coefficient ($R$).
Clark’s UH uses a time-area (TA) curve, a catchment storage coefficient ($R$), and the time of concentration ($T_c$) to develop a translation hydrograph. The conceptual idea is illustrated in Figure 4.3; the catchment is divided into several areas with equal travel time to the outlet by isochrones, and these isochrones are based on the distribution of the physical characteristics of a catchment. From these areas between adjacent isochrones, a TA curve is developed and used to determine a time discharge histogram. The time discharge histogram is then routed through a linear reservoir to account for catchment storage (Clark, 1945). The basic concepts and equations are described in HEC-HMS Technical Reference Manual by Feldman (2000) as follows:

The Clark’s UH begins with the continuity Equation 4.1

$$\frac{ds}{dt} = I_t - O_t$$  \hspace{1cm} 4.1

Where $\frac{ds}{dt}$ is time rate of change of water in storage at time $t$

$I_t$ is average inflow to storage at time $t$

$O_t$ is outflow from storage at time $t$

With the linear reservoir model, storage at time $t$ is related to outflow as Equation 4.2

$$S_t = R O_t$$  \hspace{1cm} 4.2

Where $R$ is a constant linear reservoir parameter. Combining and solving the equations using a simple finite difference approximation yields Equation 4.3

$$O_t = C_A I_t + C_B O_{t-1}$$  \hspace{1cm} 4.3

Where $C_A, C_B$ are routing coefficients. The coefficients are calculated from Equations 4.4 and 4.5 as follows:

$$C_A = \frac{\Delta t}{R + 0.5\Delta t}$$  \hspace{1cm} 4.4

$$C_B = 1 - C_A$$  \hspace{1cm} 4.5

\[11\] After plotting the TA histogram (TAH), the runoff hydrograph may be determined through convolution (Bahram et al., 2002)

$$Q_j = \sum_{k=1}^{j} E_k \cdot A_{j-k+1}$$

Where $j$ is the time step number, $Q$ is the runoff discharge, $E$ is the excess rainfall intensity, and $A$ is the area bounded by isochrones.
The average outflow during period $t$ is calculated from Equation 4.6

$$ \overline{O_t} = \frac{O_{t-1} + O_t}{2} $$

where $O_t$ is the outflow at time $t$.

As a modified Clark model in HEC-HMS, ModClark is a distributed parameter model in which spatial variability of characteristics and processes are considered explicitly. This model accounts explicitly for variations in travel time to the catchment outlet from all regions of a catchment (Kull and Feldman, 1998; Peters and Easton, 1996).

For each cell of the grid presentation of the catchment, the distance to the catchment outlet is specified. Translation time to the outlet is computed by Equation 4.7

$$ t_{cell} = T_c \frac{d_{cell}}{d_{max}} $$

where $t_{cell}$ is time of travel for a cell,

$T_c$ is time of concentration (see section 4.4.2) for the watershed,

$d_{cell}$ is travel distance from a cell to the outlet,

$d_{max}$ is travel distance for the cell that is most distant from the outlet.

Equation 4.7 assumes that the velocity of spreading surface runoff to the outlet is a constant, and it does not account for the distribution of physical characteristics over a catchment. However, usually, this is not the case in the real world.
The area of each cell is specified, and from this, the volume of inflow to the linear reservoir for each time interval $\Delta t$, is computed as the product of area and precipitation excess. The excess is the difference between MAP and losses for each cell:

\[
\text{precipitation excess} = \text{MAP in the cell} - \text{losses in the cell.}
\]

The inflows thus computed are routed through a linear reservoir, yielding an outflow hydrograph for each cell. HEC-HMS combines these cell outflow hydrographs to determine the catchment direct runoff hydrograph (USACE, 2000). Figure 4.4 illustrates the conceptual idea of ModClark.

Additionally, ModClark method requires a grid-cell-based loss model such as Gridded SCS Curve Number, and the grid-cell-based precipitation must be in DSS format which is specially designed for HEC-HMS package.

The gridded SCS CN method used in this study will be applied to estimating the losses for both Clark’s UH and ModClark methods. If the same CN values were used in each cell, then theoretically, it should produce the same result as Clark where the time area curve is essentially derived from the times of travel and areas of the individual grid cells (Murari, et al., 2009).

The details of the estimation of the above parameters will be illustrated in section 4.4.
4.2 The Natural Resources Conservation Service Curve Number Method

The Natural Resources Conservation Service (NRCS), formerly Soil Conservation Service (SCS), Curve Number (CN) method is a mathematical model relating precipitation to runoff (Brian, 2003) and will be referred to as the SCS CN method. This method was empirically developed based on significant research on small rural watershed areas, and this method has proven to be a very useful tool for evaluating effects of changes in land use and treatment\textsuperscript{12} on direct runoff (Raillison and Miller, 1982).

4.2.1 Summary of SCS CN Method Runoff Equations

Runoff is calculated from the following equations:

\[
Q = \frac{(P-I_a)^2}{(P-I_a)+S}
\]

Where \(Q\) is runoff (in)

\(P\) is rainfall (in)

\(S\) is potential maximum retention after runoff begins (in)

\(I_a\) is initial abstraction (in)

Initial abstraction \((I_a)\) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. \(I_a\) is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, \(I_a\) was found to be approximated by the following empirical equation (Feldman, 2000):

\[
I_a = 0.2S
\]

By removing \(I_a\) as an independent parameter, this approximation allows the use of a combination of \(S\) and \(P\) to produce a unique runoff amount. Substituting Equation 4.10 into Equation 4.9 gives

\[
Q = \frac{(P-0.2S)^2}{(P+0.8S)}
\]

\textsuperscript{12} A cover type modifier to describe the management of cultivated agricultural lands. It includes mechanical practices, such as contouring and terracing, and management practices, such as crop rotations and reduced or no tillage (USDA, 1986).
S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by

\[ S = \frac{1000}{CN} - 10 \]

4.12

The major factors that determine CN are the hydrologic soil group (HSG) cover type, treatment, hydrologic condition, and antecedent runoff condition (ARC). Another factor considered is whether impervious areas outlet directly to the drainage system (connected) or whether the flow spreads over pervious areas before entering the drainage system (unconnected). Figure 2.2c in the TR-55 [Technical release 55 of the NRCS, “Urban Hydrology for Small Watersheds.”] (USDA, 1986) is provided to aid in selecting the appropriate figure or table for determining curve numbers.

4.2.2 Limitations of SCS CN Method

The initial abstraction \( (I_a) \), consisting of interception, initial infiltration, surface depression storage, evapotranspiration, and other factors, was generated as \( 0.2S \) based on data from agricultural watersheds. This approximation can be especially important in an urban application as the combination of impervious areas with pervious areas can imply a notable initial loss that may not happen (USDA, 1986). Also, a greater initial loss can take place if the impervious areas have surface depressions which store some runoff. To use a relation other than \( I_a = 0.2S \), Equation 4.9 should be regenerated.

The SCS CN method is not suitable for estimating runoff from snowmelt or rain on frozen ground (USDA, 1986).

4.3 Data Processing and Preparation of Model Inputs

4.3.1 Subcatchment Delineation

In Brookland's (2004) research, two GIS tools were mentioned for terrain analysis and hydrological network generation:

- ArcHydro (see section 2.1.2), which is always available for using and downloading from ESRI support web site\(^{13}\).
- HEC-GeoHMS is a package that uses ArcView and Spatial Analyst to develop a number of hydrologic modelling inputs which are directly ready for HEC-HMS. It

\(^{13}\) [http://support.esri.com/index.cfm?fa=downloads.datamodels.filteredgateway&dmid=15](http://support.esri.com/index.cfm?fa=downloads.datamodels.filteredgateway&dmid=15)
was considered as a powerful tool for developing grid-cell-based datasets for linear quasi-distributed runoff transformation - ModClark, the HEC-HMS basin model, physical catchment characteristics, and background map file\textsuperscript{14}. Unfortunately, it is not compatible with ArcGIS Desktop 9.2.

For this study, another possible way is using Hydrology Toolset inside Spatial Analysis Toolbox for terrain analysis and hydrological network generation, and it is illustrated in Figure 4.5. The outputs of subcatchment delineation by this means shown in Figure 4.6 are determined from the calculated stream links (see the ‘StreamLink Raster’ in Figure 4.5), which are usually considered as the conceptual outlet for those delineated subcatchments. However, in the real world, the number of subcatchments can be practically determined from the hydrologic modelling adopted and also from the locations of existing discharge gauges. In this study, there is only one discharge gauge at Old Highway Bridge (see Figure 2.3). Therefore, in order to continue and extend both Brookland’s (2004) and Witham’s (2006) research, it is better to keep the subcatchment boundaries the same.

\textsuperscript{14} In this study, it can be replaced by ESRI shapefiles.
4.3.2 Catchment Grid Cell File Creation

The Catchment Grid Cell File is required by the ModClark transformation, this gridded file must be created before creating the simulation runs component. Figure 4.7 shows the registration of this gridded file. The catchment characteristics gridded input file for the chosen basin model can be created by several GIS tools and Microsoft Excel 2007, and the detailed procedure is illustrated in Figure 4.8.
Figure 4.8 Creating the catchment characteristics gridded file for ModClark
4.3.3 MAP from Rain Gauge by Thiessen Polygon Method

Thiessen polygons method (Equation 4.13) attempts to allow for non-uniform distribution of gauges by providing a weighting factor for each gauge (Linsly and Kohler, et al., 1982). Linsly and Kohler (1982) pointed out that the greatest limitation of this method is its inflexibility as new polygon layout is required every time there is a change in the gauge network. Also, this method does not allow for orographic\textsuperscript{15} influence. It simply assumes linear variation of precipitation between stations and assigns each segment of area to the nearest station.

\[
MAP = \sum_{i=1}^{n} \frac{r_i a_i}{A}
\]

Where \(a_i\) is the area of the polygon surrounding rain gauge \(i\), \(r_i\) is the rainfall at gauge \(i\), and \(A\) is the total catchment area. The MAP using Thiessen’s polygons is a weighted mean, with the weighting being based on the size of each representative area (polygon).

The locations of existing rain gauges can be processed as the point layer, which is the input point layer for creating Thiessen polygons (Figure 4.9) using ‘Create Thiessen Polygon’ Analysis Tool in ArcToolbox within ArcCatalog (a component of ArcGIS Desktop).

\[\text{Figure 4.9 Thiessen polygons based on the existing gauging sites}\]

\[\text{\textsuperscript{15}[Geology] The influences pertaining to mountains, especially in regard to their location and distribution.}\]
4.3.4 Gridded Precipitation

The gridded input precipitation must be in DSS format as this is the only recognised format by HEC-HMS package. This DSS file can be derived from ai2dssgrid.exe program originally obtained from HEC.

For the gridded cell based event, the radar precipitation was stored in ASCII format. These ASCII files (see section 3.4.1) with radar precipitation in millimetres can be converted into DSS format by creating a batch processing file as the example shown in Figure 4.10

```
ai2dssGrid gr=LOCAL in=r080100.txt dss=prcp_radar.dss
pa=/LOCAL/SA4ModClark/PRECIP///radar/ sd=08jan2004 st=0000
ed=08jan2004 et=0100
ai2dssGrid gr=LOCAL in=r080200.txt dss=prcp_radar.dss
pa=/LOCAL/SA4ModClark/PRECIP///radar/ sd=08jan2004 st=0100
ed=08jan2004 et=0200
......
ai2dssGrid gr=LOCAL in=r091900.txt dss=prcp_radar.dss
pa=/LOCAL/SA4ModClark/PRECIP///radar/ sd=09jan2004 st=1800
ed=09jan2004 et=1900
```

Figure 4.10 Batches processing from ASCII to DSS

4.3.5 SCS CN/Gridded SCS CN

The empirical SCS curve numbers can take values between 0 (pervious) and 100 (impervious) and are a function of hydrologic soil type and land use and treatment (Ponce, 1989). A number of event-based models required the SCS curve number to estimate the initial soil moisture condition and the infiltration characteristics of a catchment (USACE, 2000).

To assign SCS curve numbers, the first step was to reclassify the coded soil types from New Zealand Land Resource Inventory (LRI) into the soil group from A to D. The SCS soil classes A to D were assigned to the coded soils of LRI. Details of these groups can be found in many hydrological publications and curve numbers are available for urban, cultivated agricultural, other agricultural, arid and semi-arid land uses.

The reclassification of the vegetation cover data is based on assumed relationships between the LRI and SCS vegetation classes referred to in Table 2.2c “Runoff curve numbers for other agricultural land” in TR-55 (USACE, 2000).

Once the soil group and the vegetation cover type were reclassified, the SCS curve numbers were estimated from Soil Type A to D in category of cover types. The SCS curve numbers for
the study area are all derived from Brookland’s calculations and SCS CN shapefile originally created by Brookland.

However, the catchment characteristics grid-cell-based input ASCII file generated from the procedures illustrated in Figure 4.8 is not sufficient for fully providing the gridded SCS curve numbers, and an independent gridded SCS curve number input file in DSS format must be created for ensuring ModClark simulations. Unfortunately, the problem was encountered when typing a space for any of the six parts 16 of the proposed DSS file; the ai2dssGrid program was terminated with an error. However, according to the HEC-HMS package User’s Manual (2006, ver 3.1.0), the C-part (data descriptor) must be “CURVE NUMBER” with a space between these two words, which made the ai2dssGrid program very problematic, and left the ModClark transformation definitely unavailable for any further analysis. Therefore, an alternative transformation has to be applied to achieve the goals.

As stated in section 4.1.5, ModClark and Clark’s UH methods require the same set of parameters apart from extra gridded losses (gridded SCS CN) and precipitation required by the former. Therefore, Clark’s UH can be an alternative method for taking on this study. Therefore, the following steps will be only focusing on the Clark’s UH method for both of the two scenarios:

- MAP from grid-cell-based radar estimated precipitation for each subcatchment
- MAP from point gauges by Thiessen polygon method

The average SCS CN for each subcatchment can be used as an input for running Clark’s UH method other than its gridded counterpart required by ModClark transformation at the very least. The calculation can be easily done by opening the attribute table of the Base point layer with both SCS CN and identified subcatchment attributes (see Figure 4.8) in ArcMap, and the average SCS CN can be calculated by ‘Summarise Tool’ within the attribute table (Table 4.9).

4.3.6 MAP from Radar Precipitation

The procedures for getting the MAP for radar precipitation ASCII file can be illustrated in Figure 4.11. Note that all the ASCII files (see section 3.4.1) will be processed one by one each time as each ASCII file only represents the incremental precipitation for the duration of its temporal resolution (one hour in this study).

16 By default, all computed results are stored in the project DSS file. The result from each element is stored in a separate record. Some elements compute different types of results; each result is stored in a separate record. The record is identified with a pathname. Each record pathname contains six parts called the A-part, B-part, C-part, D-part, E-part, and F-part. The pathname parts are separated with a slash and may contain spaces. The complete pathname, including slashes and spaces, can total up to 256 uppercase characters (Scharffenberg and Fleming, 2006).
For instance, for the ASCII file - r081700.txt, it records the precipitation depth (mm) between 16:00 and 17:00 on 8 of January (in 2004). The visualisation and the MAP for each subcatchment during this hour can be illustrated in Figure 4.12 & 4.13.

Figure 4.12 Gridded precipitation visualisation from radar at a specified moment
4.3.7 Reference Flow at the Outlet

For the calibration/optimisation purpose, the observed flow at the outlet/sink must be obtained externally. All the flow data for this study was delivered by ECan. However, the only discharge gauge is located at Old Highway Bridge (OHB), and the observed flows for the outlet of the study area were not directly measured. Therefore, the flows at outlet (Waimakariri Gorge) need to be estimated based on the observed flows at OHB (see Figure 4.9).

The possible relationship (Equation 4.14) between these two locations was presented by North Canterbury Catchment Board and Regional Water Board (1986) as follows:

\[
\text{Mean Flow@WG} = \text{Mean Flow@OHB} + 11.33 \text{ m}^3/\text{s}
\]

4.4 Basin Model Parameterisation

4.4.1 Baseflow Estimation

Baseflow is an optional parameter for the ModClark / Clark’s UH methods. In this study, based on the observed flow records at OHB between the beginning of 2003 and the end of 2007, the average monthly baseflow for the years from 2003 to 2007 have been estimated (see Table 4.1).
Table 4.1 Baseflow (m$^3$/s) estimations for the study area

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>66</td>
<td>86</td>
<td>71</td>
<td>66</td>
<td>86</td>
<td>75</td>
</tr>
<tr>
<td>February</td>
<td>65</td>
<td>106</td>
<td>58</td>
<td>56</td>
<td>57</td>
<td>68.4</td>
</tr>
<tr>
<td>March</td>
<td>51</td>
<td>106</td>
<td>59</td>
<td>58</td>
<td>46</td>
<td>64</td>
</tr>
<tr>
<td>April</td>
<td>59</td>
<td>63</td>
<td>73</td>
<td>51</td>
<td>47</td>
<td>58.6</td>
</tr>
<tr>
<td>May</td>
<td>73</td>
<td>75</td>
<td>73</td>
<td>71</td>
<td>53</td>
<td>69</td>
</tr>
<tr>
<td>June</td>
<td>101</td>
<td>87</td>
<td>71</td>
<td>77</td>
<td>60</td>
<td>79.2</td>
</tr>
<tr>
<td>July</td>
<td>89</td>
<td>87</td>
<td>71</td>
<td>70</td>
<td>65</td>
<td>79.2</td>
</tr>
<tr>
<td>August</td>
<td>68</td>
<td>96</td>
<td>69</td>
<td>86</td>
<td>63</td>
<td>76.4</td>
</tr>
<tr>
<td>September</td>
<td>116</td>
<td>121</td>
<td>76</td>
<td>88</td>
<td>64</td>
<td>93</td>
</tr>
<tr>
<td>October</td>
<td>151</td>
<td>133</td>
<td>84</td>
<td>117</td>
<td>201</td>
<td>137.2</td>
</tr>
<tr>
<td>November</td>
<td>101</td>
<td>121</td>
<td>43</td>
<td>144</td>
<td>83</td>
<td>100.4</td>
</tr>
<tr>
<td>December</td>
<td>91</td>
<td>88</td>
<td>56</td>
<td>109</td>
<td>64</td>
<td>81.6</td>
</tr>
</tbody>
</table>

Then, based on the area ratio$^{17}$ of each subcatchment to the whole study area, the average monthly baseflow for each subcatchment can be further calculated as shown in Tables 4.2, 4.3 and 4.4 for 2004, 2006, and 2007, respectively.

Table 4.2 Average monthly baseflow (m$^3$/s) for the ten subcatchments in 2004

<table>
<thead>
<tr>
<th></th>
<th>2004</th>
<th>Subcatchment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>January</td>
<td>12.53</td>
<td>11.37</td>
</tr>
<tr>
<td>February</td>
<td>15.44</td>
<td>14.02</td>
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<tr>
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<td>14.02</td>
</tr>
<tr>
<td>April</td>
<td>9.18</td>
<td>8.33</td>
</tr>
<tr>
<td>May</td>
<td>10.92</td>
<td>9.92</td>
</tr>
<tr>
<td>June</td>
<td>12.67</td>
<td>11.51</td>
</tr>
<tr>
<td>July</td>
<td>11.80</td>
<td>10.71</td>
</tr>
<tr>
<td>August</td>
<td>13.98</td>
<td>12.70</td>
</tr>
<tr>
<td>September</td>
<td>17.63</td>
<td>16.00</td>
</tr>
<tr>
<td>November</td>
<td>17.63</td>
<td>16.00</td>
</tr>
<tr>
<td>December</td>
<td>12.82</td>
<td>11.64</td>
</tr>
</tbody>
</table>

4.4.2 Time of Concentration ($T_c$)

Many hydrologic models require a catchment characteristic to describe the timing of runoff, and travel time is a parameter for this purpose. Travel time ($T_t$) is the time it takes water to

---

$^{17}$ Baseflow estimation in this study assumes that the groundwater is evenly distributed over the study area. However, the real case is much more complicated. Additionally, baseflow solely equates to groundwater discharge is not always valid. Water can be released into streams over different timeframes from different storages such as connected lakes, wetlands, or from snow. Also, temporary storage within the river bank following the passage of high-flow events (bank storage) can also contribute to the baseflow regime (http://www.connectedwater.gov.au/processes/baseflow.html).
travel from one location to another in a watershed. $T_t$ is a component of time of concentration ($T_c$), the longest travel time it takes a particle of water to reach a discharge point in a catchment (Wanielista et al., 1997). $T_t$ is conceptually computed by summing all the travel times for consecutive components of the drainage conveyance system (USDA, 1986).

Table 4.3 Average monthly baseflow ($\text{m}^3/\text{s}$) for the ten subcatchments in 2006

<table>
<thead>
<tr>
<th>Subcatchment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>9.61</td>
<td>8.73</td>
<td>14.31</td>
<td>10.71</td>
<td>0.62</td>
<td>10.84</td>
<td>2.38</td>
<td>3.42</td>
<td>4.65</td>
<td>0.74</td>
</tr>
<tr>
<td>February</td>
<td>8.16</td>
<td>7.41</td>
<td>12.14</td>
<td>9.08</td>
<td>0.52</td>
<td>9.20</td>
<td>2.02</td>
<td>2.90</td>
<td>3.94</td>
<td>0.63</td>
</tr>
<tr>
<td>March</td>
<td>8.45</td>
<td>7.67</td>
<td>12.58</td>
<td>9.41</td>
<td>0.54</td>
<td>9.53</td>
<td>2.09</td>
<td>3.00</td>
<td>4.08</td>
<td>0.65</td>
</tr>
<tr>
<td>April</td>
<td>7.43</td>
<td>6.74</td>
<td>11.06</td>
<td>8.27</td>
<td>0.48</td>
<td>8.38</td>
<td>1.84</td>
<td>2.64</td>
<td>3.59</td>
<td>0.57</td>
</tr>
<tr>
<td>May</td>
<td>10.34</td>
<td>9.39</td>
<td>15.40</td>
<td>11.52</td>
<td>0.66</td>
<td>11.66</td>
<td>2.56</td>
<td>3.68</td>
<td>5.00</td>
<td>0.80</td>
</tr>
<tr>
<td>June</td>
<td>11.22</td>
<td>10.18</td>
<td>16.70</td>
<td>12.49</td>
<td>0.72</td>
<td>12.65</td>
<td>2.77</td>
<td>3.99</td>
<td>5.42</td>
<td>0.86</td>
</tr>
<tr>
<td>July</td>
<td>13.11</td>
<td>11.90</td>
<td>19.52</td>
<td>14.60</td>
<td>0.84</td>
<td>14.78</td>
<td>3.24</td>
<td>4.66</td>
<td>6.34</td>
<td>1.01</td>
</tr>
<tr>
<td>August</td>
<td>12.53</td>
<td>11.37</td>
<td>18.65</td>
<td>13.95</td>
<td>0.80</td>
<td>14.13</td>
<td>3.10</td>
<td>4.45</td>
<td>6.06</td>
<td>0.96</td>
</tr>
<tr>
<td>September</td>
<td>12.82</td>
<td>11.64</td>
<td>19.08</td>
<td>14.27</td>
<td>0.82</td>
<td>14.46</td>
<td>3.17</td>
<td>4.56</td>
<td>6.20</td>
<td>0.99</td>
</tr>
<tr>
<td>October</td>
<td>17.04</td>
<td>15.47</td>
<td>25.37</td>
<td>18.98</td>
<td>1.09</td>
<td>19.22</td>
<td>4.21</td>
<td>6.06</td>
<td>8.24</td>
<td>1.31</td>
</tr>
<tr>
<td>November</td>
<td>20.98</td>
<td>19.04</td>
<td>31.23</td>
<td>23.36</td>
<td>1.34</td>
<td>23.66</td>
<td>5.19</td>
<td>7.46</td>
<td>10.14</td>
<td>1.61</td>
</tr>
<tr>
<td>December</td>
<td>15.88</td>
<td>14.41</td>
<td>23.64</td>
<td>17.68</td>
<td>1.02</td>
<td>17.91</td>
<td>3.93</td>
<td>5.65</td>
<td>7.67</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Table 4.4 Average monthly baseflow ($\text{m}^3/\text{s}$) for the ten subcatchments in 2007

<table>
<thead>
<tr>
<th>Subcatchment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>12.53</td>
<td>11.37</td>
<td>18.65</td>
<td>13.95</td>
<td>0.80</td>
<td>14.13</td>
<td>3.10</td>
<td>4.45</td>
<td>6.06</td>
<td>0.96</td>
</tr>
<tr>
<td>February</td>
<td>8.30</td>
<td>7.54</td>
<td>12.36</td>
<td>9.25</td>
<td>0.53</td>
<td>9.36</td>
<td>2.05</td>
<td>2.95</td>
<td>4.01</td>
<td>0.64</td>
</tr>
<tr>
<td>March</td>
<td>6.70</td>
<td>6.08</td>
<td>9.98</td>
<td>7.46</td>
<td>0.43</td>
<td>7.56</td>
<td>1.66</td>
<td>2.38</td>
<td>3.24</td>
<td>0.52</td>
</tr>
<tr>
<td>April</td>
<td>6.85</td>
<td>6.22</td>
<td>10.19</td>
<td>7.62</td>
<td>0.44</td>
<td>7.72</td>
<td>1.69</td>
<td>2.43</td>
<td>3.31</td>
<td>0.53</td>
</tr>
<tr>
<td>May</td>
<td>7.72</td>
<td>7.01</td>
<td>11.49</td>
<td>8.60</td>
<td>0.49</td>
<td>8.71</td>
<td>1.91</td>
<td>2.75</td>
<td>3.73</td>
<td>0.59</td>
</tr>
<tr>
<td>June</td>
<td>8.74</td>
<td>7.93</td>
<td>13.01</td>
<td>9.73</td>
<td>0.56</td>
<td>9.86</td>
<td>2.16</td>
<td>3.11</td>
<td>4.22</td>
<td>0.67</td>
</tr>
<tr>
<td>July</td>
<td>9.47</td>
<td>8.60</td>
<td>14.10</td>
<td>10.54</td>
<td>0.61</td>
<td>10.68</td>
<td>2.34</td>
<td>3.37</td>
<td>4.58</td>
<td>0.73</td>
</tr>
<tr>
<td>August</td>
<td>9.18</td>
<td>8.33</td>
<td>13.66</td>
<td>10.22</td>
<td>0.59</td>
<td>10.35</td>
<td>2.27</td>
<td>3.26</td>
<td>4.44</td>
<td>0.71</td>
</tr>
<tr>
<td>September</td>
<td>9.32</td>
<td>8.46</td>
<td>13.88</td>
<td>10.38</td>
<td>0.60</td>
<td>10.51</td>
<td>2.30</td>
<td>3.32</td>
<td>4.51</td>
<td>0.72</td>
</tr>
<tr>
<td>October</td>
<td>29.28</td>
<td>26.58</td>
<td>43.59</td>
<td>32.60</td>
<td>1.88</td>
<td>33.02</td>
<td>7.24</td>
<td>10.41</td>
<td>14.15</td>
<td>2.25</td>
</tr>
<tr>
<td>November</td>
<td>12.09</td>
<td>10.98</td>
<td>18.00</td>
<td>13.46</td>
<td>0.77</td>
<td>13.63</td>
<td>2.99</td>
<td>4.30</td>
<td>5.84</td>
<td>0.93</td>
</tr>
<tr>
<td>December</td>
<td>9.32</td>
<td>8.46</td>
<td>13.88</td>
<td>10.38</td>
<td>0.60</td>
<td>10.51</td>
<td>2.30</td>
<td>3.32</td>
<td>4.51</td>
<td>0.72</td>
</tr>
</tbody>
</table>

However, travel time is dependent on many parameters including length and slope of the flow path, ground surface roughness (land use classification), rainfall intensity and conveyance medium. These parameters can be difficult and time consuming to estimate. Because of the difficulty in defining complete flow paths and determining the necessary parameters,
empirical equations have been developed from basin average parameters to simplify the estimation of travel time (Green & Nelson, 2002).

Based on the summary of Witham (2006), five empirical equations were used to obtain $T_c$ for each subcatchment, and the average $T_c$ values were used as the input for each subcatchment.

Californian Culverts Practice (1942) (Chow, Maidment and Mays, 1988)

$$T_c = 60 \left(11.9 \frac{L^3}{H}\right)^{0.385} \quad 4.15$$

Where $L$ is length of the longest water course (mi)

$H$ is elevation difference between divide and outlet (ft)

SCS Lag Equation (1973) Using Average Values for CN

$$T_c = \frac{100 L^{0.8} \left(\frac{1000}{CN}\right)^{0.7}}{1900 S^{0.5}} \quad 4.16$$

Where $L$ is hydraulic length of watershed (longest flow path) (ft)

$S$ is average watershed slope (%)

$CN$ is average SCS curve number for each subcatchment

SCS Lag Equation (1973) Using Mode Value for CN

$$T_c = \frac{100 L^{0.8} \left(\frac{1000}{CN}\right)^{0.7}}{1900 S^{0.5}} \quad 4.17$$

Where $L$ is hydraulic length of watershed (longest flow path) (ft)

$S$ is average watershed slope (%)

$CN$ is mode SCS curve number for each subcatchment

Bransby-Williams (Ministry of Works and Development, 1980)

$$T_c = \frac{0.953 L^{1.2}}{A^{0.1} H^{0.2}} \quad 4.18$$

Where $L$ is maximum flow length (km)
A is watershed area (km²)

H is elevation difference between the highest and lowest points along the main channel (m)

US Soil Conservation Service (Martin et al., 1997).

\[
T_e = \left( \frac{0.87 L^3}{H} \right)^{0.385}
\]

4.19

Where \( L \) is maximum flow length (km)

H is elevation difference between the highest and lowest points along the main channel (m)

All the physical parameters required in the formulas above can be derived from the digital elevation model (DEM) for the study area within ArcMap by attributes queries operations and ‘Surface Analysis extension’. The results, as calculated by Witham (2006) are shown in Table 4.5

<table>
<thead>
<tr>
<th>Subcatchment</th>
<th>Eq 4.15</th>
<th>Eq4.16</th>
<th>Eq4.17</th>
<th>Eq4.18</th>
<th>Eq4.19</th>
<th>Average</th>
<th>Fixed Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3</td>
<td>2.3</td>
<td>2.5</td>
<td>8.90</td>
<td>3.40</td>
<td>4.08</td>
<td>2.88</td>
</tr>
<tr>
<td>2</td>
<td>3.6</td>
<td>2.3</td>
<td>2.5</td>
<td>9.30</td>
<td>3.70</td>
<td>4.28</td>
<td>3.03</td>
</tr>
<tr>
<td>3</td>
<td>5.2</td>
<td>3.6</td>
<td>3.5</td>
<td>13.20</td>
<td>5.40</td>
<td>6.18</td>
<td>4.43</td>
</tr>
<tr>
<td>4</td>
<td>4.9</td>
<td>3.1</td>
<td>3.1</td>
<td>12.80</td>
<td>5.00</td>
<td>5.78</td>
<td>4.03</td>
</tr>
<tr>
<td>5</td>
<td>1.2</td>
<td>0.8</td>
<td>1.0</td>
<td>3.20</td>
<td>1.30</td>
<td>1.50</td>
<td>1.08</td>
</tr>
<tr>
<td>6</td>
<td>3.6</td>
<td>2.3</td>
<td>2.4</td>
<td>9.00</td>
<td>3.70</td>
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<td>1.2</td>
<td>5.90</td>
<td>2.50</td>
<td>2.64</td>
<td>1.83</td>
</tr>
<tr>
<td>8</td>
<td>2.7</td>
<td>2.0</td>
<td>2.2</td>
<td>7.90</td>
<td>2.80</td>
<td>3.52</td>
<td>2.43</td>
</tr>
<tr>
<td>9</td>
<td>2.8</td>
<td>2.1</td>
<td>2.3</td>
<td>8.00</td>
<td>2.90</td>
<td>3.62</td>
<td>2.53</td>
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<tr>
<td>10</td>
<td>2.9</td>
<td>1.5</td>
<td>1.5</td>
<td>5.80</td>
<td>3.00</td>
<td>2.94</td>
<td>2.23</td>
</tr>
</tbody>
</table>

The \( T_e \) values calculated from Equations 4.18 (the grey column in Table 4.5) are much larger than those from any other equations, whose calculated \( T_e \) values are within a narrow range. Therefore, unlike the \( T_e \) values in the ‘Average’ column which contains the average \( T_e \) values from all the five equations, the ‘Fixed Average’ column contains only the average \( T_e \) values from the other four equations except Equation 4.18, and they (see Table 4.9) will be used as one of the initial estimated parameters for the simulation runs.
4.4.3 Reach Lag Time

Lag model is the simplest of the HEC-HMS routing models. With it, the outflow hydrograph is simply the inflow hydrograph, but with all ordinates translated (lag in time) by a specified duration (Figure 4.14). The flows are not attenuated, so the shape is not changed. This model is widely used, especially in urban drainage channels (Pilgrim and Cordery, 1983).

Figure 4.14 Lag time concepts (Feldman, 2000)

The lag time can be calculated as:

\[
\text{Lag time (min/km)} = \frac{\text{Average peak travel time (min)}}{\text{Flow length (km)}}
\]

4.20

The Lag time value of 5.8min/km was chosen in this study and it was based on Waimakariri River catchment flow data from ECan in 2004 (Table 4.6). The calculated lag time for each river reach (see Figure 4.15) within the study area is shown in Table 4.7

| Table 4.6 Waimakariri river catchment flow data (ECan, 2004) |
|-----------------|-----------------|-----------------|-----------------|
| River reach     | Flow distance   | Peak travel     | Peak travel     |
|                 | (km)            | time (general)  | time (08-09/01/2004) |
| Waimakariri Esk to WG | 44              | 2.25~5 hours   | 3.5 hours       |
| WaG to OHB      | Approx 55       | 5~12 hours     | 6.25 hours      |

4.4.4 Storage Coefficient ($R$)

The basin storage coefficient, $R$, is an index of the temporary storage of precipitation excess in the watershed as it drains to the outlet point. Clark (1945) indicated that $R$ can be calculated as the flow at the inflection point on the falling limb of the hydrograph divided by the time derivative of flow, so it has the unit of time.
Based on Clark’s (1945) indication, the storage coefficient for the whole Upper Waimakariri Catchment was estimated at around 44 hours. The storage for each subcatchment was estimated by the contribution of its area ratio to the total study area (see Table 4.9).

Figure 4.15 Basin model visualisation with hydrologic elements

4.5 Analysis Plans

All the running models will use Clark’s UH transformation as there is significant difficulty creating gridded SCS CN DSS file, which made ModClark transformation unavailable in this study. The basic objective of this analysis is to examine how well the initial estimates of parameters fit the observed flows with different MAP inputs from radar and Thiessen polygons interpolation for the four chosen study cases, which are listed in Table 4.8. Calibration/optimisation will be performed if necessary.

<table>
<thead>
<tr>
<th>Reach</th>
<th>River Length (m)</th>
<th>River Length (km)</th>
<th>Lag Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29744.84</td>
<td>29.74</td>
<td>172.52</td>
</tr>
<tr>
<td>2</td>
<td>4490.44</td>
<td>4.49</td>
<td>26.04</td>
</tr>
<tr>
<td>3</td>
<td>13739.70</td>
<td>13.74</td>
<td>79.69</td>
</tr>
<tr>
<td>4</td>
<td>18085.65</td>
<td>18.09</td>
<td>104.90</td>
</tr>
<tr>
<td>5</td>
<td>8030.80</td>
<td>8.03</td>
<td>46.58</td>
</tr>
</tbody>
</table>

\(^{18}\) One of the hydrologic elements with one or more inflow and only one outflow. It is usually used to model rivers and streams.
Table 4.8 Four case studies of three chosen events

<table>
<thead>
<tr>
<th>Rainfall event</th>
<th>Radar MAP</th>
<th>Rain gauge MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>08Jan2004 00:00 ~ 09Jan2004 19:00</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>11Jun2006 01:00 ~ 13Jun2006 09:00</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>16Oct2007 01:00 ~ 19Oct2007 23:00</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

For the case(s) of requiring calibration/optimisation, initial estimates of parameters need to be selected as a starting point. These initial estimates of parameters will be always the same for the four study cases of the three chosen events, which are summarised in Table 4.9

Table 4.9 Initial estimates of input parameters for all the four study cases

<table>
<thead>
<tr>
<th>Subcatchment</th>
<th>Area (km²)</th>
<th>Area (%)</th>
<th>Ave_ScsCn</th>
<th>S (mm)</th>
<th>Ia (mm)</th>
<th>R (hour)</th>
<th>Tc (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>350.54</td>
<td>0.15</td>
<td>64.32</td>
<td>140.89</td>
<td>28.18</td>
<td>6.41</td>
<td>2.88</td>
</tr>
<tr>
<td>2</td>
<td>318.24</td>
<td>0.13</td>
<td>64.08</td>
<td>142.36</td>
<td>28.47</td>
<td>5.82</td>
<td>3.03</td>
</tr>
<tr>
<td>3</td>
<td>521.84</td>
<td>0.22</td>
<td>59.10</td>
<td>175.75</td>
<td>35.15</td>
<td>9.54</td>
<td>4.43</td>
</tr>
<tr>
<td>4</td>
<td>390.33</td>
<td>0.16</td>
<td>61.82</td>
<td>156.90</td>
<td>31.38</td>
<td>7.14</td>
<td>4.03</td>
</tr>
<tr>
<td>5</td>
<td>22.46</td>
<td>0.01</td>
<td>67.70</td>
<td>121.21</td>
<td>24.24</td>
<td>0.50</td>
<td>1.08</td>
</tr>
<tr>
<td>6</td>
<td>395.31</td>
<td>0.16</td>
<td>62.42</td>
<td>152.92</td>
<td>30.58</td>
<td>7.23</td>
<td>3.00</td>
</tr>
<tr>
<td>7</td>
<td>86.66</td>
<td>0.04</td>
<td>61.35</td>
<td>160.03</td>
<td>32.01</td>
<td>1.58</td>
<td>1.83</td>
</tr>
<tr>
<td>8</td>
<td>124.65</td>
<td>0.05</td>
<td>65.18</td>
<td>135.71</td>
<td>27.14</td>
<td>2.28</td>
<td>2.43</td>
</tr>
<tr>
<td>9</td>
<td>169.43</td>
<td>0.07</td>
<td>65.34</td>
<td>134.76</td>
<td>26.95</td>
<td>3.10</td>
<td>2.53</td>
</tr>
<tr>
<td>10</td>
<td>26.97</td>
<td>0.01</td>
<td>79.22</td>
<td>66.62</td>
<td>13.32</td>
<td>0.50</td>
<td>2.23</td>
</tr>
</tbody>
</table>

During the calibration/optimisation, each parameter is calibrated/optimised separately. While calibrating/optimising a parameter, all other parameters are kept the same as initial values. By this means, it is possible to examine how a single parameter affects the simulation results.
5. Simulation Results and Calibration/Optimisation

This chapter will illustrate the simulation results case by case which was listed in Table 4.8, and the simulations are performed according to the Analysis Plan in the section 4.5.

5.1 Radar MAP Input Simulation

The only simulation with Radar MAP available is the 2004 event; the initial estimated parameters were listed in Table 4.9. The MAP input was calculated following the procedures in section 4.3.6. The simulation results is shown in Figure 5.1

![Figure 5.1 Radar MAP input simulation results for 2004 event](image)

The results gave a poor simulation by showing a significant difference for the peak flows and the time when the peak flows happen between the observed and simulated hydrograph (more than 12 hours difference). The reason for this can be found in the HEC-HMS user’s manual edited by Feldman (2000), all calculations during a simulation in HEC-HMS are computed assuming an arbitrary local time zone that does not observe summer time (daylight savings from December to February in New Zealand), and it is common for precipitation data from radar sources such as observed discharge or temperature to be in local time and the...
precipitation grid data is in universal time. Therefore, the time shift for the January 2004 rainfall event is 13 hours (an extra hour for daylight savings).

For the simulation with 13 hours time shift by using Clark’s UH within HEC-HMS, as shown in Figure 5.2, the simulation results were better matched with the observed flows for the time when peak flows occur.

![Graph for Sink "Sink-1"
Sink "Sink-1" Results for Run "MAP4Radar:12h"
Legend (Compute Time: 29 Jun 2009, 12:57:46)
- Run MAP4Radar:12h Element: SINK-1 Result: Observed Flow
- Run MAP4Radar:12h Element: SINK-1 Result: Outflow

Figure 5.2 Simulation results (radar MAP) for 2004 event with 13 hours time shift

However, there is still a significant difference for the peak flows between the two hydrographs even though they have a very similar time of peak flows. Therefore, based on the simulation results, the radar MAP simulation for this 2004 event is necessary to be calibrated/optimised. This will be done in section 5.3

5.2 Rain Gauge MAP Input Simulation

The rest three study cases are all based on point rain gauge MAP derived from Thiessen polygon method. The simulation runs were set up respectively for the three study cases, namely 2004, 2006 and 2007 events.
5.2.1 Rain Gauges Simulation for 2004

The simulation results are shown in Figure 5.3

Comparing the simulation results listed in Figures 5.2 and 5.3, the simulation with MAP input from point rain gauges showed much better results than its radar counterpart. The simulated and observed hydrographs match well, and there is no need to do further calibration/optimisation for this simulation. This may indicate that the initial estimates of parameters are acceptable in this case, these parameters may need further examination by applying to other rainfall events, and this can be achieved by applying all the parameters to other chosen cases - 2006 and 2007 events.
5.2.2 Rain Gauges Simulation for 2006

The simulation results for this case are shown in Figure 5.4

![Graph showing simulation results for 2006 event](image)

Figure 5.4 Simulation results (rain gauge MAP) for 2006 event

5.2.3 Rain Gauges Simulation for 2007

As shown in Figure 5.5, there is 400 m$^3$/s flow difference which accounts for 29% of error for the peak flows, even though the shapes of the two curves are similar. This indicates that the model can be improved by calibration/optimisation. However, the calibrated/optimised parameters for 2007 event may not fit well with the other two events (rain gauge MAPs for 2004 and 2006) because for the same initial estimates of parameters, the 2004 and 2006 events have very good simulation results, while 2007 event does not fit well. In this situation, there are so many possibilities that a certain set of different values fit certain cases. Trial and error methods may apply here to examine several scenarios to determine the possible values and narrow down the ranges that can make a relative better fit for as many events as possible. More rainfall events could be added to further investigation. Only performing calibration/optimisation for a single case is extremely simple by the automated
calibration/optimisation within HEC-HMS. However, it should be noted that the calibrated/optimised parameters may not represent the real world reasonably and properly.

5.3 Calibration/Optimisation for 2004 Radar MAP Event

As planned in section 4.5, calibrate/optimise the parameter one by one, and during the optimisation of one parameter, all the others are kept the same. Thus, theoretically, one could be examined and show the general trend of how a single parameter affects the simulation results.

5.3.1 SCS CN Calibration/Optimisation

The results of calibrating SCS CN are shown in Figures 5.6 and 5.7

The optimised values for CN for subcatchment 4 is 99, and it does not make any sense as subcatchment 4 is not a lake (water surface may assume close to CN = 100 as any precipitation on the surface water will come up with direct runoff instantly). The general trend
for the calibrated/optimised CN increases as it can decrease the initial losses and, thus, make
the higher peak flow. As a result, the calibrated/optimised CN improved the original
simulation results significantly. However, it only provided a mathematical fit, and it is
definitely not a good presentation for the real world.

Figure 5.6 Optimised CN for 2004 radar MAP simulation

Figure 5.7 Hydrograph comparison based on CN for 2004 radar MAP event
5.3.2 Lag Time Calibration/Optimisation

Figures 5.8 and 5.9 show the results after calibrating/optimising the parameter of lag time:

**Figure 5.8 Optimised lag time for 2004 radar MAP simulation**

**Figure 5.9 Hydrograph comparison based on lag time for 2004 radar MAP event**

The lag time parameter does not change the total volume of runoff based on the original simulation (Figure 5.10) and calibrated simulation (Figure 5.11). The simulation after
applying calibrated/optimised lag time shows a better match with the time when peak flows occurred and with the changes in lag time, the shape of simulated curve can change, but the total volume will be the same. Thus, it is expected that solely calibrating/optimising the lag time values will not significantly improve the model’s performance.

5.3.3 Time of Concentration ($T_c$) Calibration/Optimisation

Figures 5.12 and 5.13 show that optimised time of concentration $T_c$ values vary in different directions among the subcatchments. It is not easy to see the trend for $T_c$ changes and how
they affect the output runoff in this way. After calibration/optimisation, there is a decrease in
the total $T_c$ for the study area (sum of $T_c$ for all the subcatchments), which means that less
time being spent for the runoff flowing through the whole catchment to the final outlet/sink
leads to higher peak flow at the sink. Therefore, the optimised curve gets a little closer to the
observed one. However, the calibrated/optimised curve is still not optimised enough to well
match with the observed hydrograph solely on the basis of calibrating/optimising $T_c$ for each
subcatchment (see Figure 5.1).

All the $T_c$ values calculated from different methods (see section 4.4.2) can be examined in
here. The optimised $T_c$ values calculated from Equation 4.16 (SCS Lag Equation Using
Average Values for CN) give better simulation for radar MAP-based 2004 event & rain
gauge-based MAP 2007 event, for the MAP from rain gauge-based events of 2004 and 2006,
the original simulation of both cases showed the simulated runoff was overestimated. $T_c$
calculated from Equation 4.15 (Californian Culverts Practice) provided better simulation
results with or without calibration/optimisation for these two cases. Unfortunately, it is still
difficult to tell which equation can provide more suitable $T_c$ resulting in better simulation for the
study area than the others only based on the four chosen cases of the three rainfall events.
However, the $T_c$ values in “Fix Averaged” (see Table 4.5) are acceptable for the initial
simulation at least.

![Figure 5.12 Optimized $T_c$ for 2004 radar MAP simulation](image-url)
5.3.4 Storage Coefficient ($R$) Calibration/Optimisation

Based on the storage coefficient ($R$) calibration/optimisation results illustrated in Figures 5.14 and 5.15, the optimised $R$ values generally decreased and the peak flows are more than what the original simulation produced. The less $R$ (in time unit) indicates less time for the temporary storage of excess rainfall in the catchment as it drains to the sink, which results in higher peak flows. Therefore, calibrated/optimised $R$ values have been generally reduced, especially for subcatchments 3 and 4; they have been largely reduced by more than 70%.

Figure 5.13 Hydrograph comparison based on Tc for 2004 radar MAP event

Figure 5.14 Optimised R for 2004 radar MAP simulation
The calibrated/optimised R values did not make a noticeable improvement compared to the original simulated hydrograph.
6. Discussion and Conclusions

Theoretically, the direct runoff can be conceptually calculated as taking the total losses out of the total precipitation. Therefore, it could be a way of considering how the input precipitation and the loss method affect the output runoff.

For the two MAP inputs, namely from radar grid cells and from point gauges, 2004 event is the only case with both MAPs available. Therefore, three scenarios will be examined to compare these two MAP inputs, and try to evaluate the reliability of the MAP estimated from radar grid cells.

The first scenario illustrates the incremental hourly precipitation from radar and rain gauges for the whole Upper Waimakariri Catchment for the 2004 event. The hyetographs from both sources were shown in Figure 6.1.

![MAPs from Radar and Rain Gauge (event 8-9 Jan 2004) over the study area](image)

Figure 6.1 MAPs comparison over the study area

Figure 6.1 indicates that radar had presented a relatively good MAP as it matches the one calculated from Thiessen polygon method from the observed rain gauges. Both methods can be acceptable when examining the simulation results, which were shown in Figures 5.2 and 5.3. However, MAP from Thiessen polygon method gave much better simulation results before/after calibration/optimization. The total rain over the study area for this event is 93.00
mm for rain gauge MAP and 80.04 mm for radar MAP. When assuming that the observed rainfall from point rain gauges is accurate, more calibration need be carried out on the relationship between radar reflectivity and observed rainfall.

To compare the MAP from point rain gauges with that from radar, in the second scenario, the rain gauge locations reporting valid data completely within the study area boundary are identified. The rainfall measured by each gauge is compared to the amount estimated by the radar at that gauge location. Figures A01 – A09 in Appendix A show the compared hyetographs for the nine identified rain gauge locations illustrated from top to bottom, namely Arthurs Pass, Carrington, Cheeseman, Grasmere, Nigger Hill, Ranger Stream, Bull Creek, ESK, and Waimak Gorge.

From these figures, it can be easily seen that there is a noticeable deviation between radar-based and point gauge-measured precipitation for more than half of these locations. This may indicate two things; the first is that radar is not as good at presenting the point precipitation as the point rain gauge is, and it is supposed to give a relatively good presentation for the rainfall falling in an area in a spatially distributed manner (see Figure 6.1). Secondly, the results of the compared hyetographs imply that further measures need to be taken on calibrating the estimated rainfall from radar reflectivity on the basis of these identified point rain gauges with observed rainfall which is supposed to be accurate, and more investigations need to be carried out on the correlation between radar reflectivity and actual rainfall. Additionally, the distance between gauge locations for both Arthurs Pass - Carrington and Bull Creek – Ranger Stream are much closer than all the others geographically (see Figure 4.9), Figures A01 - A02, A06 - A07 show that the point gauge MAPs of these two ‘pair’ locations are generally similar. However, the corresponding radar MAPs are extremely different, which indicates more radar rainfall datasets are required for examining the reliability of applying radar precipitation to runoff modelling in New Zealand.

The third scenario examines the two MAPs for each subcatchment for 2004 rainfall event (see Figures B01 – B10 in Appendix B), and the two MAPs with the area ratios are summarised for the ten subcatchments in Table 6.1.

In this scenario, six of the ten subcatchments have the deviations of over 130%; obviously, it gives a poor presentation for the total rainfall over most of the ten subcatchments. However, the hyetographs present well enough on the generally similar trend in which the incremental

---

39 There are altogether nine point rain gauges identified for this criterion (see Figure 4.9).
precipitation increases or decreases for most of the ten subcatchments (see Figure B01 – B10 in Appendix B).

<table>
<thead>
<tr>
<th>SubCatchment</th>
<th>Area ratio (%)</th>
<th>Gauge MAP (mm)</th>
<th>Radar MAP (mm)</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.57</td>
<td>265.54</td>
<td>97.05</td>
<td>63.45</td>
</tr>
<tr>
<td>2</td>
<td>13.22</td>
<td>84.10</td>
<td>114.87</td>
<td>36.59</td>
</tr>
<tr>
<td>3</td>
<td>21.69</td>
<td>129.02</td>
<td>65.98</td>
<td>48.86</td>
</tr>
<tr>
<td>4</td>
<td>16.22</td>
<td>43.46</td>
<td>38.14</td>
<td>12.24</td>
</tr>
<tr>
<td>5</td>
<td>0.93</td>
<td>27.00</td>
<td>92.91</td>
<td>244.12</td>
</tr>
<tr>
<td>6</td>
<td>16.43</td>
<td>43.96</td>
<td>105.29</td>
<td>139.51</td>
</tr>
<tr>
<td>7</td>
<td>3.60</td>
<td>26.92</td>
<td>81.62</td>
<td>203.14</td>
</tr>
<tr>
<td>8</td>
<td>5.18</td>
<td>22.23</td>
<td>69.27</td>
<td>211.62</td>
</tr>
<tr>
<td>9</td>
<td>7.04</td>
<td>23.42</td>
<td>70.38</td>
<td>200.54</td>
</tr>
<tr>
<td>10</td>
<td>1.12</td>
<td>11.50</td>
<td>50.44</td>
<td>338.65</td>
</tr>
</tbody>
</table>

SCS CN, one of the losses models in HEC-HMS for this study, needs more investigations in future studies. Brian (2003) states that the choice of the appropriate CN and Antecedent Moisture Conditions (AMC) for a certain watershed or model segment and storm event is critical for effective modelling. As the attributes of existing land use and land cover (LULC) datasets do not correlate directly with tabulated CN values. The use HSG method and LULC to determine CN is subject to the modeller’s judgment. Storm to storm variation in CN can only be represented by choice of AMC and the most appropriate choice of AMC may vary across large watersheds such as the Upper Waimakariri River Catchement in this study. It is critical therefore that the modeller examines sensitivity of model outputs to the choice of both CN and AMC.

Also it is important and worthwhile to simulate and then calibrate/optimise the models for more than one rainfall events based on observed flows. Even though for well-calibrated parameters, they need other real cases to examine how these parameters affect the output runoff and thus make better decision on flood prediction. With more historical data, the parameters’ sensitivity could be determined by large amount of model calibration, and empirical calculation and estimates of parameters might be developed locally in an acceptable and practical manner.

6.1 Achievement of Objectives

- Set up the required input parameters for both ModClark and Clark UH transformation
The difficulty was encountered when trying to create gridded SCS CN (Chapter 4.3.5). Clark UH worked well enough to make the simulations run.

- **Investigate time of concentration methods**
  
  As discussed in section 5.3.3, $T_c$ is hard to choose for a specific case in order to obtain better simulation results. However, it is acceptable to use the “Fix Averaged” $T_c$ values (see Table 4.5) as initial $T_c$ input values. Then, by calibration/optimisation, improved $T_c$ values could be achieved (in some extreme cases, such as the chosen cases of 2004 event with radar MAP and 2207 event with MAP from rain gauges, none of $T_c$ values can result in good simulation results or $T_c$ values are not acceptable in real world).

- **Check the outputs of the simulation runs with the three rainfall events, and calibrate/optimise the output runoff by the observed flows**
  
  The radar MAP simulation was calibrated/optimised for the purpose of examining how a single parameter (SCS CN, lag time, $T_c$ or $R$) affects the output runoff (see section 5.3). The general trend for these parameters during calibration/optimisation might be identified rather than narrow down the ranges of these calibrated/optimised parameters resulting in better simulations with the limitation of only three events being chosen in this study.

- **Examine the precipitation from radar and MAP from Thiessen polygons.**

  By exploring three scenarios for the single rainfall event (2004) with both MAPs in this study, there are several findings; first, the hydrographs over the whole study area present a relatively good match (first scenario). Secondly, comparing the two MAPs for both identified point rain gauge locations (second scenario) and the ten subcatchments (third scenario), a poor match was presented and this could imply that the reliability of radar rainfall data is still unclear until more events with radar data available from other sources being examined.

### 6.2 Future Research Recommendations

- More studies on understanding the reliability of radar data
- For radar, further calibration from reflectivity to actual rainfall needs to be carried out in the future study
- DSS conversion and more clear understanding of the Radar-related files
- SCS Curve Number needs more investigation on how AMC affect CN for different rainfall events
- It would be much better if comparing and evaluating the same rainfall events with original radar reflectivity obtained from different sources other than relying on one source.
Acknowledgements

This piece of research was technically and financially supported by Natural Resource Engineering Group in Lincoln University. Also, some other external data were provided by Environment Canterbury (ECan). The support from the following people is gratefully acknowledged.

Magdy Mohssen – For more technical support and encouragement

Crile Doscher – For GIS supports and DSS conversion package

Kerrie Osten (ECan) – For providing the rain gauge data for the study area

Tony Gray (ECan) – For providing the flow data at Old Highway Bridge

Aarno Korpela (NIWA) – For some free technical support in Radar information
References


Appendices

Appendix A – MAPs Comparisons Based on Gauge Locations (2004)

Figure A01: MAPs comparison for the rain gauge location of Arthurs Pass

Figure A02: MAPs comparison for the rain gauge location of Carrington
Figure A03: MAPs comparison for the rain gauge location of Cheeseman

Figure A04: MAPs comparison for the rain gauge location of Grasmere
Figure A05: MAPs comparison for the rain gauge location of Nigger Hill

Figure A06: MAPs comparison for the rain gauge location of Ranger Stream
Figure A07: MAPs comparison for the rain gauge location of Waimak Bull Creek

Figure A08: MAPs comparison for the rain gauge location of Waimak ESK
Figure A09: MAPs comparison for the rain gauge location of Waimak Gorge
Appendix B – MAPs Comparisons for the Ten Subcatchments (2004)

Figure B01: MAPs comparison for subcatchment 1

Figure B02: MAPs comparison for subcatchment 2
Figure B03: MAPs comparison for subcatchment 3

Figure B04: MAPs comparison for subcatchment 4
Figure B05: MAPs comparison for subcatchment 5

Figure B06: MAPs comparison for subcatchment 6
Figure B07: MAPs comparison for subcatchment 7

Figure B08: MAPs comparison for subcatchment 8
Figure B09: MAPs comparison for subcatchment 9

Figure B10: MAPs comparison for subcatchment 10
Appendix C – DATA CD-ROM