Hydrological transport model calibration and integration by GUI in 52°North/ILWIS OS for the Dinkel River for supporting water quality studies

Zun Yin

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by

Zun Yin

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Degree Assessment Board

Chairman	Prof. Dr. Ing. Wouter Verhoef
External Examiner	Dr. Ir. M.J. Booij
First Supervisor	Dr. Ir. Chris Mannaerts
Second Supervisor	Dr. Ir. Suhyb Salama

INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

ENSCHEDE, THE NETHERLANDS

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Abstract

Fresh water quantity and quality are the crucial components for human life and sustainable development. Hydrological transport model is the emphasis of water resources management and water quality prediction. Water quality models are all based on the hydrologic information of the basin. But the complexity of hydraulic information collection and expensive hydrological softwares strongly influence the development of hydrological modeling. It's necessary to find a low-cost but high quality way for hydrological modeling study. With the development of geoinformation (GIS) and remote sensing (RS) technique, it is possible to retrieve hydrological parameters from the Digital Elevation Model (DEM). How to integrate and manage hydrological information on a GIS platform for hydrological transport modeling is the main aim of this research.

This thesis will apply Full EQuation model (FEQ) in study area for 1-D open channel unsteady flow simulation. From the hydro pre-processing package in Integrated Land and Water Information System (ILWIS Open), river network can be extracted. Hydraulic parameters can be collected by measurement or DEM, which will be used as input for lookup table generation. After the initial and boundary conditions are defined, mass and momentum equations are applied for discharge and water level calculation. The FEQ model will be calibrated by observed data to specify the coefficient of roughness (Manning's n). The linkage between Hydro Preprocessing and FEQ model is done by a new created Graphic User Interface (GUI) in ILWIS Open during this research, which is able to integrate and manage required data of FEQ model from multi sources. A small basin-Dinkel River, which flows through the urban and rurual area at the boundary of Netherlands and Germany, is chosen as study area.

The results show a good match between simulated and observed data. Both Hydro Preprocessing and FEQ are succeed in Dinkel River basin. On the other hand, the GUI is successful created to support water quality and quantity modeling in ILWIS Open. This open source interface enhances the utility of ILWIS Open and offers a free but effective way for water science research. Some reasons for errors are discovered, discussed and summarized during the discussion. In addition, some possible directions for further study are given at the end of this thesis.

Keywords

Hydrological model, FEQ, FEQUTL, Dinkel, ILWIS, GUI

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Chapter 1

Introduction

Fresh water quantity and quality are the crucial components for human life and sustainable development. High accuracy forecast of water quality is required for health security and environmental monitoring. Hydrological transport model is the precondition of water quality modeling, which is a model used to describe river or stream flow processes and retrieve water quality parameters. The discharge and water level simulation simulated by hydrological transport model will be used as input for water quality forecast. Based on the process of flow simulation, there 3 compulsory issues for hydrological transport model application.

1. Which model is suitable for unsteady flow simulation?
2. How to collect the hydraulic information effectively?
3. How to calibrate and validate the model?

Recently, many softwares offer platforms for hydraulic data management and preprocessing for water quality forecast. Duflow is a software which successfully links the water quantity and water quality together (Duflow, 2004). It simulates the flow part in a simple way and support user defined water quality model. But it's not free of charge and doesn't have platform for data preprocessing. Although, the free version is available, limitations of free version make it hardly to meet the requirements of study. HEC-RAS (river analysis system) is designed for one-dimensional steady, unsteady flow and sediment transport simulation (Brunner, 2008), but a huge amount of measurement is required.

Since the limitations of current softwares, a free hydrological transport model on an excellent open source RS platform is urgently needed for open channel flow simulation. In many hydrological transport modeling applications, FEQ is a open source program for solution of the full, dynamic equations of motion for 1-D unsteady flow in open channels and through control structures (Franz and Melching, 1997). It can simulate most of hydraulic structures and create a matrix of equations effectively by the river network. In addition, the FEQ model can detect the change of flow during the simulation and change the

temporal interval to increase the accuracy.

ILWIS is one of the excellent remote sensing and GIS software with open source supported by 52^onorth. It's accomplished in data editing, analysis and displaying with support of powerful packages for multi applications. It supports a wide range of data formats for import and export. Hyrdo Preprocessing package has already been developed in ILWIS (Hengl et al., 2009), which is a precondition of hydrological modeling. In addition, the Surface Energy Balance System (SEBS) developed by Su (2002) is also imported in ILWIS as a package for soil moisture and evaportranspiration research. ILWIS Open is a potential excellent platform for hydrological research in the future.

Using the hydraulic parameters retrieved from the ILWIS platform, the FEQ model can complete the unsteady flow process calculation for the water quality forecast. The friendly graphic user interface developed in this research will allow users to operate FEQ model in ILWIS. A good link between the FEQ and ILWIS will offer an effective way for hydrological research with free of charge.

1.1 Literature Review

1.1.1 Hydrological Transport Model

Hydrological transport model can be classified into physical model and stochastic model, which use physical and statistical method for simulation respectively. In the flow processes simulation, open channel flow is one of the common cases in hydrological study. Open channel flow is the flow in a transport system where the free surface is subject to atmospheric pressure (Anderson and McDonnell, 2005). Open channel flow can be divided into steady and unsteady flow according to the change of flow depth (Anderson and McDonnell, 2005) or other flow variables (Franz and Melching, 1997). As early as 1770, Chézy developed probably the oldest open channel formula to calculate the velocity of channel flow (Mouret, 1921). Another famous formula is Gauckler-Manning equation (Williams, 1971). Brutsaert (2005) summarized these empirical equations into one common form with unspecified constants. These equations displayed are applied to simulate the linkage of hydraulic parameters in a certain position at a certain time, which are suitable for steady flow calculation. For unsteady flow with spacial and temporal dynamic parameters, empirical equations are limited because it can't explain the essential relations of various changes. Water mass balance equation and Navier-Stokes momentum equation are the 2 fundamental equations commonly used in unsteady flow simulation. They describe the 2 balances, quantity and momentum, in the spacial and temporal dynamics(Lane, 1998). These 2 equations are partial differential equations and are described in deferent forms based on dimensions and specific situations. The dimension and equation form are selected by the relative scale of research objects and requirements of accuracy. Equation 1.1 and 1.2 are 1-D momentum and mass equations respectively used in FEQ model.

$$\frac{\partial Q}{\partial t} + gA\frac{\partial y}{\partial x} + \frac{\partial Q^2}{A\partial x} = gA(S_0 - S_f) \tag{1.1}$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1.2}$$

where Q = discharge; t = time; x = distance along the channel; g = gravity acceleration; S_0 = bottom slope of the channel; S_f = momentum slope in the channel; q = lateral inflow per unit length along the channel.

1.1.2 Hydraulic Information Collection

Hydraulic information includes geometric elements and hydrological variables required in the hydrological transport model. The traditional hydraulic information collection is field survey and observation. The geometry of river channels, such as length, cross section and elevation, should be measured by field work. Water level and discharge should be observed at gauging stations.

Recently, hydrological data and spacial hydraulic information can be retrieved from DEM on GIS platforms (Maidment, 2002; Hengl et al., 2009). ArcHydro developed in ArcGIS (Maidment, 2002) is a powerful toolbox in hydrological modeling. Based on the GIS platform of ArcGIS, ArcHydro can easily retrieve hydrological variables and integrate large amount of data into a system for hydrological modeling. In ILWIS, Hengl et al. (2009) realized the similar function by Hydro-Preprocessing package. But the package is still limited in data management for hydrological model application.

1.1.3 Model Calibration and Validation

Calibration is the critical process in hydrological modeling. Beven (2001) figured out 5 limitations to distribute the hydrological modeling, nolinearity, scale, equifinality, uniqueness and uncertainty. Parameters and coefficients vary by the change of situation. The structure of objective function should be carefully designed for uncertainty analysis and model optimization. The Generalized Likelihood Uncertainty Estimation (GLUE) shows a direct optimal approach (Beven and Binley, 1992; Beven, 2001), which is widely used in hydrological modeling. Abbaspour et al. (2004) improved the Sequential Uncertainty Fitting (SUFI) model and compared it with GLUE in the soil hydrologic parameters calibration process. 3 optimization algorithms are compared by using 3 criterions on the result of HYDRUS-1D model and observed data (Wöhling et al., 2008). In this research, the manning's n will be calibrated by using 3 criterions (Wöhling et al., 2008) in the FEQ model.

Validation is the process of checking whether the simulated result satisfies some certain criterions. In this research, calibrated FEQ model will be used for unsteady flow simulation in 3 flooding periods. The result will be compared with the observed data and evaluated by criterions.

1.2 Objectives

The main aim of this research is to retrieve hydrological variables from DEM, and integrate them with other information in FEQ model for open channel unsteady flow simulation by creating user interface in ILWIS. Based on the main aim of this project, several questions from different aspects are presented naturally.

1.2.1 Research Questions

1. How to retrieve hydrological information from DEM?
2. How to design the GUI to link the Hydro Preprocessing with FEQ?
3. How to integrate the information into FEQ model?
4. How to calibrate the FEQ model by observed data?

1.2.2 Specific Objectives

From the research questions described in previous subsection, 4 specific objectives are divided from the main objective.

1. To retrieve information for DEM by Hydro Preprocessing.
2. To develop an interface for linking Hydro Preprocessing with FEQ model.
3. To integrate required information into FEQ model for unsteady flow simulation.
4. To calibrate the FEQ model and validate the result.

Chapter 2

Study Area

2.1 Dinkel River

The Dinkel River is located at the northern boundary of Germany and Netherlands (Figure 2.1). It originates in North Rhine-Westphalia, Germany, between Ahaus and Coesfeld, and flows north to Gronau, crosses the border at Overijssel, Netherlands, flows through Denekamp and recross the boundary to Germany at Lower Saxony. Finally Dinkel joins the Vecht in Neuenhaus. The total length is $93km$ with $46km$ in Netherlands. The elevation of Dinkel River is from $15m$ to $110m$ above the mean sea level with drainage basin as $643km^2$ (Wolfert et al., 2002). Since the limitation of the data, this thesis only focus on the Dutch part.

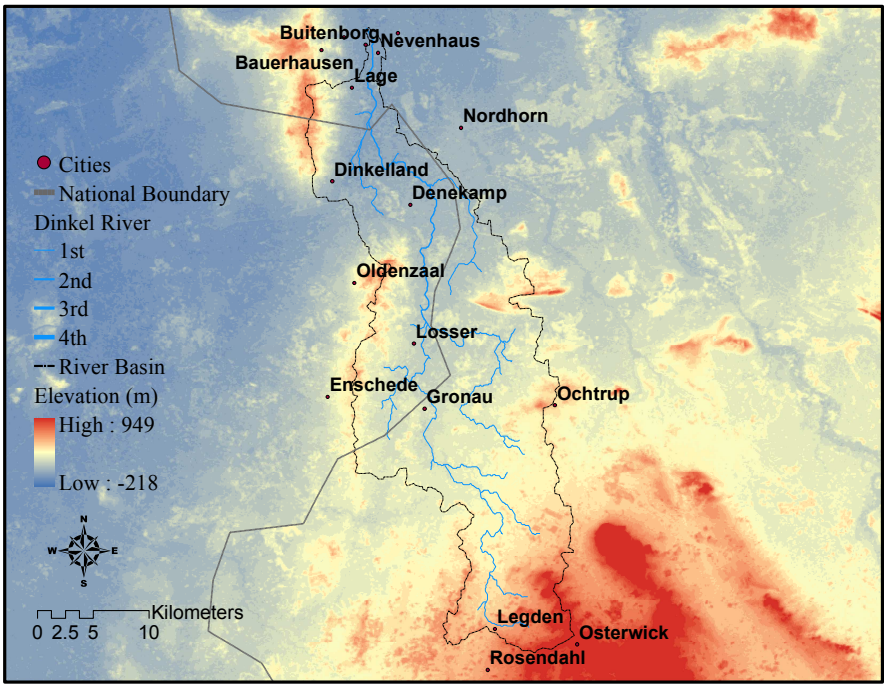


Figure 2.1: The Basin of Dinkel River

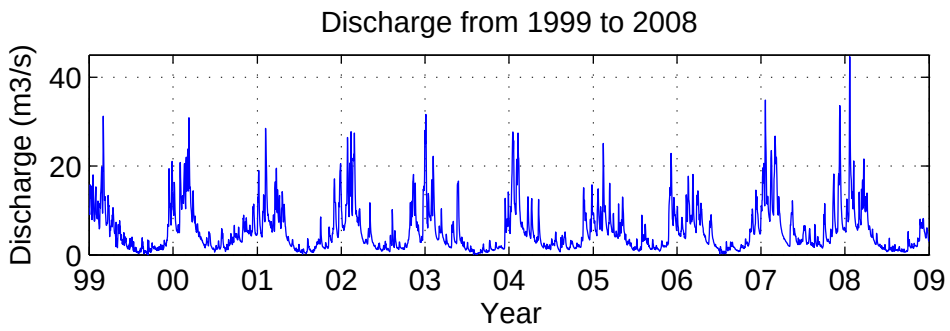
2.1.1 Climate

The average of temperature at the Dinkel Basin is between 6^oC and 10^oC, which increased a little year by year. The precipitation is about $700 \sim 800mm$ per year with a maximum at August and a minimum at March. The climate has a strong influence to the temperature of the water, which fluctuates around 10^oC annually (Jansen et al., 2001a).

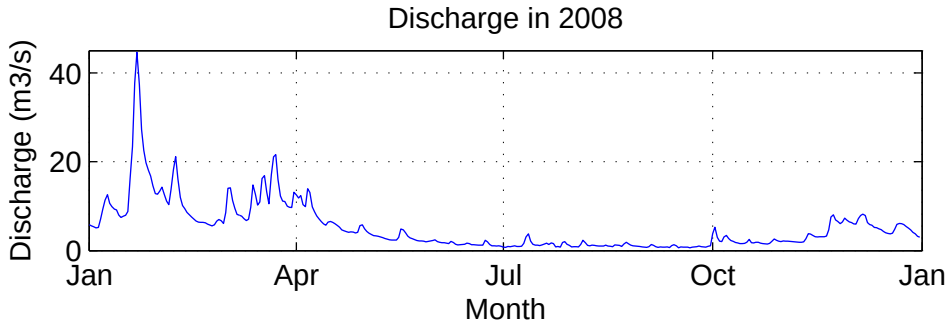
2.1.2 Land Cover

The land cover in the Dinkel catchment includes grass, forest, crops, maize, fallow and urban area (Hailegiorgis, 2006). Nearly half part of the land is covered by grass. The forest covers 14 percent of the basin. The area chosen for the study is meanly covered by forest (Figure A.1a) and grass (Figure A.1b).

2.1.3 Hydrology



(a)



(b)

Figure 2.2: Daily discharge at Stokkenspiek

There are about 14 gauging stations in the Dutch part for water level and discharge monitoring. Discharge and waterlevel data are available as early as 1950's when the first gauging station was established. Because the data loss and change of the channel and environment, discharge data at Stokkenspiek station from 1999 to 2008 are used for hydrological research.

Figure 2.2a displays the daily discharge at Stokkenspiek station from 1999 to 2008. The discharge varies from base flow (near $0m^3/s$) to flood peak ($30m^3/s$ to $45m^3/s$). From Figure 2.2a, it's clear that the annual runoff fluctuates seasonally. The majority part of annual runoff happens in winter and spring[1] (Figure 2.2b). There are 3 characteristics of the Dinkel River flow:

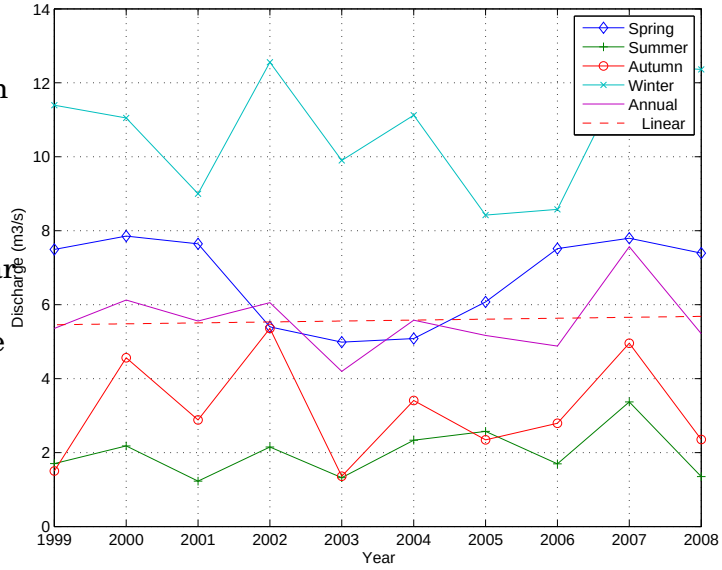


Figure 2.3: Seasonal discharge at Stokkenspiek (1999-2008)

1. Clear seasonal distribution of discharge. Floods always happen in winter and spring, while during summer and autumn the discharge stays as base flow.

2. As shown in Table B.1, B.2, B.3 and B.4, the variance of discharge is very huge in every season. The main source of the discharge of Dinkel River is precipitation.

3. The dotted line in Figure 2.3 is the linear regression of the annual average discharge of Dinkel River. Although a huge fluctuate existed in the last 10 years, the discharge still increased slowly.

2.2 Data

There are 2 main sources for the data collection. One is internet (SRTM of NASA and ITC database) for the DEM. Another is the Regge en Dinkel Waterboard for hydraulic and hydrological data.

2.2.1 DEM

The Shuttle Radar Topography Mission (SRTM) created the complete, high resolution digital elevation model on a global scale (Farr et al., 2007). The resolution of the SRTM is 1" (about $30m$), however 1" resolution data is only available over United States. 3" (about $90m$) resolution data are offered for the rest area

[1]Season are separated as spring: Feb to May; summer: Jun to Aug; autumn: Sept to Nov; winter: Dec to Feb in next year.

of the world. Rodriguez et al. (2005) assessed the accuracy of the SRTM production. They summarized 4 types of errors in different continents (Table 2.1). Another source of DEM is the Dutch national digital elevation model (AHN).

Table 2.1 4 types of errors in different area

Error (m)	Africa	Australia	Eurasia	N.America	S.America
Absolute Geolocation Error	11.9	7.2	8.8	12.6	9.0
Absolute Height Error	5.6	6.0	6.2	9.0	6.2
Relative Height Error	9.8	4.7	8.7	7.0	5.5
Long Wavelength Height Error	3.1	6.0	2.6	4.0	4.9

It is a product generated from the XYZ point elevation data set of the AHN-2 (Waterschappen, 2010). The spatial resolution of AHN data is around $5m$ (Elberink et al., 2003), which is good compared the average width of the main Dinkel River channel (about $10m$). The resolution of elevation of AHN and SRTM are $0.01m$ and $1m$ respectively. But for an international river, the AHN has its limitation for the river catchment retrieval. AHN is only available in Dutch part, and it also contains a lot of details of the terrain, which makes the AHN cannot represent the general trend of the terrain change (see Section 6.1). In sum of reasons above, SRTM is the first choice in this research.

2.2.2 Hydraulic & Hydrological Data

The waterboard of Regge en Dinkel supplies all aspects of hydraulic and hydrological information needed in this research. The details are listed in Table 2.2.

Table 2.2 Data supplied by Waterboard Regge en Dinkel

Data	Remark
Cross section	only the tributaries
Water level	4 stations, 2000 – 2009
Discharge	2 stations, 1950 – 2007
River channel map	in Dutch part
Land cover map	in twente area
Gauging station map	in Dinkel catchment
Cities map	in Dinkel catchment
Documents	Reports related projects

Chapter 3

Methodology

This chapter includes the general procedure, theory of the Hydro Preprocessing, methodology of the FEQ model, calibration and validation process. The general procedure of this research will be discussed first. Then, Hydro Preprocessing and FEQ model will be introduced separately. The method used for calibrating and validation are included in the following 2 sections. The algorithm of user interface design is discussed in the last section.

3.1 Modeling Procedure

This research can be divided into 4 main steps (Figure 3.1). DEM image will be analyzed by hydro processing plug-in in ILWIS for river channel retrieval. After that, the information of hydraulic structures will be put into FEQUTL model to create lookup tables. River channel data, lookup tables, boundary and initial conditions will be integrated in the FEQ model. After setting the calculation part, the FEQ model can be run and generate the time series of simulated discharge and water level. A part of the results will be compared with the observed data by 3 criterions for calibrating uncertain variables. After the calibration, the FEQ model will be run again for validation. In Section 3.6, the design of user interface will be illustrated.

3.2 Hydro Preprocessing

The Hydro Preprocessing package developed by Maathuis and Wang (2006) in ILWIS is used for river network and basin retrieval to support rainfall-runoff modeling. A large amount of attributes are generated from DEM image during the process to describe the main spatial and hydrological information in the area of interest. A part of the results are also useful for open channel flow simulation.

Figure 3.2 illustrates the procedure for Hydro Preprocessing. There 3 parts for Hydro Preprocessing application that will be used in this research. **Flow Determination** can calculate the flow direction and flow accumulation values at each pixel in the DEM image. **Flow Modification** is an optional part for

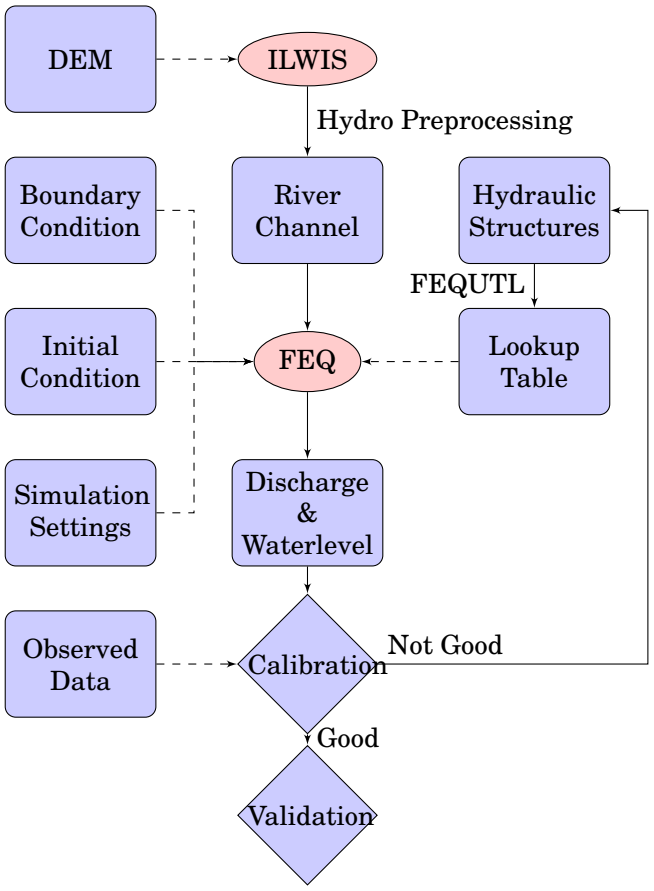


Figure 3.1: The flowchart of hydrological modeling

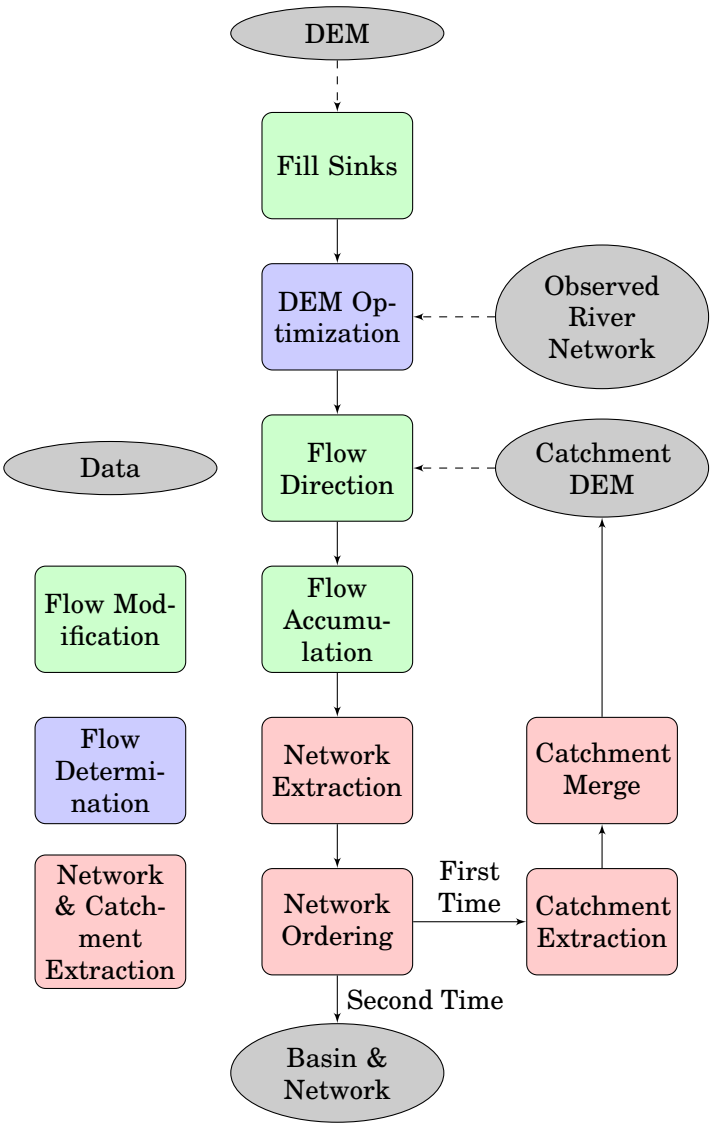


Figure 3.2: The flowchart of Hydro Preprocessing

enhancing observed drainage features in the DEM. **Network & Catchment Extraction** is used to determine the river network, river catchments, order of tributary and sub-catchments. After the outlet point map created, the DEM of river basin your interested in can be masked for the catchment hydrological information management.

3.2.1 Flow Determination

Flow Determination is the first and necessary step for Hydro Preprocessing. It includes 3 operations: `Fill Sinks`, `Flow Direction` and `Flow Accumulation`.

`Flow Sinks` is used to remove some local depressions from DEM to make sure the connectivity of the future river network. The DN (Digital Number) value of local depression will be recovered by the minimum value of the 8 neighbors (Figure 3.3a). It can fix the local depressions problem (Figure 3.3b), on the other hand, it limits the ability of Hydro Preprocessing to retrieve the network of closed basins (Section 6.1).

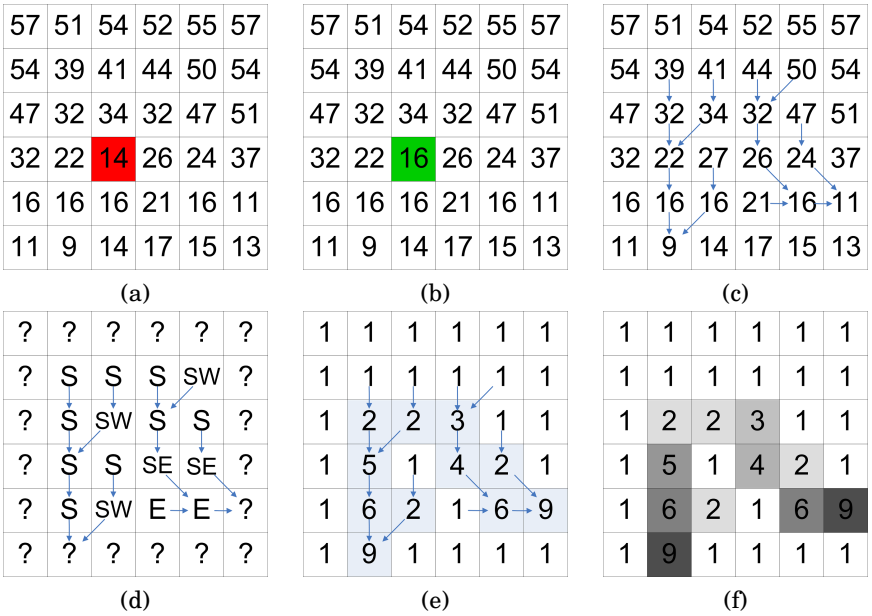


Figure 3.3: Algorithm of **Flow Determination**

`Flow Direction` applies the Deterministic-8 model to determine the flow direction at each pixel (Figure 3.3c and 3.3d). The slopes from the center pixel to its 8 neighbors[1] will be calculated by Equation 3.1.

$$Slope_i = \begin{cases} \frac{DN_{center} - DN_i}{L_i} & DN_{center} \geqslant DN_i \\ NA & DN_{center} < DN_i \end{cases} \tag{3.1}$$

[1]Pixels at boundary and corner will compared with its 5 and 3 neighbors respectively.

where DN_{center} = the DN of center pixel; DN_i = DN of neighbor pixels; L_i = the distance between the centers of 2 pixels.

Then the maximum of the slopes will be determined, and the flow direction of the center pixel points to the corresponding direction. In ILWIS, a raster map will be created to represent the flow direction information by "FlowDirection" domain.

`Flow Accumulation` is the operation after `Flow Direction`. The value of a certain pixel in the flow accumulation map is equal to the number of pixels that drain into the certain pixel. The output, a raster image (Figure 3.3e and 3.3f), will be used to find the drainage pattern and define river network by given a threshold.

3.2.2 Flow Modification

The **Flow Modification** part is optional. This operation will be applied to enhance the river network if the observed river network is available when the resolution is too low to sense the terrain change of channels. In this operation, a drainage map is required. The DEM image will be changed along the network in the drainage map by defining buffer distance, smooth drop and sharp drop (Figure 3.4). After the **Flow Modification**, the river network can be detected better from the DEM. The buffer distance is the width of the channel. Sharp drop controls the enhancing depth at floodplain area. The sharp drop determines the enhancing depth of the channel.

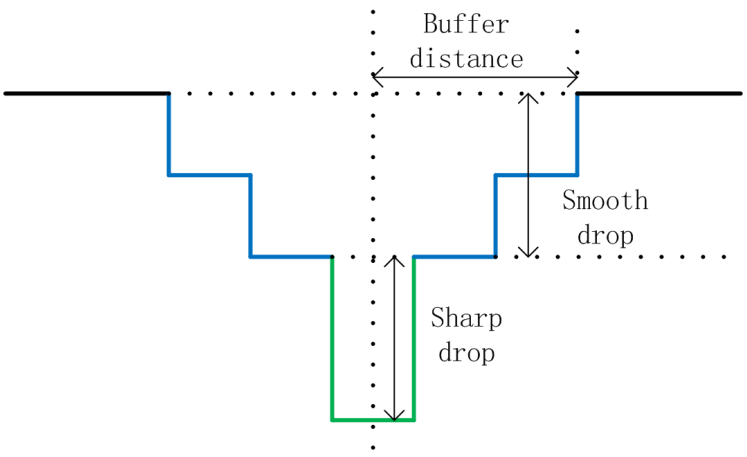


Figure 3.4: **Flow Modification** schematization

3.2.3 Network & Catchment Extraction

This step is used for river network and catchment determination. The first operation, `Drainage Network Extraction`, can create a raster map after the accumulation threshold has been defined by the user. This raster map uses

”Bool” domain to classify 2 group of pixels. The group with a TRUE value are these pixels whose accumulation value are larger than the threshold. The other group contains the rest of pixels. The first group illustrates the river network. But it is a raster map, which cannot describe the spacial and hydrological characteristics of the river basin.

The second operation is called `Drainage Network Ordering`. This operation can transfer the result of previous operation to a vector image by defining the minimum length of the drainage. The geometry of the river network is retrieved in this operation. The channels in the watershed are ordered by Strahler method (Strahler, 1957). And an attached table is generated to save the channel information. The part of attributes that will be used in this research are shown in Table 3.1.
`Catchment Extraction` is an operation to extract the area of the catchment.

Table 3.1 Part of contents in the attached table

Content	Contained Information
UpstreamLinkID	ID of the connected channel at upstream
UpstreamElevation	Elevation of the upstream node
DownstreamLinkID	ID of the connected channel at downstream
DownstreamElevation	Elevation of the downstream node
Length	Length of the channel

A point map of outlet should be created first. The point in the outlet map should on the river channel where you consider as the outlet of the catchment. After the point defined, the catchment extraction can detect pixels where water will drain into the outlet point. The area composed by these selected pixels is the catchment with the defined point as outlet.

The last part of this step is `Catchment Merging`. Using the images created in the past steps, the DEM of the pointed catchment can be masked from the initial DEM image, and a feature map of the catchment will be obtained. After this operation, the new DEM map can be analyzed again by the Hydro Preprocessing package to focus on the area of interest.

3.3 Full Equation Model

The FEQ model is a one dimensional unsteady open channel flow programming package developed by U.S. Geological Survey (USGS) (Franz and Melching, 1997). It simulates the unsteady flow in 1D by solving 2 fundamental equations (Equation 1.1 and 1.2) with attached lookup tables. Each channel are transformed into a form of 2 equations. The river network will be represented by a matrix of nonlinear equations. Since the whole process is simulated by solving a large amount of equations, this model is called full equations model. Some researches by using FEQ model in Illinois (Turner et al., 1996; Ishii and Turner, 1997) showed good results of stage and discharge simulation in high-flow peri-

ods.

In this section, the FEQ model will be introduced from 4 aspects. First the basic features and their coefficients are discussed. The numerical method for solving nonlinear equations is present in the next subsection. The third part introduces the backwater analysis, frozen time and boundary initial conditions, which are the initial settings for the FEQ model. The last subsection is the theory of FEQUTL model.

3.3.1 Basic Features & Coefficients

The basic features in the FEQ model can be classified into 4 parts, branch, node, hydraulic structures and environmental conditions. Branch and node are 2 fundamental features in FEQ. The simplest case is a single branch unsteady flow model with 2 nodes at two sides (Figure 3.5a).

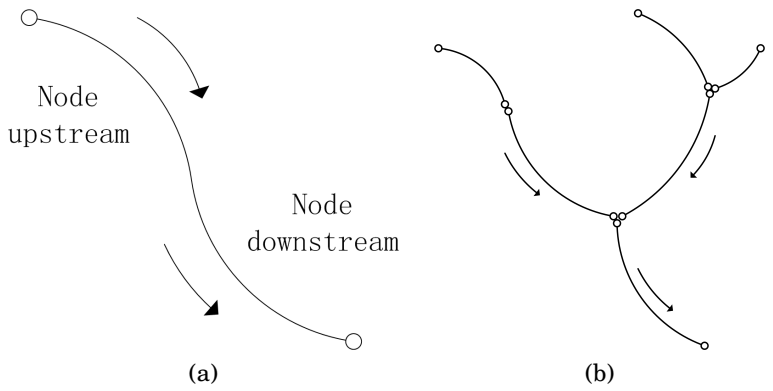


Figure 3.5: The basic structure and network in FEQ model

Branch is the basic unit of a channel for calculation. Length, flow direction, elevation at upstream and downstream must specified for each branch. In a complex river network model (Figure 3.5b), it's also required to contain the identities of connected branches upstream and downstream. All of the information of branch was collected by field work, In this research, they will be retrieved from the Hydro Preprocessing package in ILWIS.

Node is another compulsory feature in FEQ model. It is the control point on the river channel which contains specified cross section and discharge data. Nodes are put at 2 sides of channels to offer the geometry of cross section and boundary condition. In some special cases, node also will be used as the joint point at confluence or bifurcation.

Hydraulic structures have significant influence to the dynamics of water flow. The method of simulating hydraulic structures in FEQ is creating lookup tables by FEQUTL. 1D, 2D or 3D lookup tables can be created for each specified hydraulic structure by corresponding empirical equations. Because this research

doesn't have any hydraulic structures, the details about generating lookup tables are not discussed here.

The FEQ model also consider the effects brought by environmental and climate conditions, such as lateral flow, wind speed and wind direction. Since there is not enough observed data in the research area, these aspects are neglected during the modeling.

3.3.2 Full Equations & Numerical Method

The equation part is the spirit of the FEQ model. Mass and momentum equations (Equation 1.2 and 1.1) are used for simulating the spatial and temporal dynamics of the open channel flow. But the 2 equations here are partial differential equations that cannot be used for calculation directly. In FEQ, mass and momentum equations are transferred into integral form at first. Then integral equations can be transferred by Preissmann four points scheme. Finally, nonlinear equations are solved by Newton's iteration method. Here, the simplest case, 1 channel, is studied to introduce the solving process. The conceptual graph is shown in Figure 3.6. The horizontal line represent the single channel from x_0 (upstream) to x_n (downstream) at a certain time t_i. For the numerical theory, this channel is separated into n parts as length interval. The vertical direction is the temporal interval. The crossing points in the graph are the positions where the discharge and water level will be calculated. Green points along the first horizontal axis represent the initial conditions, where discharge and water level are known at beginning of calculation. The value at green points along the first vertical axis are also known at the beginning as boundary condition. The following part will explain how Preissmann four points theme is applied in the FEQ model. The first term of Equation 1.2 is selected as an example.

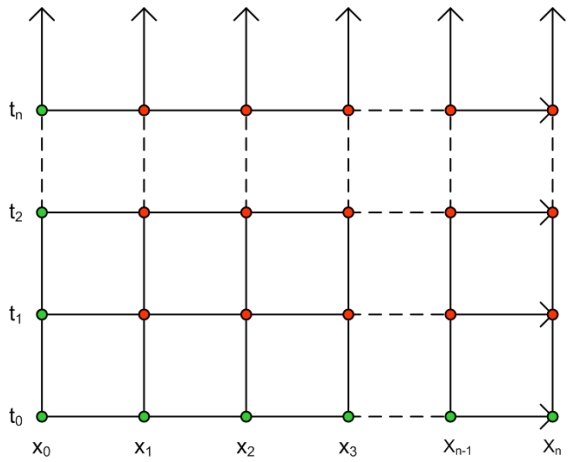


Figure 3.6: Preissmann four points algorithm

Integrate Partial Differential Equations

The first step for calculation is transfer partial differential equations to integral form. There are spatial interval (x) and temporal interval (t) in the two equations. For calculate discharge $Q(x_1, t_1)$ and water level $h(x_1, t_1)$ Both sides of the equations are integrated by x and t from x_0 to x_1, t_0 to t_1 respectively. For example, The first part in Equation 1.2 can be transferred as below.

$$\int_{x_0}^{x_1} \int_{t_0}^{t_1} \frac{\partial A(x,t)}{\partial t} dt dx = \int_{x_0}^{x_1} [A(x,t_1) - A(x,t_0)] dx$$

where $A(x,t)$ = cross section area at position x at time t; other similar forms have the same temporal and spatial meanings.

The detailed process is discussed in FEQ manual (Turner et al., 1996).

Preissmann Four Point Scheme

After integrating the equations, the Preissmann four point scheme is applied to obtain the value at point (x_1, t_1). In the two integral equations, $A(x,t)$ can be obtained by the lookup table of $h(x,t)$ and $A(x,t)$ at the certain position. $v(x,t)$ can be replaced by $Q(x,t)$ and $A(x,t)$ (Equation 3.2).

$$v(x,t) = \frac{Q(x,t)}{A(x,t)} \tag{3.2}$$

All of the variables are known except $Q(x_1, t_1)$ and $h(x_1, t_1)$. But integral equations are still hard to solve for the nonlinear relations. Based on mean value theorem and first mean value theorem for integration (Equation 3.3), the first term of Equation 1.2 can be linearized as 3.4.

$$\int_a^b f(x)dx = (b-a)[(1-w)f(a) + wf(b)] \tag{3.3}$$

where a = maximum of interval; b = minimum of interval; $f(x)$ = a continuous function on the interval $[a, b]$; w = weight function satisfy $0 \leqslant w \leqslant 1$.

$$\begin{aligned} \int_{x_0}^{x_1} [A(x,t_1) - A(x,t_0)]dx =& \Delta x\{(1-w)[A(x_0,t_1) - A(x_0,t_0)] \\ &+ w[A(x_1,t_1) - A(x_1,t_0)]\} \end{aligned} \tag{3.4}$$

where $\Delta x = x_2 - x_1$. For the numerical method, weight function w is simplified as a constant. In common cases, the value of w is between 0.5 and 1.0. For linear equations $w = 0.5$ is acceptable, while for nonlinear equations w should have a higher value. FEQ has 2 parameters (BWT and DWT) in input file for user to define the w. In this research, w is set as 0.55 for convenience.

Newton's Iteration Method

After previous step, 2 integral equations are transferred into 2 linear equations with 2 variables unknown. But in equations, there is a hidden nonlinear relationship between water level (h) and discharge (Q). So the 2 unknowns cannot be solved directly. In FEQ model, Newton's Iteration Method is applied for solving nonlinear equations. Suppose here is a nonlinear function $f(x)$ with 1 unknown x. First find a point x_0 where x_0 is close to the location of a root. Then $f(x)$ can be expanded as Talyor series about x (Equation 3.5).

$$f(x) = f(x_0) + f'(x_0)(x - x_0) = 0 \tag{3.5}$$

where $f'(x)$ = derivative of function $f(x)$. x can be solved from Equation 3.5 (Equation 3.6)

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)} \tag{3.6}$$

where x_1 = second approximation for the root.

Figure 3.7 is the conceptual graph for this method. It shows that the next approximation is a better estimation of the root. This process will be repeated until the difference of approximation and the root is small enough to be accepted. The common form for this process can be summarized as Equation 3.7

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)} \tag{3.7}$$

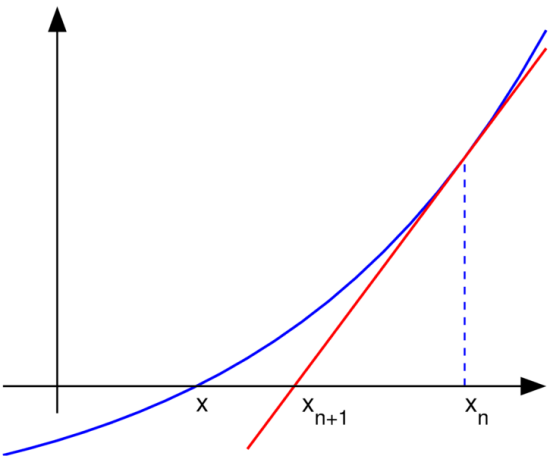


Figure 3.7: Newton's iteration method

For each Channel, there are 2 equations. For the whole river network, there are a matrix of equations to represent all channels and hydraulic structures (Equation 3.8).

$$\mathbf{Jx} = \mathbf{b} \tag{3.8}$$

where **J** = Jacobian matrix of coefficients for the linear system; **x** = vector of unknowns; **b** = vector of residuals. FEQ model use a direct method based on Gaussian elimination to calculate the successive corrections to approximations. Both absolute and relative criterions are used to control the iteration.

3.3.3 Initial Settings for FEQ

Boundary & Initial Condition

Boundary condition is the time series record of discharge or water level at boundaries in the system. Initial condition is the water level and discharge

information of all nodes at the beginning of calculation. Both of the conditions should be specified before simulation and the boundary condition should cover the whole period of output. In FEQ model, It's not necessary to define the initial waterlevel at all nodes. In stead, only the water level of the outlet should be specified, then FEQ model can compute the initial water level data at other nodes by **Backwater Analysis**.

Backwater Analysis

In FEQ model, a special part called **Backwater Analysis** is applied for initial condition preparation. When the unsteady flow simulation starts, the FEQ model will do backwater analysis first. FEQ assumes that the flow before simulation is steady with a constant discharge and there is no water loss in the system. With the known water level and discharge at outlet, FEQ can retrieve the initial condition of other nodes upstream by Manning's Formula. At confluences and bifurcations, FEQ assumes that water levels are same for every branches. Most of hydraulic structures are neglected in this operation.

Frozen Time

After the **Backwater Analysis**, there is an optional operation called **Frozen Time** before starting simulation. The FEQ model will compute for a period by keeping boundary condition constant. This operation is used to calibrate the initial condition for eliminating influences brought by inappropriate initial condition settings.

3.3.4 Methodology of FEQUTL

FEQUTL is an attached model for FEQ. It is used to create lookup tables for node and hydraulic structures. This research just introduce the lookup tables for nodes.
The most important part of node information is the cross section. The relation-

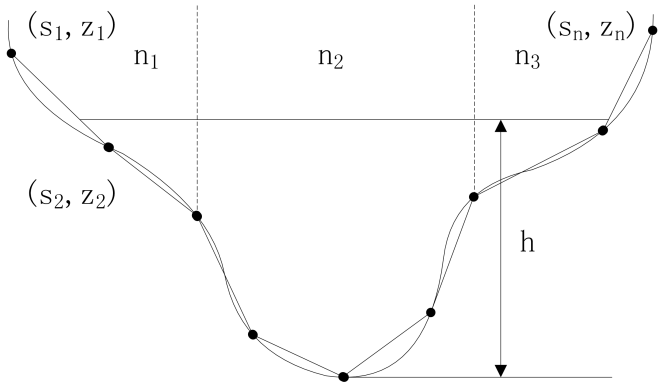


Figure 3.8: The Dinkel River cross section schematization

ship between water level and flow area is not linear and cannot be descried by

function. Thus lookup tables are necessary to be generated for unsteady flow simulation. Figure 3.8 is a conceptual graph for the cross section. The shape of the cross section is described by the width-depth method in FEQ. From the left side of the cross section several points are taken in different distance based on the change of the cross section shape. For sample i, the horizontal distance between it and the right side will be recorded as s_i, and the elevation of this sample will be recorded as z_i. So a array of $\{s_i, z_i\}$ represents the geometry of the cross section.

In the FEQUTL, several hydraulic characteristics that change based on the water level are calculated to form a lookup table for each cross section. The basic theory of this process is the Manninng's formula (Equation 3.9).

$$Q = \frac{k}{n} A R^{2/3} \cdot S_0^{1/2} \tag{3.9}$$

where k = conversion constant equal to 1.0 for SI units or 1.486 for U.S. units; R = hydraulic radius; n = manning roughness coefficient.

The hydraulic radius is defined as the ratio of cross section area (A) over the wetted perimeter (P). Wetted perimeter is the perimeter of the cross section area where touches the water body. The manning's n is required to specified for each cross section. FEQ model allows user define one value for each cross section. In addition, user can also specify manning's n for each offset in one channel. The method of separating the cross section into several offsets are defined by user based on the issue of research. In this case study, each cross section is given 1 manning's n.

Hydraulic characteristics and corresponding symbols are listed in Table 3.2.
J is the first moment of area with respect to the water surface. J can be

Table 3.2 Contents of lookup table for cross sections

Symbol	Comment
y	Width of the water surface
T	Depth of the water
A	Area of the flow through the cross section
$\sqrt{K}$	K is the conveyance
β	Momentum flux correction coefficient
J	First moment of area about the water surface
α	Energy flux correction coefficient
Q_c	Critical flow rate

simulated by Equation 3.10. The conveyance K is defined as Equation 3.11. β is used to correct errors from use of the average velocity instead of the local

velocity field in the cross section. It can be calculated by Equation 3.12. The defining equation of energy flux coefficient α is Equation 3.13. And Q_c is defined as Equation 3.14.

$$J = \int_0^y (y - z)T(z)dz \tag{3.10}$$

where y = water depth; $T(z)$ = top width changed by z; z = depth variables from 0 to y.

$$K = \frac{k}{n}AR^{2/3} \tag{3.11}$$

$$\beta = \frac{1}{Q\bar{v}}\int_A v^2 dA \tag{3.12}$$

where $\bar{v}$ = average velocity; v = the velocity at each point in the cross section.

$$\alpha = \frac{Q}{\bar{v}^2}\int_A v^3 dA \tag{3.13}$$

$$Q_c = A\sqrt{\frac{gA}{T}} \tag{3.14}$$

Lookup tables show the value of hydraulic parameters at corresponding water depth in a certain interval. After lookup tables are created, FEQ model can retrieve values of any hydraulic characteristics at any water depth by linear interpolation as Equation 3.15.

$$f(h) = f(h_i) + \frac{(h - h_i)}{(h_{i+1} - h_i)}(f(h_{i+1}) - f(h_i)) \tag{3.15}$$

where $f(h)$ = value of a specified hydraulic parameter at water level h; h = water level in the calculation; h_i, h_{i+1} = 2 known water levels in lookup tables and meet $h_i < h < h_{i+1}$.

3.4 Calibration

In this study, only Manning's n is calibrated in the FEQ model for the Dinkel case. Manning's n is a parameter to describe the roughness of the river channels. It cannot be measured directly, but can be retrieved from Manning's Formula (Equation 3.9). Considering that roughness of the channel changes with the season, this research will define a probable range for Mannning's n and change its value to compare the result of the FEQ model ($\{s_i\}$) and observed data ($\{o_i\}$). 3 criterions will be used to evaluate the results based on the method of Wöhling et al. (2008).

R^2 gives the square of the Pearson product moment correlation coefficient of 2 data sets. It is used to evaluate the strength of linear dependence of two variables. Value of R^2 ranged between 0 and 1. The higher the value of R^2 is, the higher dependence of the 2 variables is. R^2 can be described by Equation 3.16.

$$R^2 = \frac{(\sum_{i=1}^{n}(s_i - \bar{s})(o_i - \bar{o}))^2}{\sum_{i=1}^{n}(s_i - \bar{s})^2 \sum_{i=1}^{n}(o_i - \bar{o})^2} \tag{3.16}$$

where s_i = the ith simulated value; o_i the ith observed value; $\bar{s}$ and $\bar{o}$ =average value of simulated data and observed data; n the number of elements in the data sets.

Root Mean Square Error ($RMSE$) is also popular in hydrological research. $RMSE$ is a measurement of the differences between 2 data sets[2] The $RMSE$ can be calculated by Equation 3.17

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(s_i - o_i)^2}{n}} \tag{3.17}$$

Efficiency coefficient C_e (Nash and Sutcliffe, 1970) can be used to evaluate the accuracy of model's result. Its value ranges from $-\infty$ to 1. There is a perfect match of observed data and simulated result when $C_e = 1$. The formula of C_e is as

$$C_e = 1 - \frac{\sum_{i=1}^{n}(o_i - s_i)^2}{\sum_{i=1}^{n}(o_i - \bar{o})^2} \tag{3.18}$$

3.5 Validation

The validation process is used to check if the results of the FEQ model have a good match with observed data. In this research, linear regression is applied to compare the simulate results with observed data. $Slope$, $intercept$ and correlation coefficient of linear regression (R^2) are calculated as criterions to evaluate the results. In addition, $bias$, $RMSE$ and C_e are also included in the validation process.

Linear regression is used to model the relationship between observed ($\{o_i\}$ denoted by $\{x_i\}$) and simulated ($\{s_i\}$ denoted by $\{y_i\}$) data. If the model can simulate the variable perfectly, the linear regression equation should be as

$$y = x \tag{3.19}$$

However, the common form for linear regression equation is like Equation 3.20.

$$y = ax + b \tag{3.20}$$

In Equation 3.20, a is the slope used for validation. $Slope$ can also be represent by Equation 3.21.

$$slope = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{3.21}$$

[2]In this research, the 2 data sets are the simulated and observed data.

where $\bar{x}$ = average value of samples $\{x_i\}$.

$Intercept$ is the position at which the best-fit regression line will intersect the y-axis, which is the b shown in Equation 3.20. It also can be obtained after the $slope$ is known (Equation 3.22).

$$intercept = \bar{y} - slope \cdot \bar{x} \tag{3.22}$$

$Bias$ is used to test the difference between expectations of simulated and observed data. Equation 3.23 is the formula for $bias$ calculation.

$$bias = \mathbf{E}[x] - \mathbf{E}[y] \tag{3.23}$$

where $\mathbf{E}[x]$ = expectation of $\{x_i\}$, which is equal to $\frac{1}{n}\sum_{i=1}^{n} x_i$.

3.6 User Interface

User interface was designed for user to understand the model and prepare inputs effectively. In addition, the user interface for the FEQ model in this research also have the function of linking the output in Hydro Preprocessing package as input in the FEQ model directly. Based on the basic simulation unit of the FEQ model, the structure of user interface for FEQ model is designed as Figure 3.9. This program can be divided into 3 dialogues. First Dialogue is **Node**. **Node** contains all information related with node. It has 4 sub dialogues. The first sub dialogue records the general information about the node ID, initial condition, ID of cross section, boundary condition and hydraulic structures to link the attached hydrological information with the specified node. The second dialogue include the information of cross sections. The **Boundary** sub dialogue contains the time series data of discharge or water level for boundary condition input. The **Hydraulic Structure** dialogue is left empty because the limited time of this research.

The second dialogue is called **Branch**. It obtains some branch information from the output of Hydro Preprocessing package in ILWIS, such as channel length, elevation upstream and downstream, etc. It also record the branch ID upstream and downstream to represent the topology of river network. The node ID saved in **Branch** is used to establish a linkage with the node information.

The **FEQ_GUI** is used to set calculation parameters, such as the start time, end time, time interval for output and directory of input data. After input are prepared, the **FEQ_GUI** can run **Lookup Table** first for creating lookup tables by FEQUTL. Then the FEQ can be run for unsteady flow simulation. Graphs of dialogues and the data structures for inputs are display in Appendix D.

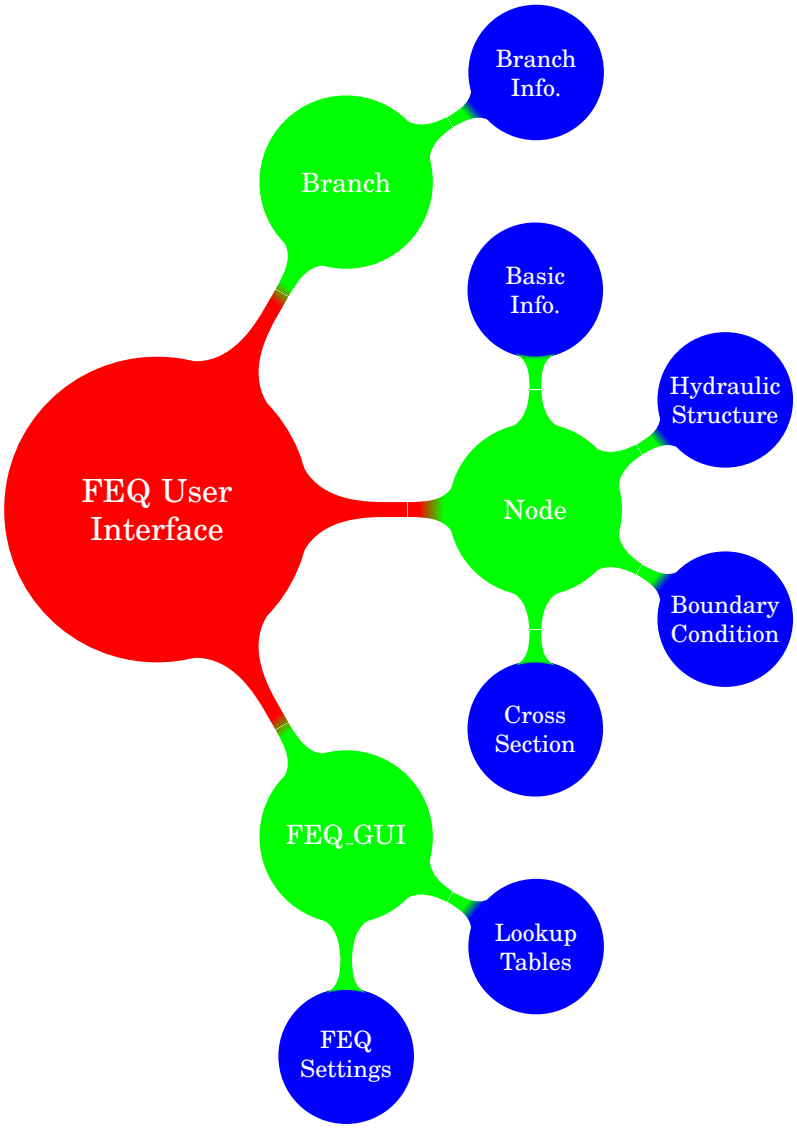


Figure 3.9: Structure of user interface design for FEQ

Chapter 4

Data Preparation

In this chapter, the process for data preparation is discussed, including Hydro Preprocessing analysis, FEQ input collection and preprocess for some problems in the data. The quality of data and the result of Hydro Preprocessing will be analyzed. In addition, a original evaluation for the data and conclusion for the Hydro Preprocessing package are included at the end of corresponding sections.

4.1 Hydro Preprocessing

In this research, we tested the retrieved hydrological information from a DEM image instead of fieldwork. The detailed process of river network retrieval by Hydro Preprocessing is illustrated in Appendix C. Here we use the STRM image that covers the Netherlands and Germany for river network retrieval. As the procedure introduced in Section 3.2, Dinkel River catchment and network are obtained from the DEM. Since the resolution of DEM is $90m$, which is very low compared with the channel width ($10 \sim 20m$). The mean river network retrieved are evaluated by comparing it with river network map from Water Board and Google Earth (Figure 4.1). The black line is the main channel of the Dinkel River retrieved from Google Earth. Blue lines are the Dinkel River system obtained from SRTM by Hydro Preprocessing. Some samples ($\{pnt_i\}$) are taken along the simulated main river channel. The distances (d_i) between the sample pnt_i and the channel retrieved from Google Earth are calculated for the accuracy study. The distance here is defined as the length between a sample on the simulated river channels and the corresponding nearest point on the river

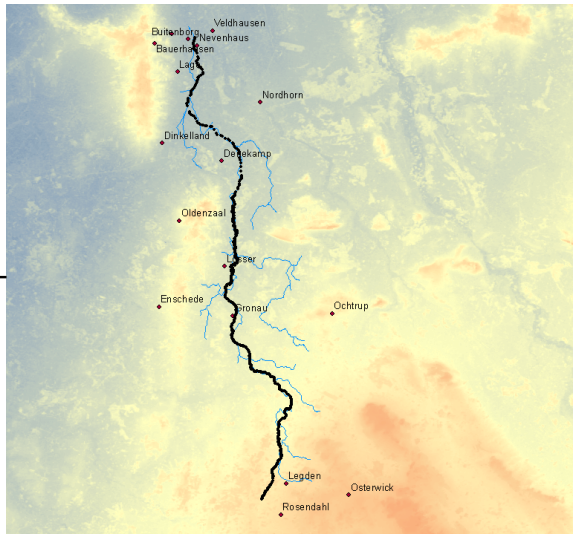


Figure 4.1: River network from Google and ILWIS

channels from the Google Earth image.

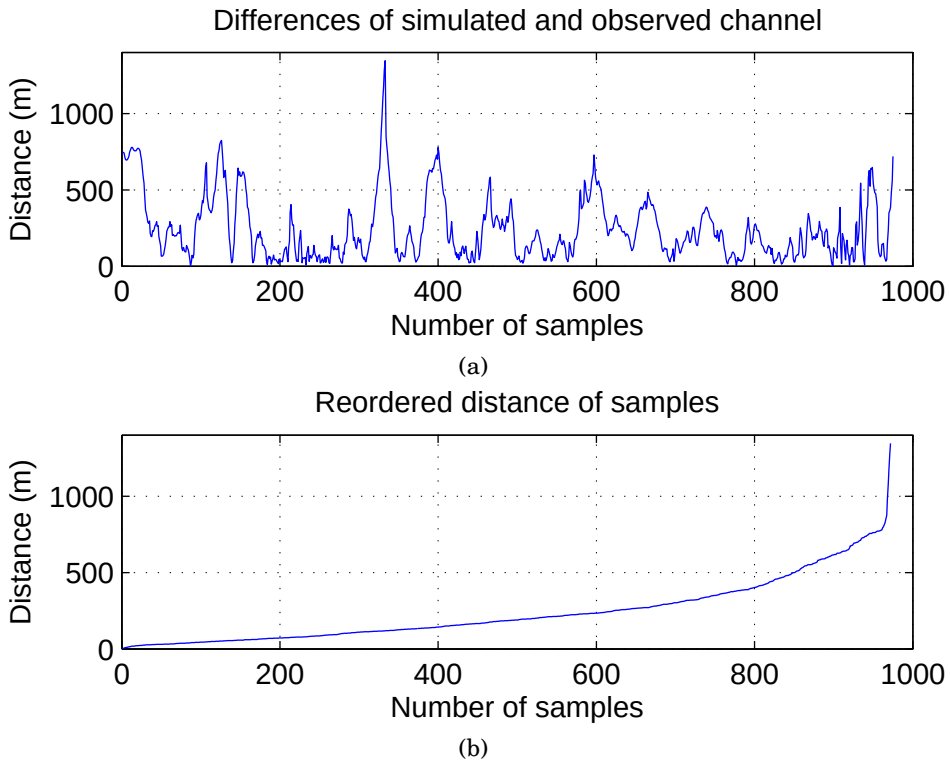


Figure 4.2: Differences of simulated and observed networks

Figure 4.2a plots the differences of the simulated and observed channel. Figure 4.2b resorts the samples in an ascending order based on the length of distance. Nearly 99% of the samples has a distance less than $800m$ and about 80%'s distances are less than $400m$. Comparing with the total length of the Dinkel River, this result is acceptable. The reasons for this error are the flat terrain in the basin and projects on the Dinkel River. The elevation of Dinkel River basin in Dutch part varies from $80 \sim 19m$. The range of the elevation at the area near the main channel is from $38 \sim 19m$. The resolution of SRTM is too low to detect the river channel directly. SRTM only can represent the trend of the terrain change. Another reason is about the human activities in this area. Some engineer programs for the river are also possible to make changes for the channel.

Finally, the attached table of the Hydro Preprocessing is used to obtain some hydrological information as input for FEQ model. One thing should be mentioned is that the table here will not be used directly in the FEQ model, because the low resolution and low accuracy for the elevation (Table 2.1). This issue will be analyzed in next section.

4.2 Input for FEQ

There are 3 parts of data for the input of FEQ model:

1. The geometry and physical parameters of the Dinkel River
2. The observed hydrological data for initial and boundary conditions
3. Calculation settings

The first part of the data are quite invariant for the Dinkel River. They are changed only after artificial modifications. The second part include the hydrological information that change as a function of time. It should be updated every time when using FEQ model. And last part is based on user's research aim and accuracy required.

Figure 4.3: Test area in the Dinkel River basin

In this research, a FEQ model including 3 channels is built. Figure 4.3 shows the area of interest. There are 3 channels in the test area. Channel 1 and channel 2 join together at the upstream of channel 3. Zoekerbrug, Ficksbrug and Bossinkbrug are 3 gauging stations at the boundary of this area. The FEQ model is used to simulate unsteady flow processes at Bossinkbrug by using time series data from Zoekerbrug and Ficksbrug during flooding periods. Based on the algorithm of the FEQ model, 6 nodes are defined as upstream and downstream for each channel. The linkage of the channels are recorded in the Hydro Preprocessing table.

4.2.1 Geometry & Physical Parameters

Figure 4.4 is the conceptual graph for the network structure. In this study, we consider that the network is composed by 3 channels with 2 nodes at each side. Geometry and physical parameters can be separated into the information of channels and nodes. For the nodes part, the geometry of cross section are obtained from the data and reports (Gels et al., 2001) supplied by Water Board. The cross section at node 1, 2, 4 and 3(5)[1] are specified. For channel 1, interpolation of cross section at node 1 and 3 is applied to define the cross section along channel 1. Interpolation method will also be used for channel 2 by cross section specified at node 2 and 4. Channel 3 is very short. There is not much change about the cross section shape. In addition, no data available for cross section information at node 6. Here cross section at node 5 will be used for the whole channel 3.

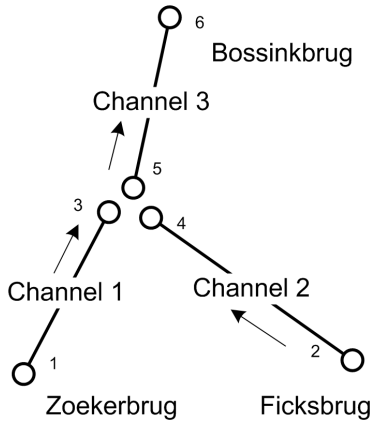


Figure 4.4: Conceptual network

Manning's n is also necessary to define for each cross section. This parameter is a empirical value and cannot be measured directly. In many literatures and handbooks, the value of Manning's n of natural open channels varies in a range between 0.025 and 0.15. Jansen et al. (2001b) gave value for roughness coefficient with different land cover in Dinkel River basin. In Section 5.1, manning's n will be discussed for initial value selection and calibration.

The channels' part includes the length and elevation upstream and downstream. The length data can be obtained from the Hydro Preprocessing table. But the Dinkel River is very sensitive to the elevation due to the flat terrain. The elevation from the SRTM cannot meet the requirement in FEQ modeling. Comparing the cross section (blue lines) and nodes' elevations (green lines) from SRTM in Figure 4.5, it's easy to find that the SRTM cannot detect the channel because its $90m$ resolution. The elevations from the SRTM are equal to the elevation of the river banks. Thus the elevation of cross section's bottom is used to calibrate the channels' elevation. There is one exception that the minimum water level record at Ficksbrug is $34.34m$ while the elevation of cross section bottom at node 2 is $34.63m$. The changes at node 6 in the past several years led to this error for the cross section information was collected in 2001. Finally the elevation at node 2 is specified as $34.2m$ based on the base flow from channel 2.

4.2.2 Discharge & Waterlevel Data

This study uses water level data at the 3 gauging stations and discharge data at Zoekerbrug. These time series data last from as early as 1952 until 2009 with hourly measurement. There are several gaps in the data before 2006. In

[1]Because the channel 1 and channel 3 are main channels, the cross sections at node 3 and 5 are assumed the same.

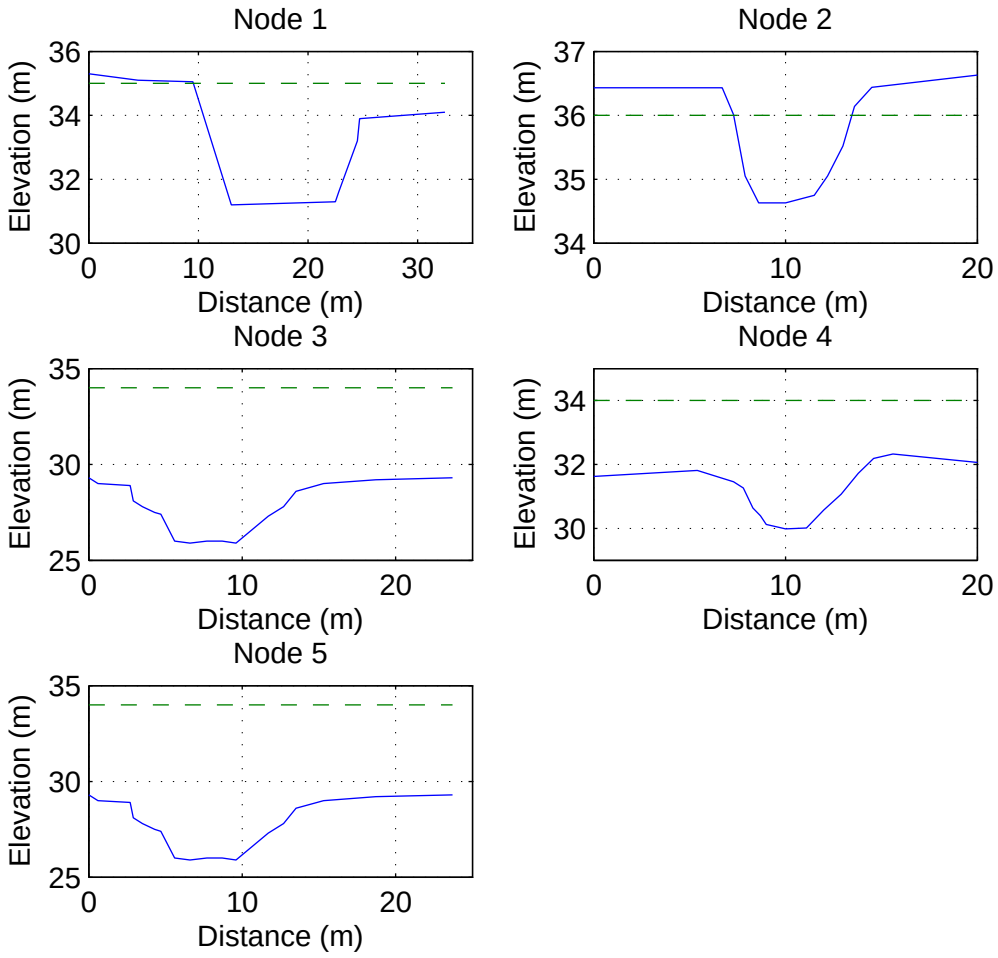


Figure 4.5: Cross sections and elevations at 5 nodes

addition, very old data are not good to be used in recent channel flow simulation. The data from spring in 2007 to autumn in 2009 are used to calibrate and validate the FEQ model. The time series data at Zoekerbrug and Ficksbrug are for input as boundary conditions. Water level records in Bossinkbrug are for FEQ model calibration and validation. As the requirement of the FEQ model, the initial condition, water level and discharge, at the node 1, 2 and 6 must be specified for the beginning of calculation. As the discussion in methodology, the initial condition is necessary for solving partial differential equations. It will influence the backwater analysis at the beginning, after a short time, the flow simulation will not be changed by different settings for initial condition. The first water level data can be used for define the boundary condition of water level. For the discharge boundary condition at Ficksbrug, a H-Q relation will be used. For the calibration and validation processes, a short part of data will be deleted for erasing the effect of boundary condition settings (Section 5.2).

4.2.3 Calculation Settings

Calculation part varies based on the requirement of user. In this research, each channel was divided into 10 branches as spatial calculation interval. The time interval is set at 1 hour to keep the temporal resolution same as observed data. The settings of start time and end end time are up to the duration of the boundary conditions.

4.3 Data Interpolation

In the water level data from 2007 to 2009, there are still many blanks of data. Since there is a strong linear relationship between water level at Zoekerbrug and Bossinkbrug (Figure 4.6), dependent linear interpolation method is applied for data recovery at Zoekerbrug and Bossinkbrug (Equation 4.1) if other data set has record during the data loss period. If data at both stations are lost at same time, a simple interpolation method (Equation 4.2) will be applied. For the Ficksbrug station, the discharge is very small compared with the main channel. Simple linear interpolation (Equation 4.2) is used for data recover in Ficksbrug.

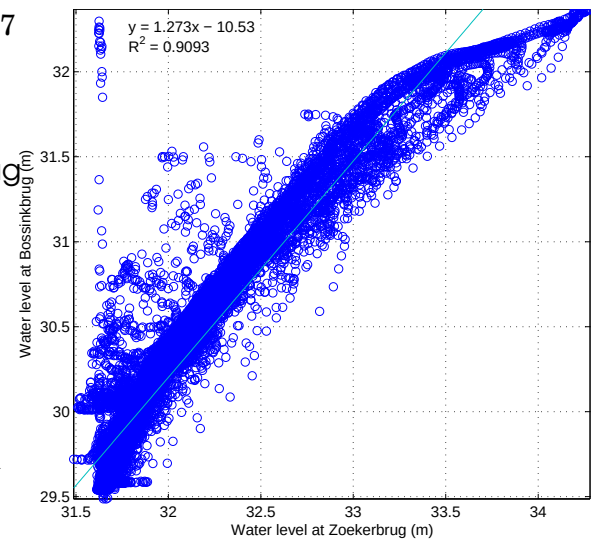


Figure 4.6: Correlation of water level at Zoekerbrug and Bossinkbrug

$$h^1_{t+i} = h^1_t + (h^2_{t+i} - h^2_t)\frac{h^1_{t+n} - h^1_t}{h^2_{t+n} - h^2_t} \tag{4.1}$$

where $\{h_i^1\}$ and $\{h_i^2\}$ are water level data at 2 gauging stations at time i; here $\{h_i^1\}$ missed data between time t and $t+n$, it can be recovered by comparing the data in $\{h_i^2\}$ between time t and $t+n$.

$$h_{t+i} = h_t + \frac{i}{n}(h_{t+n} - h_t) \tag{4.2}$$

where h_i = water level data at time i.

Chapter 5

Result

This chapter introduces the process of calibration and validation. From the initial value of Manning's n, the calibration starts to optimize the n's value for best result. Finally the validation of the FEQ model is shown for several flooding periods.

5.1 Manning's *n* Retrieval

Manning's n is the only unspecified variable for input of FEQ. It represents the roughness of river channel in Manning's Formula (Equation 3.9). It is influenced by the shape of cross section, vegetation, materials and cleanness of the channel. In Dinkel River, the natural channel is covered by grass (Figure A.1b) which strongly influences the roughness coefficient. In addition, the condition of grass growth varies with the seasons. Figure A.1c and Figure A.1f are the land cover of Dinkel River in summer and late autumn respectively. A time series data of Manning's n can be retrieved from the water level and discharge data in Zoekerbrug. Then the characteristics of roughness coefficient change will be discussed by analyzing temporal distribution of Manning's n.

5.1.1 Algorithm for *n* Retrieval

Manning's n cannot be measured directly. It only can be simulated from the changed form of Manning's Formula (Equation 5.1).

$$n = \frac{1}{Q} A R^{2/3} \cdot S_0^{1/2} \tag{5.1}$$

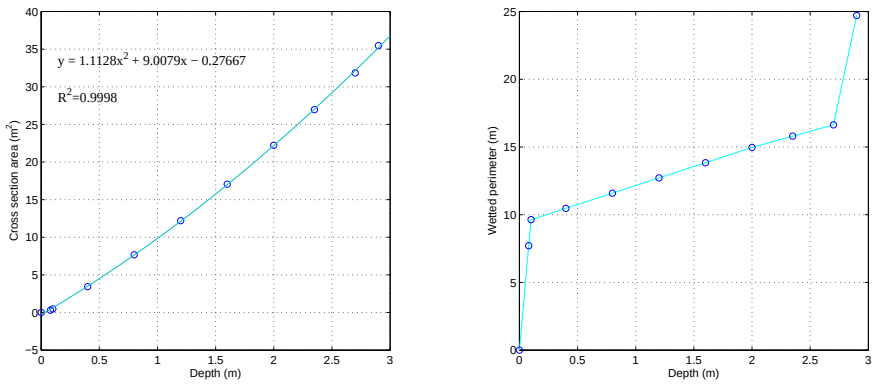
In Equation 5.1, S_0 is known, and Q is the observed discharge data. A and R should be calculated from the observed water level (h) data by using lookup table from FEQUTL. The detailed process is shown as,

1. Generate the lookup table (Table 5.1) for cross section at node 1 by setting a default value of Manning's n (for example, here n is set as 0.028).
2. Create the h-A curve and h-P curve (Equation 5.2) and do second-order polynomial and linear regression respectively.

3. Calculate Manning's n by the h-Q data and regression formulas from lookup table.

Table 5.1 Part of Lookup table for cross section at Node 1 by setting Manning's n as 0.028

Depth	Top_width	Area	Sqrt(conv)
0	0	0	0
0.0799999	7.6728358	0.306913137	1.13050961
0.0999985	9.5909081	0.479538083	1.52222681
0.3999996	10.163635	3.4427309	7.6545887
0.7999992	10.952271	7.66590834	14.416769
1.2000008	11.740911	12.2045622	20.5951157
1.5999985	12.529543	17.0586243	26.4656792
2	13.318183	22.2281895	32.149601
2.3500023	13.736368	26.9627666	37.0833626
2.7000008	14.154548	31.8436565	41.8717804
2.8999977	22.136362	35.4726906	40.1525993



(a) h-A (b) h-P

Figure 5.1: Regression of h-A and h-P curves

$$P = \frac{R}{A} = \frac{\left(\frac{0.028 \times K}{A}\right)^{\frac{3}{2}}}{A} \tag{5.2}$$

Figure 5.1a and 5.1b show the regression for h-A curve and h-P curve respectively. The formulas for calculating A and P are shown in Equation 5.3 and 5.4 respectively.

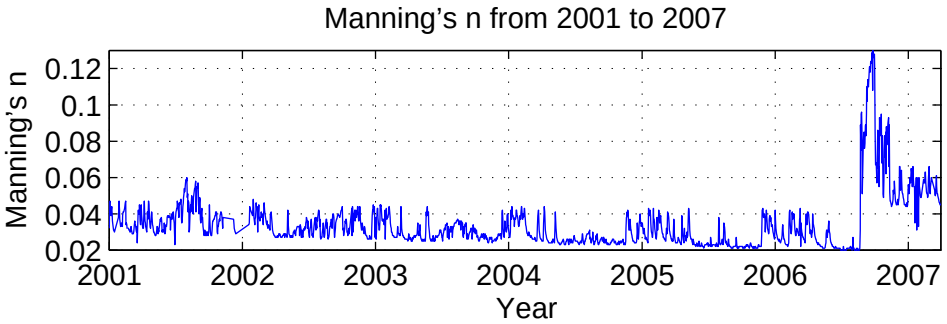
$$A = 1.1128h^2 + 9.0079h - 0.2767 \tag{5.3}$$

$$P = \begin{cases} 96.358h + 6 \times 10^{-7} & h < 0.01 \\ 2.7216h + 9.4118 & 0.01 \leqslant h \leqslant 2.7 \\ 40.365h - 92.349 & h > 2.7 \end{cases} \tag{5.4}$$

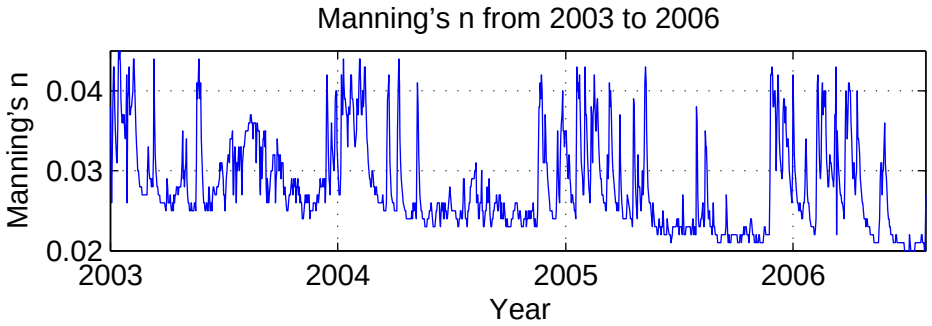
With known slope of channel 1 $S_0 = 0.000417$, Manning's n can be obtained by the method discussed above.

5.1.2 Time Series Analysis of Manning's *n*

After deleting some abnormal values[1], the time series of retrieved n is plotted in Figure 5.2a. The n's value varies normally between 0.02 and 0.06. From the data between 2003 and 2006[2] (Figure 5.2b), the n's value changed obviously with the season. n keeps nearly steady between 0.02 and 0.035 during summer and autumn. In winter and spring, n fluctuates significantly between 0.025 and 0.04. There is a steep jump from Sept. to Nov. 2006. After the jump, the n returned to the range around 0.05 to 0.065. From the view of n changing process, there is probably a project or instruments improvement at Zoekerbrug that lead to this abnormal phenomenon.



(a)



(b)

Figure 5.2: Time analysis of Manng's n

Although the value of Manning's n increased after 2006, the available data just last until Mar. 2007. Since the water level data used for FEQ unsteady flow simulation is from 2007 to 2009, Manning's n is still necessary to be calibrated. In addition, the roughness coefficient retrieved from Zoekerbrug cannot represent the channel situation in the whole area of interest. However, this basin

[1]Some samples that less than 0.015 are deleted.
[2]The data before 2003 is not integral. The time series cannot illustrate the changing cycles.

is very small and the land cover doesn't change significantly. And there is no discharge data to calculate n on each branch. This study assume that the n's value doesn't change at any branches during a same period.

5.2 Calibration

The calibration of the FEQ model is the process to specified a n's value for the best simulation result comparing with observed data. From the analysis above, n is initialized at 0.055 and the data during the spring and winter in 2007 are used for calibration. The flow during summer and autumn is near base flow. The discharge is little and the water level at Ficksbrug is very low. The flow in these 2 seasons are not used for unsteady flow simulation here. The calibration starts from the second day of simulation to avoid the error brought by improper settings for boundary condition. Table 5.2 displays the 3 criterions under different n's FEQ model. The change of Manning's n in a considerable range results in a little differences for 3 criterions. As the result shown in Table 5.2 and 5.3, Manning's n is fixed at 0.045 for spring and 0.175 for winter.

Table 5.2 Calibration for spring

Manning's n	R^2	$RMSE$	C_e
0.04	0.992899	0.1022	0.9755
0.043	0.992913	0.1022	0.9755
0.045	0.992917	0.1022	0.9755
0.05	0.992911	0.1023	0.9755
0.055	0.992883	0.1024	0.9754
0.058	0.992864	0.1025	0.9754
0.06	0.992845	0.1025	0.9754

Table 5.3 Calibration for winter

Manning's n	R^2	$RMSE$	C_e
0.075	0.956743	0.1282	0.9405
0.085	0.957722	0.1268	0.9417
0.105	0.959346	0.1246	0.9438
0.125	0.960492	0.1229	0.9453
0.155	0.961412	0.1214	0.9466
0.165	0.961509	0.1212	0.9468
0.175	0.961520	0.1211	0.9469
0.18	0.961471	0.1211	0.9469
0.185	0.961412	0.1211	0.9469

5.3 Validation

The calibrated FEQ model runs for the unsteady flow from spring 2008 to spring 2009. Since the lack data in winter of 2009, unsteady flow in this season is not

used for validation. There is 1 day delay for validation as the calibration process. Figure 5.3 plots the simulated and observed data in 3 flooding periods. Blue lines are observed water level data, while red lines are simulated data. Table 5.4 gives the $bias$, $RMSE$ and C_e of the 3 periods for validation. In some periods, when the water level data at Ficksbrug is too low to simulate in the FEQ model, the calculation is stopped.

Table 5.4 Criterions of validation

Period	$bias$	$RMSE$	C_e
Mar. 08 – Jun. 08	0.031	0.0945	0.9721
Mar. 09 – Jun. 09	-0.0256	0.0657	0.9824
Dec. 07 – Feb. 08	0.0086	0.1545	0.9466

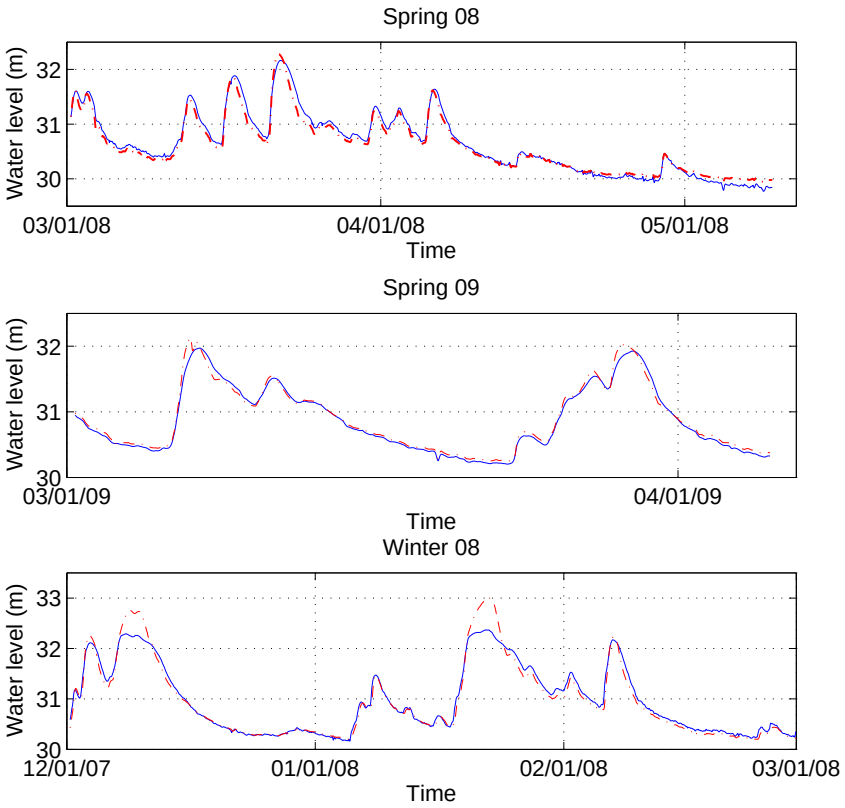


Figure 5.3: FEQ model validation for 3 flooding periods

The simulate data and observed data in 3 cases are plotted in Figure 5.4. X-axis represents observed data while y-axis represent simulated results. Red lines illustrate linear regression results for the 3 cases respectively. $Slope$,

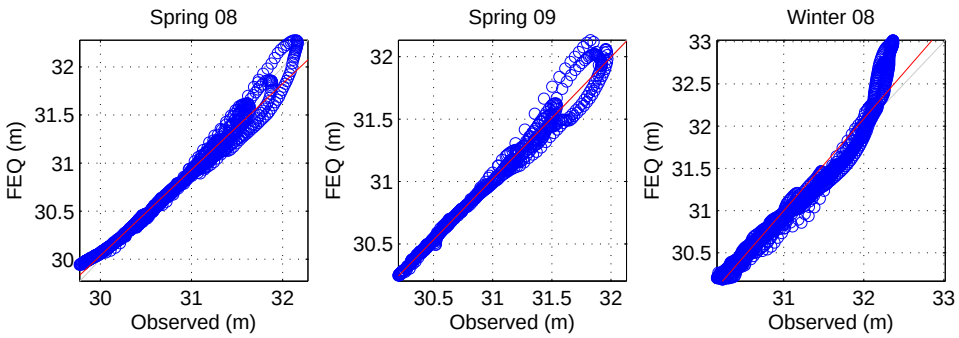


Figure 5.4: Linear regression for validation

intercept and attached R^2 are summarized in Table 5.5.

Table 5.5 Results of linear regression

Period	*slope*	*intercept*	R^2
Mar. 08 – Jun. 08	0.8943	3.209	0.9832
Mar. 09 – Jun. 09	0.9753	0.7871	0.9852
Dec. 07 – Feb. 08	1.089	-2.76	0.9631

Chapter 6

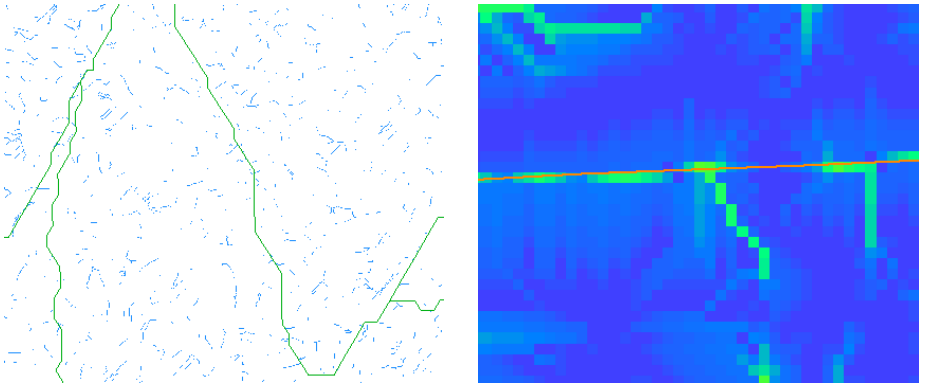
Discussion

During this research, many limitations of the methodology, models and methods are discovered. This chapter will discuss reason of errors, problems of observed data, the quality of results, limitations of the FEQ model and methodology, etc, in order of the research procedure.

6.1 Hydro Preprocessing

Hydro Preprocessing is the primary part in this research. The quality of its results directly influences the accuracy of the FEQ model. The Hydro Preprocessing package is designed for large scale river catchments (Maathuis and Wang, 2006), but the result for Dinkel River is still acceptable, especially in the test area. Anyway, there are 3 issues should be discussed here.

6.1.1 Resolution of DEM



(a) (b)

Figure 6.1: Accuracy analysis of AHN and SRTM

The spatial resolution is a crucial criterion to evaluate the quality of DEM images. In this research, 2 different resolution DEM images are checked, AHN

images with $5m$ resolution and SRTM with $90m$ resolution. Figure 6.1a compares the river network retrieved by AHN and SRTM. Green lines represent the river channel obtained from SRTM, while blue lines represent river network retrieved from AHN. It is clear to see that AHN cannot retrieve river network properly. Figure 6.1b displays a detailed part of the hydro accumulation map of AHN. The orange line is a natural channel. Figure 6.2 shows the elevation change from left to right side along the channel shown in Figure 6.1b. The operation for river network retrieval is failed because the slim elevation changes along the river channel effect the water flow direction operation significantly. As the result, for a small river basin in a flat area, the proper resolution of DEM should be able to detect the general trend of elevation changes and slope directions.

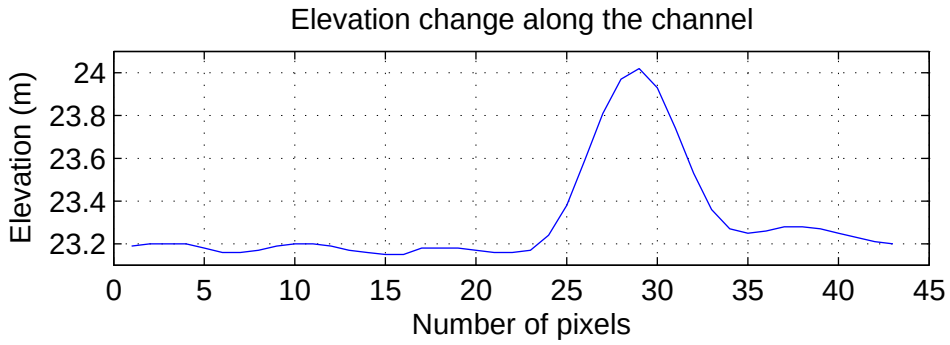


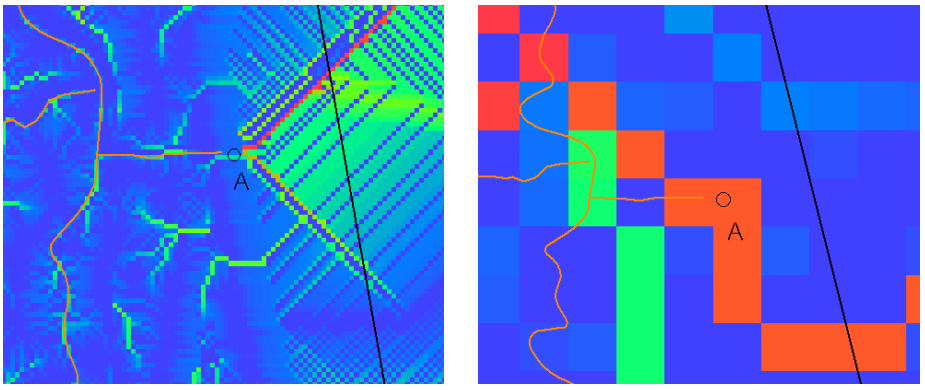
Figure 6.2: Elevation change along the channel

Another problem for AHN is that it doesn't cover the whole catchment. Figure 6.3a shows the AHN accumulation map at the boundary of Netherlands and Germany. The black line is the national boundary with Netherlands at left and Germany at right. At Point **A** there is a stream flowing into Dutch part. In the STRM (Figure 6.3b), the value for this channel is large enough for retrieval by setting a large threshold accumulation number. Due to there is no enough points in AHN drain into this channel, this tributary is neglected.

For a small river, such as the Dinkel, a $0.5m$ error of node elevation can result in huge differences in results (Section 4.2). The hydrological information from the DEM is necessary to be carefully checked for small river catchment by comparing with measured topographic data. For a large river, this uncertainty cannot influence the result too much. This checking process is an option for large scale basins.

6.1.2 Tracer for Bifurcation

Dinkel River is separated into 2 channels at the Verdeelwerk (Figure 6.4). Green lines are the natural network of Dinkel River. Blue lines represent the simulated result from SRTM by Hydro Preprocessing. For the algorithm, Hydro Preprocessing only chooses the deepest channel way as flow direction. In



(a) AHN (b) SRTM

Figure 6.3: Flow accumulation of AHN and SRTM

ArcHydro (Maidment, 2002), there is a utility called **Tracer**, which is used to seek the most probable way to an existing channels by defining a start point. Using the idea of **Tracer**, it's possible to design a utility to find the second probable downstream channel by selecting a start point in the main channel. The flow direction will be run again from the specified point on the channel to seek another direction flowing down without the main direction. As Maidment (2002) discussed in the flow direction part, for some very complex braided stream channels and constructed channel systems, the river network should be revised manually.

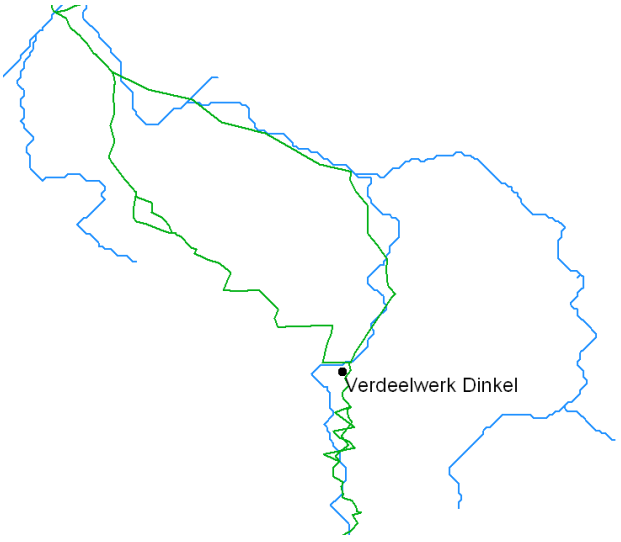


Figure 6.4: Bifurcation at Verdeelwerk

6.1.3 Cross Section Retrieval

In ArcHydro, there is a part for cross section retrieval from DEM image. After define the central lines and channel width, cross section can be read directly from DEM by given a certain length interval. In this research, the resolution of SRTM is 4 – 9 times of the main channel width. The cross section cannot be obtained from DEM in Dinkel River, but it can be considered to be developed in Hydro Preprocessing for large basin study.

6.1.4 Human Activities

Another two factors effected the accuracy of Hydro Preprocessing are human activities and structures on Dinkel River. Dinkel River flows through the rural and urban area where has a large population. The flooding hazards and irrigation problems made people changed the river a lot in the past. Some parts are channelized. Some channels are changed for human development. Anyway, although the river network simulated by Hydro Preprocessing can not make a perfect match with the really network, the general shape is generated with an acceptable accuracy. In addition, the simulated river network represents the initial situation of the channels. It can be used for the historical study of interactions between Dinkel and humans.

6.2 User Interface

The user interface developed for linking FEQ with ILWIS Open is succeed in completing the main objective of this research. However, because lack of programming experience and limitation of knowledge, some functions for hydrological data management are not convenient enough, especially for boundary condition data import. The FEQ model also considers many other factors for unsteady flow modeling, for instance the wind speed and direction, lateral flow, etc (Franz and Melching, 1997). The interface only includes the basic elements for modeling because the limited time of this Msc research.

6.3 Manning's *n*

Manning's n is an unspecified parameter in this research. It is retrieved from the Q-H data at Zoekerbrug and calibrated in the FEQ model. The situation of grass growth has a strong influence to the manning's n. Seasonal dynamics of n's value can be derived from Figure 5.2a. In additional, from Figure 5.2b a slim decrease of n's value can be detected from 2001 to 2006. Since the vegetation determines Manning's n, the long time scale change of Manning's n can be used for the vegetation growth analysis for climate change. In 2006, there is a jump of n. After the jump, Manning's n fluctuates around 0.055. This suddenly change is caused by some physical changes near the gauging station, which totally change the normal range of n's value.

In the calibration part for spring, Manning's n is optimized at 0.045. While

in the calibration for winter, n is very high (0.175). Except the effects from the grass, the Manning's n is also strongly influenced by snow and ice during winter. However, Manning's n is a abstract coefficient. The calibration process is based on the assumption that the study area is homogenous for roughness. The calibrated n represents the generate roughness situation in the study area.

6.4 FEQ Validation

The results in Table 5.4 illustrates good matches between simulated and observed data. The absolute values of $bias$ are smaller than 0.03, which means the biases between the simulated and observed data are very small. $RMSE$ and C_e also show good fitness in 3 flooding periods. From the linear regression results showed in Figure 5.4, we can see that there is a overestimation when water level is lower than $30m$ (in Spring 08), which is the steady base flow in Dinkel River. In this study, the interaction between the channel flow and hyporheic zone is not considered. The base flow in Dinkel River is small, which means the effect from hyporheic zone is relatively stronger. After the flood passes, the unsteady flow returns to steady base flow. Then the water loss for recharging the hyporheic zone becomes obvious. This contributes to the overestimation of discharge in FEQ during base flow periods.

In the first 2 graphs in Figure 5.4, there are several slim curves during flood peaks, which are attributed to small temporal errors of simulation. This temporal error is due to the variance of roughness of the channel, which influences the velocity of the flow. In addition, all of the 3 cases show a overestimation of the FEQ model during flood peaks. This overestimation is attributed to the storage zones in Dinkel River. Storage zones can store a large amount of water during flooding periods, which reduces the peak of flood. In this research, we neglected the interactions of storage zones. R^2 for linear regression are over than 0.96, which means a good relationship between simulated and observed flow processes. The results of $slope$ and $intercept$ also show that the FEQ model is appropriate for unsteady flow simulation in Dinkel River.

The quality of data is another limitation of this study. The temporal resolution at 3 gauging stations is 1 hour. And the data is available since 1952. But there are blanks in the older time series. At some parts, the observed data are very strange, which also add uncertainties for the unsteady flow modeling. In addition, the geometries of cross sections along the main channel are retrieved from reports of Dinkel projects. The physical parameters are changing slowly, which makes the historical data cannot be entirely used for high accuracy research.

Chapter 7

Conclusion & Recommendation

From the result and discussion, limitations and errors of this research are discovered. Because the time for this Msc research is limited, some data cannot be well collected. FEQ model is a very powerful model containing nearly all factors for open channel unsteady modeling. In this research, only a few part of functions are applied in the user interface for ILWIS Open. Results and experiences are summarized in Section 7.1. Some possible further development for this user interface and some suggestions for future unsteady flow modeling are figured out in Section 7.2.

7.1 Conclusions

Here the conclusions are presented in several subsections for different aspects of this research.

7.1.1 Hydro Preprocessing

- The Hydro Preprocessing package in ILWIS Open can complete the tasks for river channel and hydrological information retrieval.
- The resolution of DEM for plat terrain and small river basin research should be careful selected. The proper resolution should be able to represent the terrain change in large scale without detailed elevation dynamics.
- The AHN data set is a interpolated product from the XYZ point elevation data set of the AHN-2 (Waterschappen, 2010). The algorithm for preprocessing is not appropriate for small river network retrieval.
- It's very important for the DEM images to cover the whole river basin area.
- Human activity in the basin has changed the environment and physical factors significantly for the Dinkel River.

- The output information should be revised for small river. For large river basin, this procedure is optional.

7.1.2 Unsteady Flow Modeling

- Channels roughness coefficients (e.g. Manning's n) can be retrieved from water level and discharge data.

- Manning's n varies seasonally due to the land cover change in river bed and banks. It's also effected by ice and snow during winter. After the calibration, n is optimized at 0.175 for winter, which seems high.

- Manning's n decreased slowly until 2006 where there is a sharp jump. Then n's value returns to the range between 0.045 and 0.065. The change of n at a long time scale can be used for climate change study.

- The calibrated FEQ model can simulate the unsteady flow in Dinkel River with a high accuracy. Absolute values of $bias$ are than 0.3. $RMSE$ is between 0.065 and 0.095 for spring, while it reaches 0.155 in winter. For the coefficient of efficiency of Nash-Sutcliffe, C_e is 0.97 and 0.98 for 2 flooding periods in spring. For winter, C_e is still as high as 0.95.

- In the linear regression process, R^2 are more than 0.98 and 0.96 for spring and winter respectively. Results of $slope$ and $intercept$ are also very good for each case.

- The simulated water level is higher than the observed data during base flow period because this research doesn't consider the interaction with the hyporheic zone.

- Overestimation of the FEQ model during flood peaks is attributed to interaction of storage zones and main channels that are neglected in this research.

7.1.3 User Interface

- The user interface for FEQ in ILWIS Open is designed properly based on the algorithm and procedures of the FEQ model.

- Dialogue **Branch** and **Node** are used for checking, editing and importing data, while **FEQ_GUI** is used for calculation settings. All of them are easily understood for users. It will save a lot of time for users to study the complex input format for FEQ and make them only focus on their own research.

- Result of validation shows that the method for unsteady flow simulation developed in this research can successfully in Dinkel basin case. The whole processes of this method are completed by free open source utilities with a considerable accuracy.

- The simplified user interface of the FEQ model uses many options as default. And the user interface here only simulate the channel and node without other hydraulic structures and factors.

7.2 Recommendation

From the overview of this research, some suggestions for improvement and possible future researchs are figured out in this section.

- Some additional operations as discussed in Section 6.1 can improve the ability of Hydro Preprocessing package in ILWIS for water resources management.
- We recommend that the initial XYZ point elevation data set of the AHN-2 should be re-preprocessed by using appropriate software (e.g. SCOP++) to smooth the terrain for Hydro Preprocessing.
- Projects or accidents that lead to the unusual discharge and water level monitoring should be recorded with the observed data for future use.
- Manning's n can be studied further by linking with land cover change for climate change research.
- The Dinkel River should be studied further by considering the influences of hyporheic zone and storage zone, wind and lateral flow.
- The user interface for FEQ can be extended to support more operations in FEQ. The blocks of hydraulic control structures can be designed properly. Some calculation settings in FEQ input can be improved to set a suitable value automatically instead of a default value.
- An additional package for the output data management and visualization is possible to be generated with the user interface to users. By this package, users can extract the data they want from a large amount of outputs and export it as table or graph formats.
- Both of Hydro Preprocessing and FEQ model are successfully in unsteady flow modeling in Dinkel River. This method can be used in other small or large scale basins to test the accuracy of simulation further.
- In this research, a low-cost but high accuracy method is developed for unsteady flow simulation under ILWIS Open. In addition, Surface Energy Balance System (SEBS) is also successfully completed in ILWIS Open for soil moisture and evaportranspiration study. ILWIS Open is becoming rapidly a powerful and suitable platform for RS and GIS application in water resources management. Groundwater and rainfall-runoff model can be considered to be linked in ILWIS to enhance the ability of ILWIS in hydrological research.

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Appendix A

Photos of the Dinkel River

(a) (b) (c) (d) (e) (f)

Figure A.1: Land cover in Dinkel River basin

Appendix B

Discharge Analysis from 1999 to 2000

Table B.1 Discharge in winter

Year	Average m^3/s	Max m^3/s	Min m^3/s	Variance
1999	11.393	19.786	5.870	11.688
2000	11.049	22.011	1.976	28.392
2001	9.001	28.456	4.026	25.296
2002	12.557	27.719	3.901	40.101
2003	9.900	31.613	2.817	48.157
2004	11.124	27.662	1.275	53.331
2005	8.423	25.070	3.348	16.280
2006	8.578	22.849	3.674	16.807
2007	12.479	34.858	4.596	38.558
2008	12.364	44.627	5.104	68.290

Table B.2 Discharge in spring

Year	Average m^3/s	Max m^3/s	Min m^3/s	Variance
1999	7.494	31.240	1.644	25.523
2000	7.856	30.893	1.569	39.688
2001	7.644	19.495	1.888	16.495
2002	5.399	20.449	1.535	12.097
2003	4.987	16.602	1.548	13.308
2004	5.084	13.106	1.547	7.665
2005	6.074	16.102	2.229	7.558
2006	7.516	18.109	2.356	13.037
2007	7.797	26.758	1.901	39.135
2008	7.395	21.607	1.971	21.885

Table B.3 Discharge in summer

Year	Average m^3/s	Max m^3/s	Min m^3/s	Variance
1999	1.701	5.002	0.262	1.068
2000	2.180	5.898	0.616	1.437
2001	1.227	3.674	0.175	0.570
2002	2.150	10.170	0.731	2.494
2003	1.321	4.121	0.058	1.060
2004	2.336	5.181	0.653	1.039
2005	2.574	8.936	0.818	2.635
2006	1.697	6.464	0.189	1.222
2007	3.370	6.858	1.694	1.817
2008	1.351	3.748	0.698	0.252

Table B.4 Discharge in autumn

Year	Average m^3/s	Max m^3/s	Min m^3/s	Variance
1999	1.503	3.366	0.001	0.495
2000	4.563	8.933	2.064	2.521
2001	2.884	9.256	0.556	2.992
2002	5.357	18.135	1.198	21.787
2003	1.359	3.263	0.475	0.370
2004	3.408	15.135	1.182	10.465
2005	2.344	13.414	0.849	5.593
2006	2.794	10.351	0.732	5.243
2007	4.956	18.225	1.533	12.354
2008	2.354	8.025	0.636	3.237

Appendix C

Hydro Preprocessing

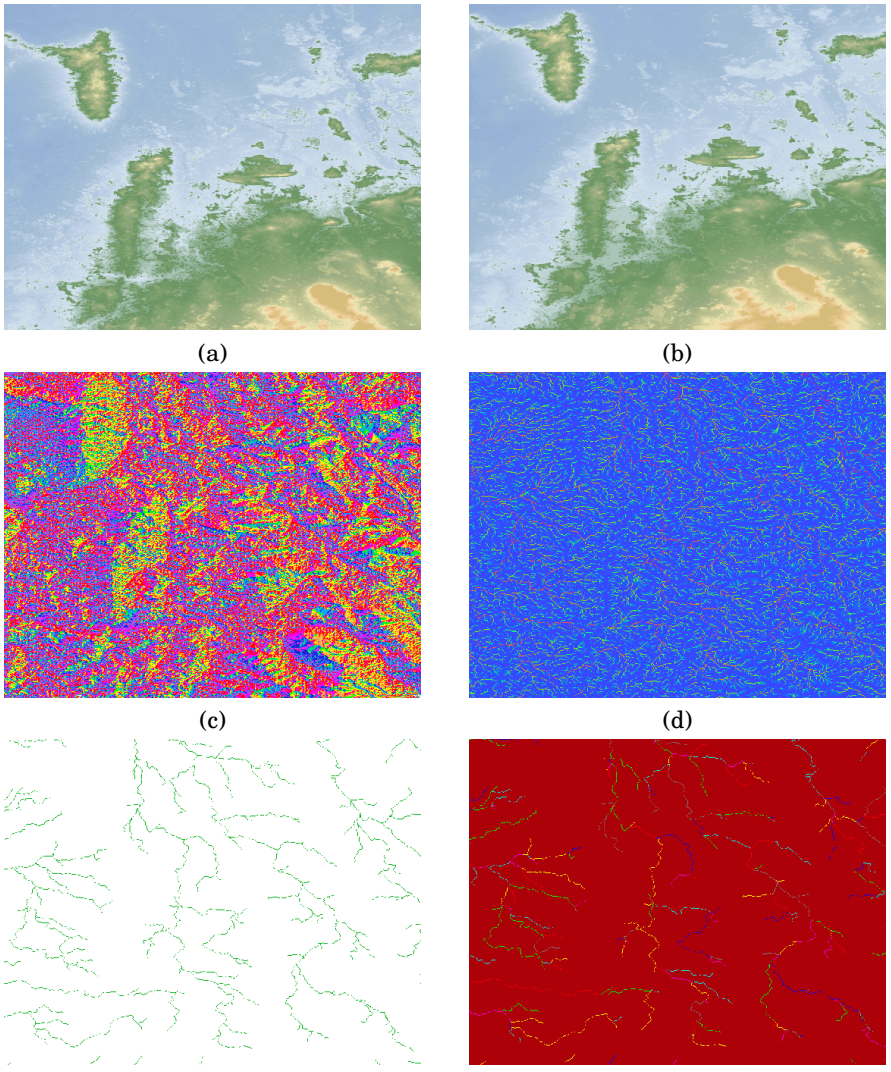

Figure C.1: Process of Hydro Preprocessing (a)

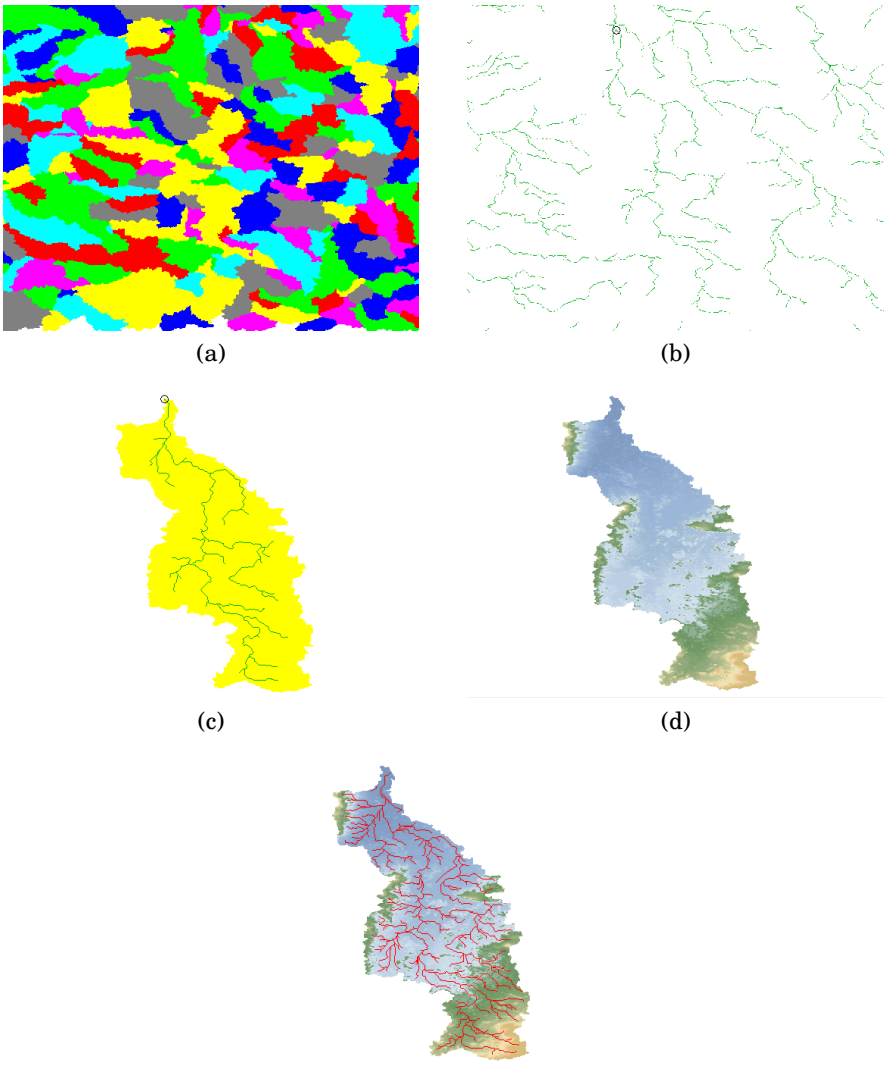

Figure C.2: Process of Hydro Preprocessing (b)

Appendix D

User Interface of FEQ

The introduction of user interface of FEQ is classified by the methodology showed in Figure 3.9. Each sub dialogue and attached table are displayed in the following 3 sections. Here we only focus on the unsteady flow modeling. These parts that are used in water quality modeling are explained in another thesis.

D.1 Branch

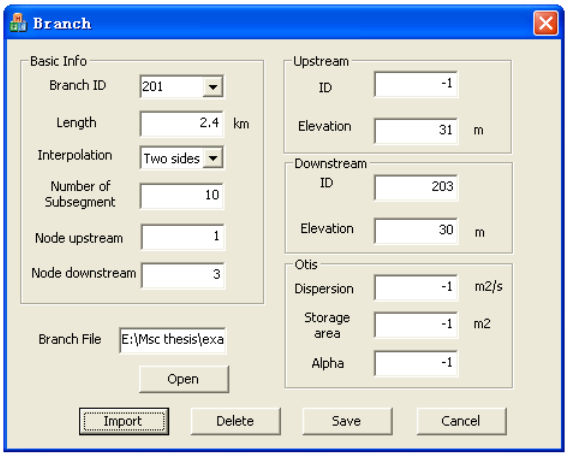

Figure D.1: GUI for branch information

Table D.1: Info. in Branch Dialogue

Content	Description	Remark
Branch ID	Identify each branch	Integer
Length	the length of this branch	

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Content	Description	Remark
Interpolation	Algorithm for specifying cross section along the branch	3 interpolation methods
No. of Subsegment	Number of branches separated for calculation	Integer larger than 1
Node upstream	ID of the node upstream	
Node downstream	ID of the node downstream	
ID	ID of connected branches upstream or downstream	-1 if none
Elevation	Elevation at upstream or downstream	

D.2 Node

D.2.1 General Information

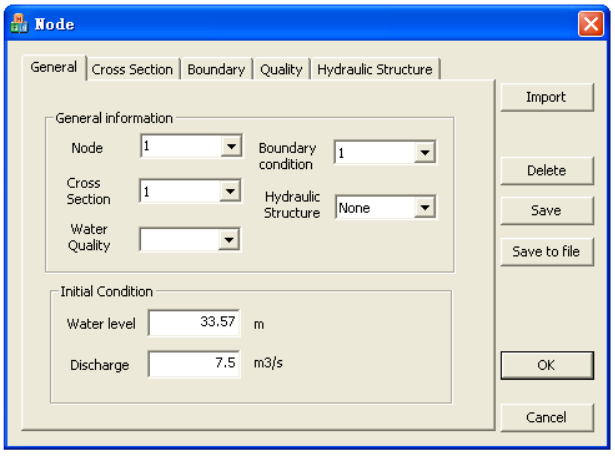

Figure D.2: GUI for node information

Table D.2: General Info. in Node Dialogue

Content	Description	Remark
Node	ID of each node	To specify the node
Cross section	ID of cross section	Cross section at this node

Continue next page...

Content	Description	Remark
Boundary condition	ID of boundary condition	Boundary condition at this node
Hydraulic structure	ID of Hydraulic structure	Hydraulic structure at this node
Water level	Initial water level at this node	Water depth + elevation
Discharge	Initial discharge at the node	

D.2.2 Cross Section

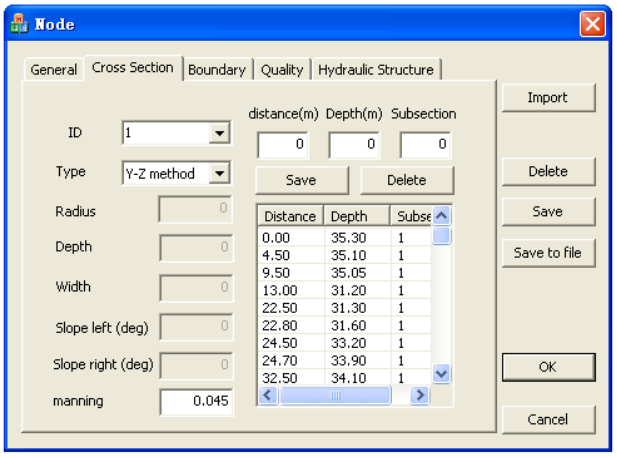

Figure D.3: GUI for cross section

Table D.3: Cross section Info. in Node Dialogue

Content	Description	Remark
ID	ID of cross section	
Type	Type of cross section	Circle, trapezium or Y-Z method
Radius	Radius of cross section	Available only for circle
Depth	Depth of cross section	Available only for trapezium
Width	Width at the top of cross section	Available only for trapezium
Slope	Slope at left (right) side of cross section	Available only for trapezium
Manning	Manning's n for cross section	

Continue next page...

Content	Description	Remark
Distance, depth & subsection	Used for edit the table	Available only for Y-Z method
Table	Define the cross section shape by Y-Z method	Subsection equal to 1 as default

D.2.3 Boundary Condition

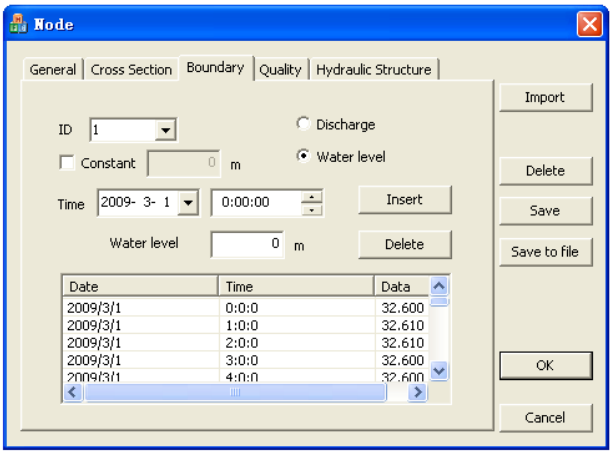

Figure D.4: GUI for boundary condition

Table D.4: Boundary condition in Node Dialogue

Content	Description	Remark
ID	ID of boundary condition	
Constant	Option for flow type	Steady or unsteady boundary condition
Discharge & Water level	Option for data type	Discharge or water level
Time	Specify time	For time series data editing
Water level (Discharge)	Input data	For time series data editing
Table	record boundary condition as time series	

D.3 FEQ_GUI

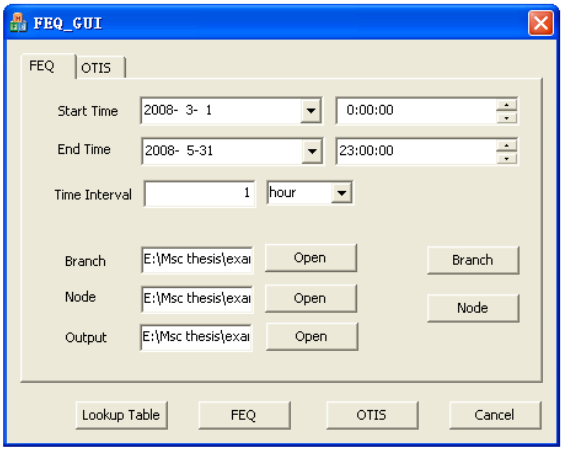

Figure D.5: GUI for calculation settings

Table D.5: Calculation settings

Content	Description	Remark
Start time	Specify the start time for simulation	
End time	Specify the end time for simulation	
Time interval	Define the time interval for calculation	
Branch	Import branch Info.	
Node	Import node Info.	
Output	Define the directory for output	