Developing water quality modelling scheme in ILWIS Open for the Dinkel River in support of climate change and adaptation studies

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by

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To the one you find time to read this work;

To the one who try to understand this little scientific piece of writing;

To the one who contacts the author for further explanation on this small volume;

And to the one who made it possible to develop this little scientific piece of writing;

This writing is fully dedicated to you!

Abstract

Freshwater of adequate quantity and quality are vital for sustainable socio-economic development in every nation. The rising population and industrial growth coupled with climate change, call for more cost effective monitoring and forecasting techniques. Geo-information and remote sensing technologies allow the retrieval and organization of complex data requirement for accurate hydrologic and water quality assessment. The ability to integrate geospatial information and earth observation data with numerical river flow and transport modeling in an open source GIS environment provides a key step to provide a level platform for all professionals to undertake water quality monitoring and management. The fate of pollutants in rivers is controlled by physical transport and biogeochemical interactions in the system. The understanding of these interactions is a critical step in predicting the fate of substances in rivers and water bodies. This can help in undertaking more effective steps towards monitoring and management of water resources. The study used the USGS open code transient storage solute transport model (OTIS) to quantify the hydraulic parameters that influence temporary storage in rivers. Transient storage detains transport of pollutants in small eddies and stagnant regions of water that are stationary relative to the movement in the main flow section. The model was successfully calibrated and validated for the Dinkel River, using experimental tracer experiments. The OTIS model component was further integrated with FEQ model (covered in another thesis) using a graphic user interface (GUI) for the generation of unsteady flow conditions in the river system. This integrated package would be implemented as a plug-in in ILWIS Open under the 52° North Initiative for Geospatial Open Source Software to "Develop a Graphic User Interface (GUI) for water quality modelling of the 52°North Dinkel River". Professional and scientific interest for using this new Open Source based hydrological evaluation tool are already well noted with the Regge and Dinkel water board and especially their cooperation partners in Eastern Europe e.g. Slovakia.

Keywords: Water quality, climate change, open source GIS, ILWIS Open, OTIS, FEQ

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1. Introduction

1.1. Background

Freshwater is an essential and finite resource and adequate quantity and quality are crucial for sustainable socio-economic development in every nation (Bartram and Ballance, 1996). The current growth of population and industries coupled with effects of climate changes call for more stringent measures on how we managed water resources. Following Agenda 21 of 1992 and reports by International Panel for Climate Change (IPCC) e.g. (Parry et al., 2007; Solomon et al., 2007) has indicated that more global efforts are needed by countries. Developing mitigation and adaptation measures calls for collaborative actions to ensure sustainable achievement of climate change. For instance, the European Union (EU) passed a new Water Framework Directive (WFD) in September 2000 with emphasis on achieving a sound ecological status of surface, ground and coastal waters on a long term basis. The new EU-WFD requires that the management of water resources be politically organised and managed at basin level with the aim of maintaining the existing quality of the rivers or improving the quality of our water resources (Lindenschmidt, 2006).

In response to the above, the Royal Dutch Meteorological Institute (KNMI), the national institute for weather, climate and seismology in 2006 did some studies on effect of the changes in temperature, precipitation, wind, and sea level for a period of 30 years (Hurk et al., 2006). The studies indicate that climate change would cause significant shifts in hydrological regime and quality of water resources (see figure 1-1). In effect, this would increase the competition for water, especially if climate change adaptation efforts in various sectors are not implemented in harmony. One solution cited is collaborative efforts and integrated land and water management strategies for river basins (Bates et al., 2008). One example of this is the development of Cross Border Plan for the Dinkel and the Dinkeldal by the Dutch and German Government. The purpose of this project has been to restore the natural drainage to achieve a sustainable ecological design and management of the Dinkel and Dinkeldal (Jansen et al., 2001).

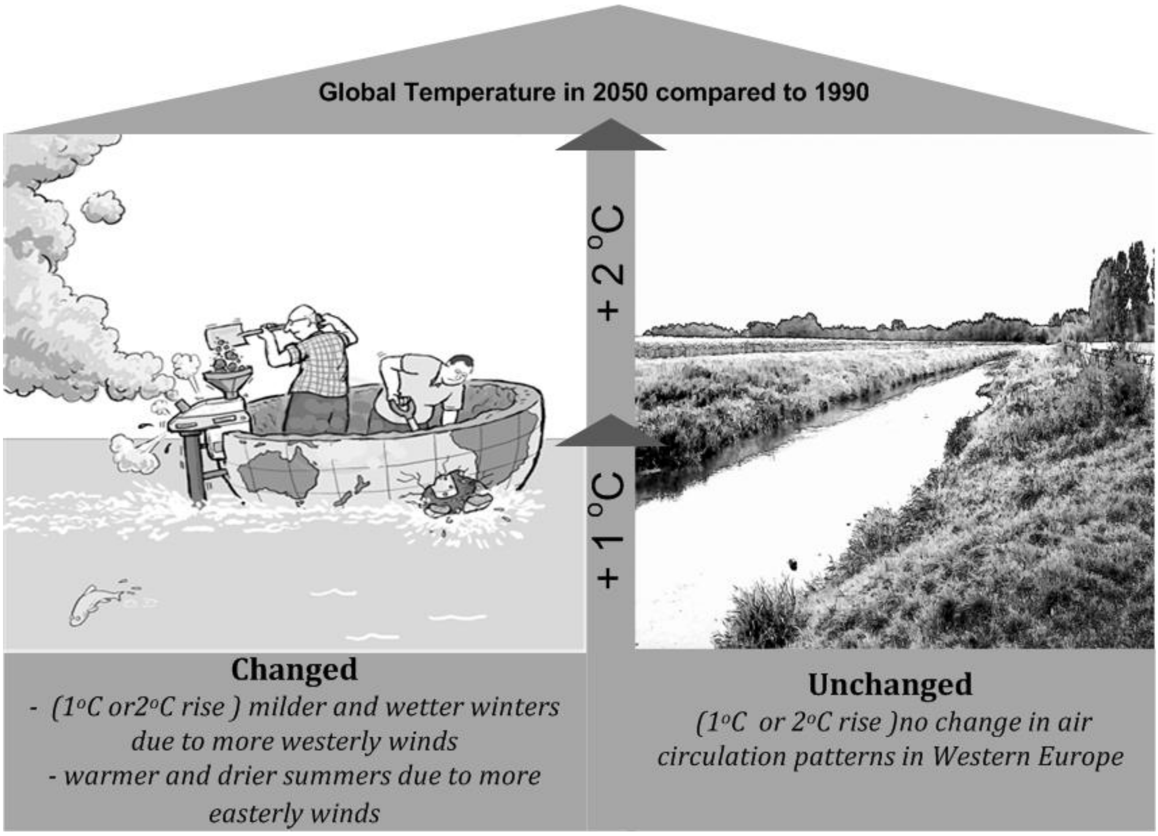


Figure 1-1 Effects of climate change in the Netherlands

Original data source from (Hurk et al., 2006)

The right photo is Dinkel River taken at Glane in November 2009 and the left photo is obtained from http://www.chrismadden.co.uk/cartoons/environment-cartoons/globe-cartoons/globe-boat-resource-depletion-cartoon.gif

To continuously provide the fuel for proper implementation of these plans and projects, better understanding of climate scenarios is required. Planning and monitoring schemes are required to regularly check the quality and quantity of the water bodies in cities, towns and villages (Loucks et al., 2005). To implement these schemes effectively especially in the area of water quality, water quality models are necessary. Water quality modelling often provides a means of understanding the suitability of water resources for various sectoral uses. These models traditionally help in understanding the trends of short term forecasts of water quality in water bodies. One of such techniques is the study of the dynamics of solute transport. This study plays a critical role in determining the fate of pollutants in rivers and streams. Several studies have proved that there exists a significant relationship between the main channel and storage zones in pools and eddies near the sides of the channel. Storage processes increase the solute retention time in channels and the contact of stream-water solutes with sediment, which stimulates biotic and geochemical processes that affect solute reaction during downstream transport (Bencala and Walters, 1983a; Workshop, 1990).

However, a major obstacle through the use of this technique is that; water sampling is often time consuming, expensive and can only be taken for small points. Hence accurate, cost-effective and minimal time consuming techniques are required especially in today's climate changing environment. Geo-information Science (GIS) and remote sensing techniques and infrastructure provide a unique opportunity to monitor and assess water quality in space and time. Over the years, water quality modelling has been emphasized to large rivers often due to their transboundary in nature and their economic priority. Water quality modelling for small rivers on the other hand pose specific problems such as data scarcity, lack of major investments as a consequence of their lesser importance, and the large number of diverse inputs, especially if they flow through densely populated areas (Marsili-Libelli and Giusti, 2008). The recent availability of high resolution images together with GIS applications make it possible to model water quality in small rivers in space and time. Furthermore, the availability of open source GIS tools which are equally effective compared to the commercial softwares can reduce the cost of water quality modelling of small rivers. Therefore, the aim of this study is to identify an appropriate water quality model for possible integration into Integrated Land Water Information System (ILWIS) Open for water quality assessment in the Dinkel River. ILWIS is GIS/Remote sensing software already capable of catchment network delineation.

1.2. Problem Statement

Water quality models for small river basins are often given little attention due to data scarcity, lack of major investments as a consequence of their relatively lesser importance, and the large number of diverse inputs, required for existing quality models (Marsili-Libelli and Giusti, 2008). The existing water quality models such as Duflow Modelling Studio (DMS) and AquaChem are not affordable due to high software cost and continuous use licensing costs; to allow end-users with limited finance such as young researchers, students and professionals across the world to utilize them. The ability to adapt these models to fit different climatic conditions is often difficult or impossible. ILWIS Open provides this opportunity for end-users to easily modify the codes to adapt to different local conditions. ILWIS also has the capability of performing hydrologic routing. However, ILWIS lack water quality functionality. The ability to include water quality functionality in ILWIS Open becomes an added advantage to the many users of ILWIS in developing countries. This research therefore is crucial to providing another plat-form on which the water quality monitoring can be performed using ILWIS Open.

The research also contributes in part to the undergoing project by 52^{o}North to 'Developing a Graphic User Interface (GUI) for water quality modelling in the 52^{o} North Dinkel River'. The products of this research would be upscaled to cover large lakes and rivers. It is envisaged that the ability of distributing this model through Open Source ILWIS would in a long-term help professionals across the world to closely monitor and assess water quality of rivers in a more effective manner, thereby increasing their understanding on the variability of water quality and their preparedness towards climate adaptation.

1.3. Research Questions

The ability to identify an appropriate water quality model for possible integration into ILWIS Open for water quality assessment in the Dinkel River raises some potential questions. The provision of relevant answers to these questions is important for achieving the objectives of this study. These questions include:

A. What are the available open source and free water quality modelling codes for small rivers and appropriate for integrating into ILWIS?

B. What is the most appropriate tracer for conducting tracer/dilution experiments in the Dinkel River?

C. What duration of tracer experiments data is relevant for calibration and validation of the selected water quality model?

1.4. Objectives

The general objective of this study is to develop a water quality modelling scheme for integration into ILWIS Open for the Dinkel River.

The specific objectives;

a. To identify and select the most appropriate water quality model for the study area

b. To perform calibration and validation of the selected model

c. To develop a Graphic User interface for OTIS and couple this model to a hydraulic flow model (FEQ)

1.5. Study Area

The Dinkel is a small meandering river running along the Dutch-German border and a left tributary of the Vecht. Its total length is 93km, of which 47km lay in Germany (Wolfert et al., 2002). The total drainage basin measures 690km^2, ranging from an elevation of 124m to 12m above mean sea level (refer to figure 1-2 for more details). The Dinkel originates in North Rhine-Westphalia, Germany, between Ahaus and Coesfeld. It flows north to Gronau, crosses the border with the Netherlands (Overijssel) in Glane, flows through Denekamp, and re-crosses the border to Germany. The Dinkel joins the Vecht in Neuenhaus.

The Dinkel river was selected for the purpose of this study for three important reasons:

1. It is of transboundary importance and hence the issue of water quality is of prime relevance to both countries
2. It is a relatively small river that fits exactly the focus of this study
3. The location is close-by and as such field visits could be carried periodically with low costs.

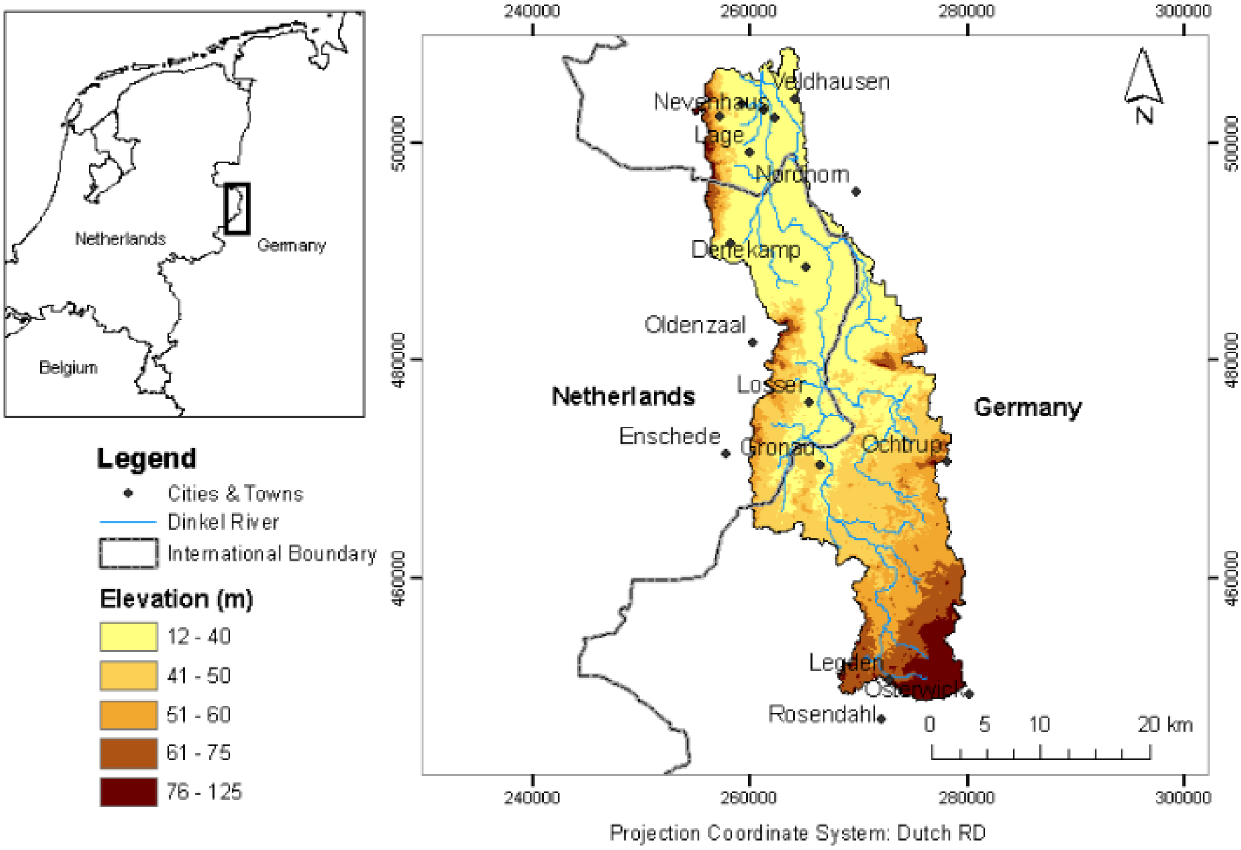


Figure 1-2 Map of Dinkel river basin

(Created from SRTM 30m DEM using Hydro-processing in ILWIS Open)

1.5.1. Climate

The Dinkel lies in a climate, characterized by slight increases in average temperatures (between 9 ºC and 10 ºC), a high number of sunny days (25-30) and a high number of frost days (> 80) and mean annual precipitation of 750-800mm was recorded in the period of 1961-1980 and mean annual evapotranspiration approximately 525mm (Jansen et al., 2001). Evapotranspiration exceeds precipitation in the period between April and August (Wolfert et al., 2002). The Dinkel valley is mainly used for dairy farming with about 10% of the area under nature reserve. There is a maximum rainfall in August and a minimum in March. The climate greatly affects the temperature of the water stream. This is annualized around 10 ºC. Typically, the colder and more shaded pathways upstream have less temperature fluctuations than the less shaded downstream pathways.

The flow of Dinkel is relatively low between 0.1 and 0.5m/s (typically between 0.2 and 0.4m/s). The magnitude of the flow over the entire course of the river is in general the same (Jansen et al., 2001).

1.5.2. Soil & Land cover Characteristics

Dinkel is characterized by glacial deposits in large parts of its catchment. In by far the largest part of the field exists; sandy soil with a relatively low water storage capacity and increased permeability. The composition and structure of the soil is largely dependent on the average water table. In the Dutch part of the Dinkel, levees are very special. These levees include weak silty soil, are created by deposition in the floodplain and have a place of many rare plant species (Jansen et al., 2001). Figure 1-3 shows the landcover for the Dutch part of the catchment.

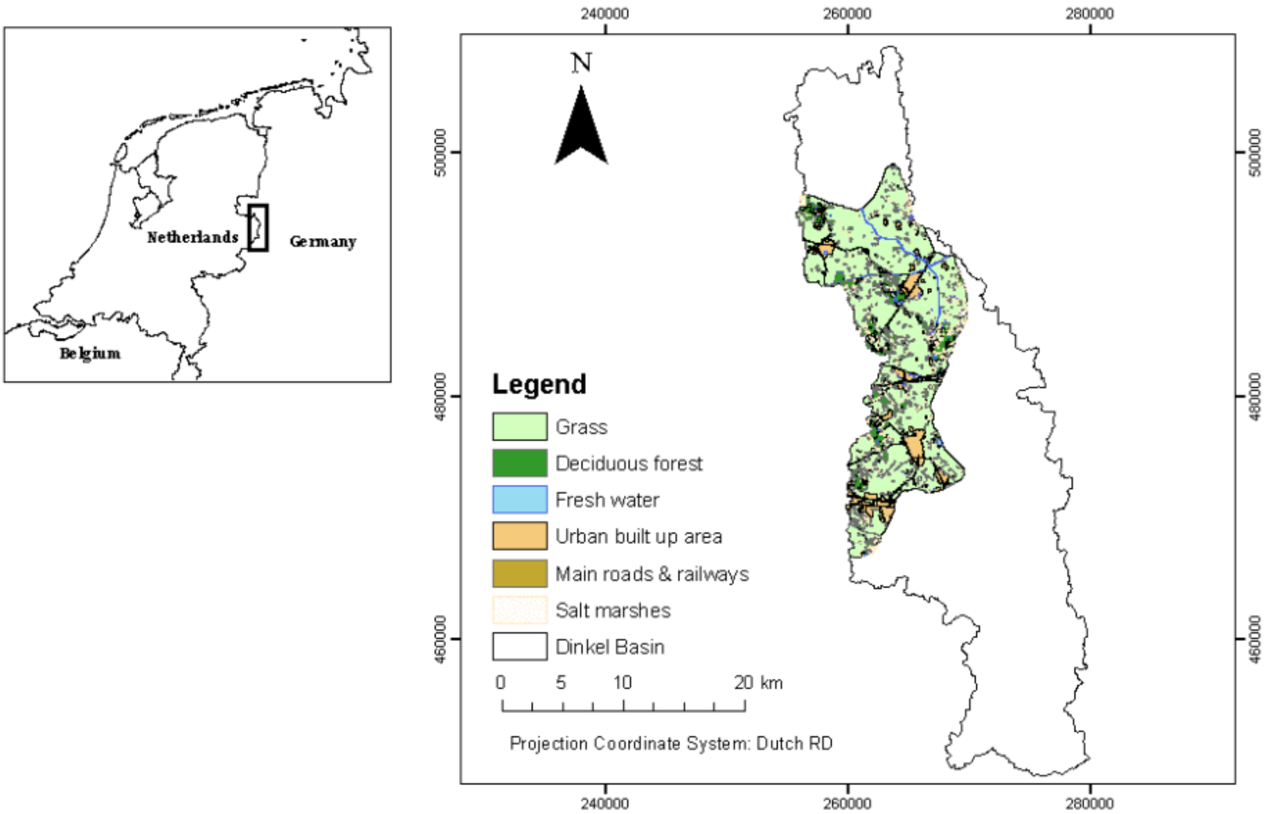


Figure 1-3 Land cover map of Dutch part of the Dinkel Catchment

Original source (Allard, 2001), modified by author for presentation purposes

1.5.3. Water quality

The Dinkel is generally eutrophic with relatively high nitrate (N-NO_3) and phosphate concentrations due to the discharge of agricultural run-off and waste water from municipalities upstream (Wolfert et al., 2002). This is due to the activities of communities resident in the Dinkel valley. They can be regarded as remnants of an old agricultural landscape in the eastern part of the Netherlands, i.e. pasture landscapes, in the adjoining area of Germany. There, river valleys were used as common pastures for extensive livestock grazing which resulted in a variegated landscape characterised by remnants of grazing woods, groups of bushes, individual trees and open grazing land (Wolfert et al., 2002).

2. Model Selection & Description

2.1. Water Quality Models

This section gives a brief account of selected water quality models. The section is not intended to give a history of all the water quality models that have been developed and use over the years but focus on selected good models used which have been recommended by professionals in the past decades. The section therefore reviews these key models and indicating their strengths and weaknesses towards water quality modelling.

Duflow Modelling Studio (DMS) is a commercial 1-D model for water quality modeling. This model can be easily be customized by users to adapt to local conditions (DUFLOW, 2004) and is however expensive, so that young researchers might find it difficult to purchase and use it. Another software freely available is Soil Water Assessment Tool (SWAT). This is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds and is good for performing studies under a number of defined scenarios. This is a very good model and requires large sets of data for implementation (Arnold et al., 1994). The Dinkel is however a small river with relatively even terrain and hence its incorporation into ILWIS might result in some difficulties. Agricultural Non-Point Source pollution model AgNPS is a non-point source water quality model capable of handling single storm events. The model however lack the capability of handling dynamic series of storm events (Young et al., 1987).

River and Stream Water Quality Model (QUAL2K) is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E model (Barnwell et al., 1989; Chapra et al., 2008). The model is available both in spreadsheet format and FORTRAN language and is capable of handling large number of water quality parameters. One-dimensional Transport with Inflow and Storage (OTIS) is 1-D Transport with Inflow and Storage and provides a numerical solution to water quality modeling in rivers (Bencala and Walters, 1983b; Runkel, 1998). De Smedt (2005) provides an analytical solution of this. The ability of this model to consider storage fluxes of water quality parameters make them more suitable for water quality modelling compared to the ordinary quality models under this current studies. In addition, it has the capability of stimulating BOD, sediment-water reaction, oxygen and nutrient fluxes.

2.2. Selection Criteria

The selection criteria indicated in figure 2-1 were used as a guide in the selection of a model for the subject under study. The key goal of this research is to make use of open source models that have proven practical applicability in water quality assessment and can also be integrated into ILWIS Open. After going through this forward and backward process with models mentioned in this section, OTIS was selected as the appropriate model for study under consideration. The next section therefore gives a brief explanation of the concepts behind this model.

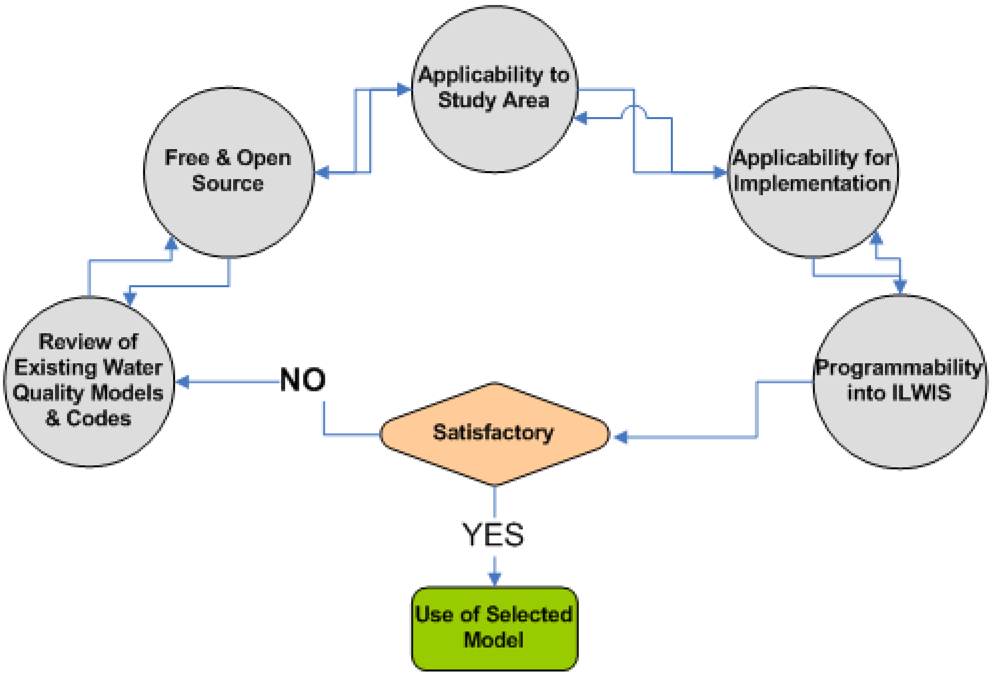


Figure 2-1 Selection criterion for model check formatting of figures

2.3. Theory

This section gives fundamental theory about the OTIS model and some fields in which it has been successfully applied. Also, other use of the OTIS model with other models in the field of geochemistry and hydrogeology has also been mentioned.

2.3.1. The OTIS Model

OTIS is stimulation model coded in FORTRAN. It may be used to characterize the fate and transport of water-borne solutes in streams and rivers (Runkel, 2000). OTIS determines the solute concentrations that result from hydrologic transport and chemical transformation. The main assumption used in OTIS is that *solute concentration* varies only in *longitudinal section*. Therefore, equations are developed for one-dimensional systems that consist of a series of segments. However, a modification is included to allow for lateral exchange and transport storage. OTIS may be used in together with field tracer experiments to quantify hydrologic parameters affecting solute transport. For instance, the model has been used in the stimulation of solute transport in a mountain pool and riffle stream with a kinetic mass transfer model for sorption; application of transient storage to small streams and the study of non-conservative solutes subjected to sorption and decay processes (Bencala, 1983; Bencala and Walters, 1983a; Bencala and Walters, 1983b; Laenen and Bencala, 2001; Runkel, 1998; Runkel, 2000; Runkel and Chapra, 1993).

2.3.2. Governing Concept and Equations

The transient storage solute model OTIS is used to quantify the hydraulic parameters that influence temporary storage in rivers and streams. Transient storage refers to the temporary detainment of solutes in small eddies and stagnant pockets of water that are stationary relative to the movement in the main channel. The transient storage model uses the plug-flow with dispersion for the main channel and includes adjacent storage zones that exchange constituents with the main flow channel (see figure 2-1).

A solute transport simulation model provides a means to quantitatively link the observed tracer concentrations to the transport processes described above. In this conceptualization the hydrologic regime is divided into two coupled systems: (1) a system of flowing water in the main stream channel and (2) a system of storage zones at the margins of the stream channel or in the subsurface that contain slowly moving or immobile water (figure 2-2). The two systems are coupled by a simple mass-transfer formulation that exchanges solutes between the main channel and storage zones (Bencala and Walters, 1983b; Wagner and Harvey, 1997).

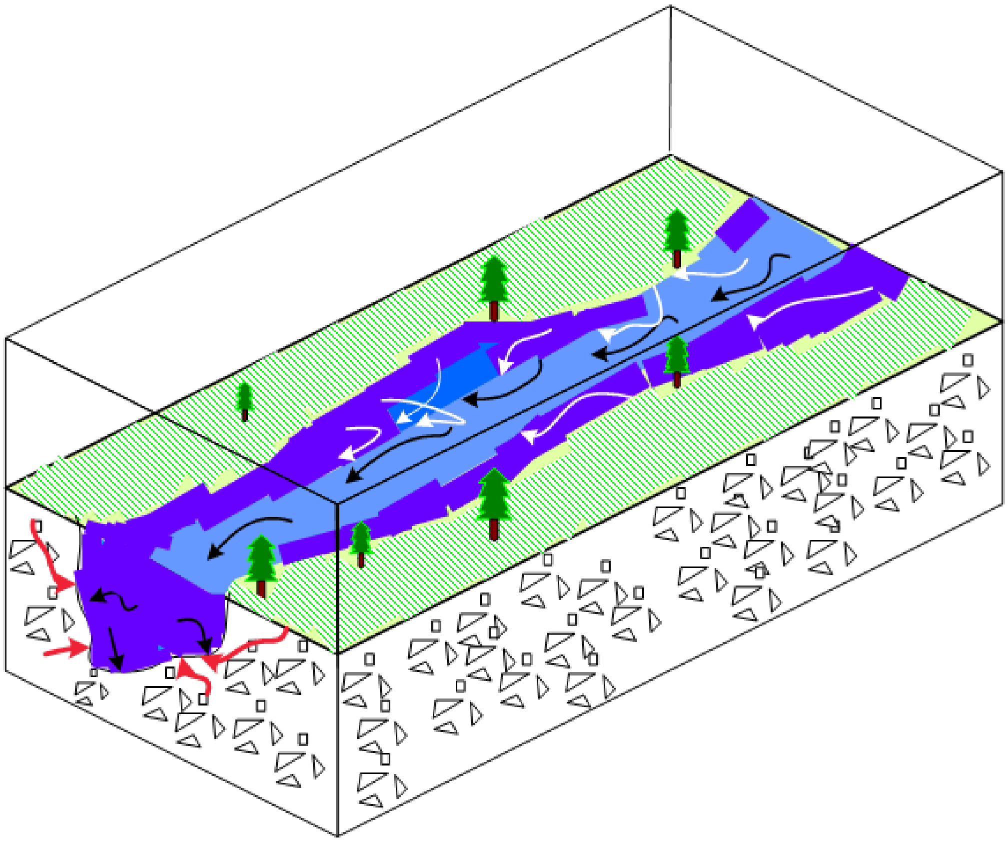


Figure 2-2 Lateral storage mechanisms

Original concept (Runkel, 2000); modified by author

Transient storage occurs (A) when solute enter small pockets of slow-moving water and (B) when solutes leave the main channel and enter the porous media that make up the bed and banks of the channel. Arrows denote solute movement between the main channel and the transient-storage zone.

The transient storage model is composed of two coupled differential equations:

$$\frac{\delta C}{\delta t} + \frac{Q}{A}\frac{\delta C}{\delta x} = \frac{1}{A}\frac{\delta}{\delta x}\left(AD\frac{\delta C}{\delta x}\right) + \frac{q_L}{A}(C_L - C) + \alpha(C_s - C) \quad \textbf{2-1}$$

$$\frac{dC_s}{dt} = -\propto \frac{A}{A_s}(C_s - C) \quad \textbf{2-2}$$

(Bencala, 1983; Bencala and Walters, 1983a; Runkel, 1998; Runkel and Chapra, 1993)

Where;

A	Main channel cross-sectional area	[m^2]
Q	Volumetric flow rate	[m^3/s]
C	Main channel solute concentration	[mg/l]
D	Dispersion coefficient	[m^2/s]
A_S	Storage zone cross-sectional area	[m^2]
C_L	Lateral volumetric inflow solute concentration per length	[m^3/s/m]
C_S	Storage zone solute concentration	[mg/l]
q_L	lateral inflow rate per length	[m^3/s/m]
t	Time	[s]
x	Distance	[m]

The complete derivation of these equations is given in Runkel (1998). The conservation of mass for each segment yields a set of differential equations that are solved numerically using the Crank-Nicolson method (Runkel and Broshears, 1991).

To simulate solute transport using equations (1) and (2) given above, the model parameters, A, D, q_L, C_L, α and As, must be specified. Since direct measurement of these parameters is difficult or impossible, the parameters must be estimated by "fitting" the model to solute concentration data obtained in stream tracer experiments. The "best-fit" parameter estimates can be obtained through manual calibration (Workshop, 1990) or a more rigorous statistics and optimization approach such as non-linear regression package STARPAC (Donaldson and Tryon, 1990). Therefore, the modified version of OTIS, OTIS-P, has the capability to determine the optimal sets of parameter values by minimizing the sum-of-squared errors between the observed and stimulated solute concentrations. Model conversion is judged by the relative change of sum-of-squared errors. In OTIS generally, the upstream boundary condition can be defined as either a constant or time variable concentration. On the other hand, the downstream boundary condition of the OTIS is a fixed dispersion flux. OTIS can be operated under either steady-state or time variable conditions.

2.3.3. Applications of OTIS

The physical characteristics of most rivers differ from the uniform and conceptually defined open channels in urban communities. Therefore the reliable prediction and interpretation of solute migration in most rivers requires careful consideration of the retention of solute mass in the transient zone (Wörman, 2000). Numerous studies have also done conducted regarding the mechanisms and stimulations of solute transport in streams and rivers (Fischer et al., 1979). One of the widely accepted approach is the use of OTIS (Bencala and Walters, 1983a; Wörman, 1998). For instance, in a mountain pool and riffle stream, diverse physical conditions exist. In this particular study, control chloride injection was carefully monitored at specified distances along the river. The tracer data were then used to quantify the model parameters. In a parallel study for the same area under investigation, the effect of solute sorption into streambed on solute migration was also carefully studied (Bencala, 1983). Here, the controlled and intensively strontium tracer injection experiment was conducted and the results used in the parameterization of the model. Runkel (1998) continued the studies on this using data from Bencala and Walters (1983a) and extended the work to quantify stream hydrology and study nutrient uptake by algal mats that cover the bed of Green Creek. In another study Runkel (2000) explains how OTIS can also be used to quantify the trace metal removal concentrations in metal-rich streams.

In another case study in St Kevin Gulch, a rocky mountain stream in Colorado contaminated by acid mine drainage, the model was applied to characterised hyporheic exchange (Wagner and Bencala, 1996). To achieve this, sub-reach scale measurements of hydraulic heads and hydraulic conductivity were used to compute streambed fluxes and reach scale modelling of in-stream solute tracer injections to determine the characteristic length and timescales of exchange with storage zones. Similarly, Scordo et al (2009) examined the hyporheic exchange flow and transient storage processes within a steep headwater stream using hydrometric and tracer approaches. Gooseff et al (2005) made the first attempt to discriminate in-channel transient storage from hyporheic exchange. The study found out channel storage processes may be appreciable especially with respect to biogeochemical transformation processes. In addition, OTIS was coupled with a second model, OTEQ (One-dimensional Transport with Equilibrium chemistry). In this study, Runkel et al (1999) combines the transport mechanisms in OTIS with a chemical equilibrium submodel that considers complexation, precipitation/ dissolution, and sorption. In this way, reliable quantification of the geochemical processes affecting trace metals was done. The hydraulics mechanisms of constructed treatment wetlands was also studied by Martinez and Wise (2003) using OTIS. The study indicates the appropriateness of the use of this model for treatment wetlands hydraulic processes.

This list is not exhaustive to illustrate the numerous works by different researchers applying the model but however, the short description here explains the great potential that exists in the use of this model in the study of in-stream storage processes such hydrodynamic, chemical and the exchange processes of surface and subsurface waters.

3. Methodology

3.1. Background

This chapter explains the methods carried out during the study. The methods included review of records with the Regge Dinkel Waterboard, conduction of tracer experiment and calibration and validation of experimental results.

The figure below summarises the entire steps that were used in this study. The highlighted part in yellow was carried out as a joint work with another MSc thesis work – *'Hydrological transport model calibration and integration by GUI in 52 North/ILWIS OS for the Dinkel river for supporting water quality studies'*. The end product of these theses work is a contribution towards the 52°North Initiative on *'Developing a GUI for Water Quality Modelling of the 52° Dinkel River' using ILWIS Open* (Kabo-bah and Zun, 2009) .

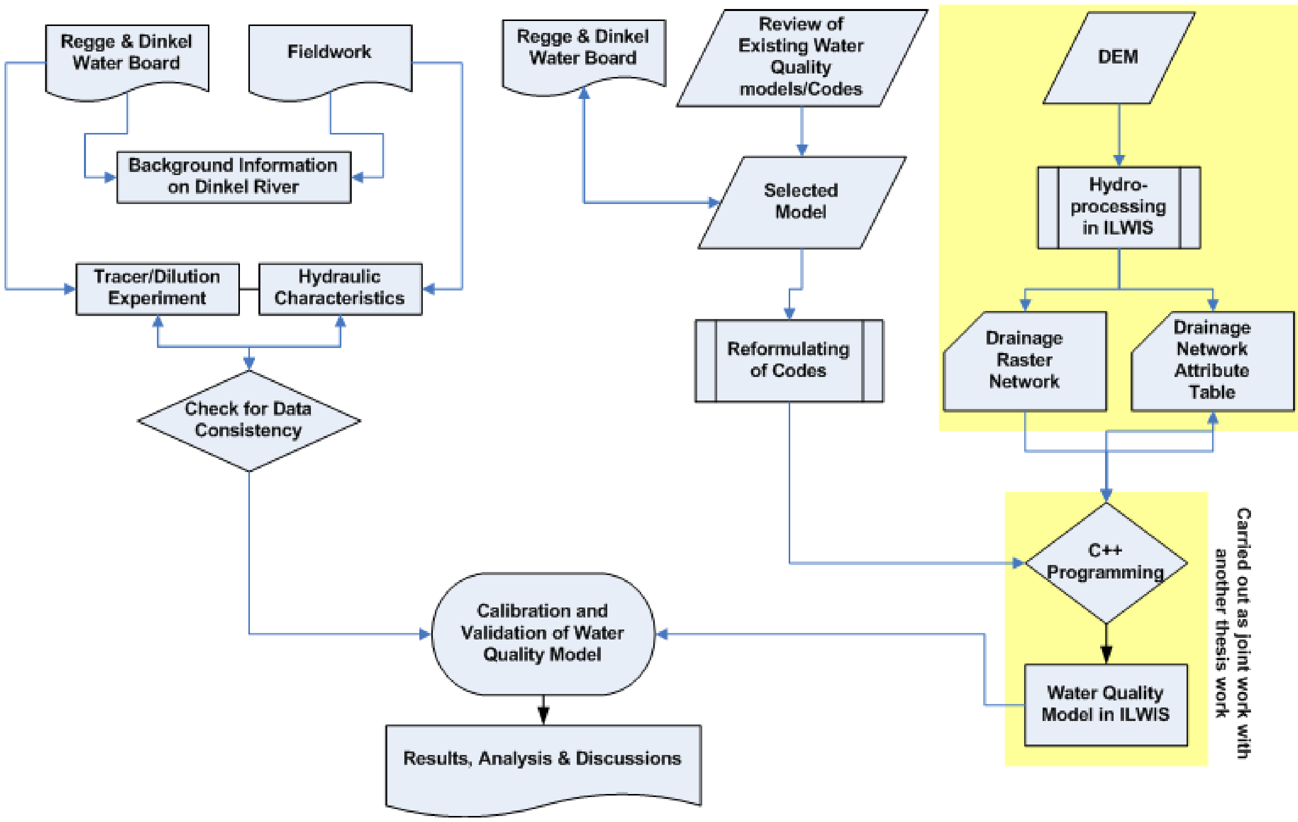


Figure 3-1 General Procedure for conducting the study

As indicated in the figure 3-1, Regge and Dinkel Water board was contacted in two critical steps under this study. The first contact was during the selection of the water quality model. After the selection of the model OTIS, they were consulted to get feedback about the applicability of the model for the Dinkel case study. This was to ensure that, the selected model fits not only in the theoretical scientific framework but also among the practitioners of water quality. Following a success story with the water board, historic hydrologic data and GIS datasets were obtained from the Waterboard. This helped greatly in also deciding the section to select for the tracer experiments for this particular case study. The next subsections emphasize the details of the fieldwork procedure that was applied. The selecting of the model has already been described in detail in the previous section (see section 2.3).

3.2. Field work design

This section details out the steps and considerations considered in carrying out the tracer experiment conducted on November 18, 2009.

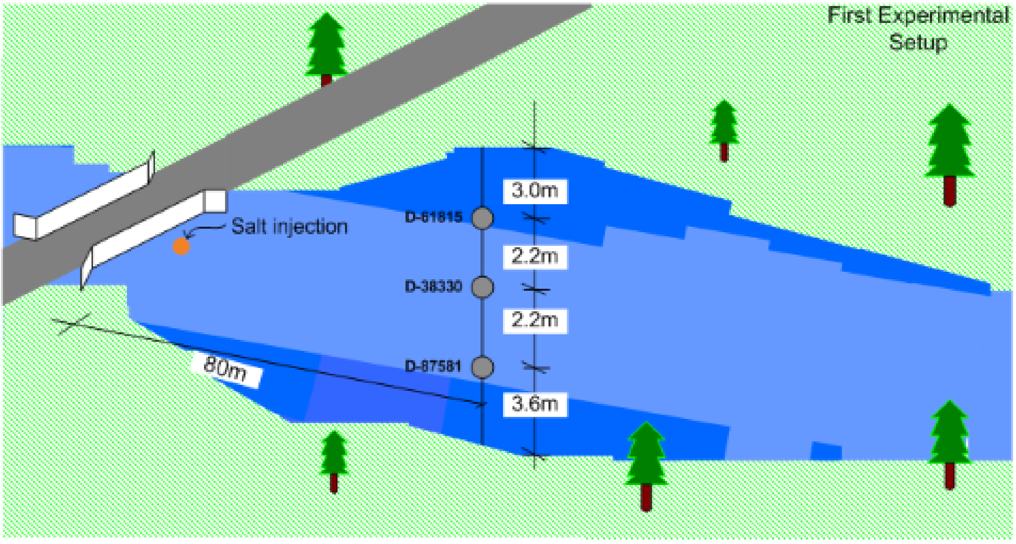
3.2.1. Tracer experiment Concept

The experiment involved the release of a known concentration of solute (Sodium Chloride) as a slug at one section of the river and making measurements downstream to determine the longitudinal pattern of tracer concentration and the timing of the passage of the solute pulse. This was very useful in determining the key parameters of the OTIS model such as dispersion, flow rate, storage zone area and storage rate coefficient.

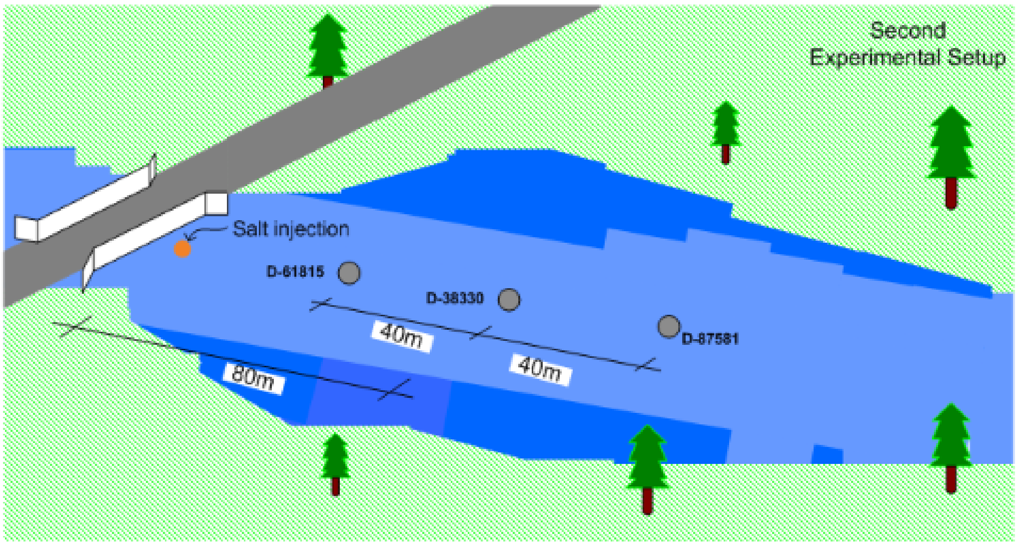
3.2.2. Experimental Setup

Two experiment setups were carried out during the fieldwork. The site was selected based on the condition that it allowed wadeable access for physical measurements and sampling. The site selected also did not have tributary input. This was to ensure that modelling of selected site confirmed to the reaches defined in the OTIS model. The hydraulic disturbance of the bridge effect flow contraction and expansion (at the experimental site) was accepted as being reasonable and not impeding the experiments and their accuracy. The following figure 3-2 illustrates the two experimental setups for the study and figure 3-3 illustrates the selected site used for the study.

- 6kg of a non-reactive tracer (NaCl), diluted in 20 litres of fresh water from the river, was injected into the stream at 11:59hrs, 12:15hrs, 13.00 and 13.10. This meant that each logger recorded four sets of measurements during each of these time steps. Measurements of temperature were also done. This was used in the correction of the EC measurements to room temperature.
- The measurements of electrical conductivity of salt were monitored with three automatic CTD loggers. Each of these loggers had an accuracy of 1% of the range of the measurements taken.
- The three loggers were first installed at a distance of 80m from the point of injection of salt. This was to assess the distribution of salt concentration across the river and possibly to investigate the presence of transient storage.
- In the second experimental setup, the loggers were spaced at distances of 40m, 80m and 120m. The information collected was used for the calibration and validation purposes.



a) First Experiment Setup



b) Second Experiment Setup

Figure 3-2 Tracer Experimental Setups in the Dinkel River on the November 18, 2009

In a) the three loggers are installed across the river at 80m and spaced as indicated. This was done to understand the lateral behaviour of solute as it travels along the river. In b) the three loggers are placed at different distances to measure the EC at each of these points. These measurements are important for the calibration and validation of the OTIS model.

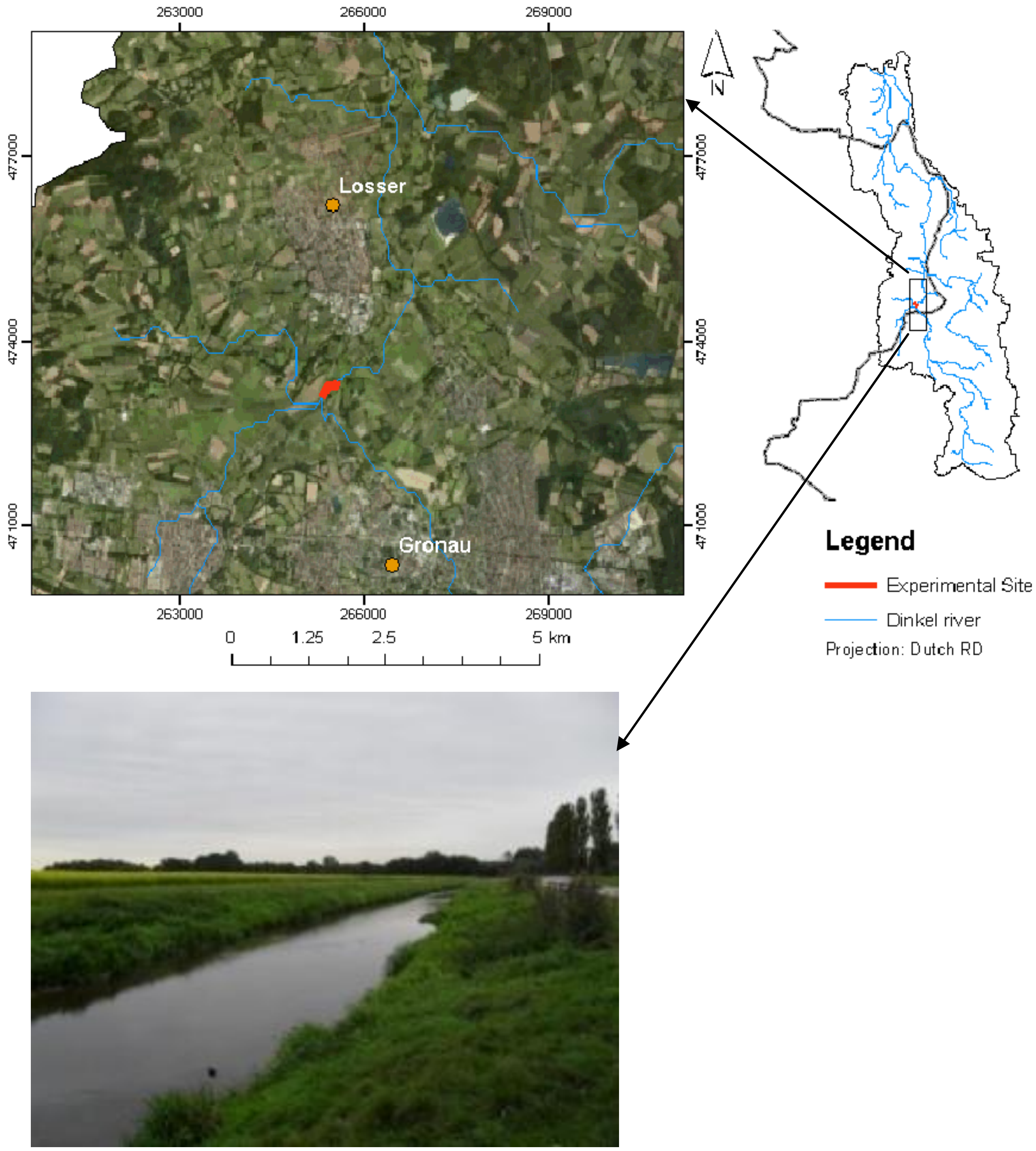


Figure 3-3 Selected site used for tracer experiment in the Dinkel River

The top left image is a google image taken from Google earth on the October 30, 2009 and the bottom image is a photo of Dinkel river taken at Glane on the November 1, 2009

3.2.3. Estimation of Initial Parameters of Model

a. EC measurements in the field were first corrected to room temperature measurements. They were further converted to concentrations in grams per litre by a factor of 0.67 (1mS/cm = 0.67g/l).

b. The estimate of longitudinal dispersion was done in two ways – Fischer et al (1979) method and Three-Point method (Thomann and Mueller, 1987). The first methods use the rapid estimate using equation 3-2 below. This approach was used for measurements taken across the river width taken by the three loggers all installed at 80m. The S, river slope was estimated from the water levels obtained from Regge and Dinkel Waterboard from measurement date (November 18, 2009).

$$D_x = 0.011\frac{B^2.U^2}{h.U_*} \qquad \textbf{3-1}$$

$$U_* = (g.R.S)^{1/2} \qquad \textbf{3-2}$$

(Fischer et al., 1979)

Where;

B	River width	[m]
U	Flow velocity	[m/s]
h	Flow depth	[m]
U_*	Shear velocity	[m/s]
R	Hydraulic radius	[m]
g	Acceleration due to gravity	[m^2/s]

The second method (three-point) as documented in Thomann and Mueller (1987) is obtained as follows:

- ✓ The time taken to peak concentration is obtained for each of the measurements at 40m, 80m and 120m

- ✓ The slope is derived by a plot of peak concentration against inverse square root of time taken to peak concentration.
- ✓ The longitudinal dispersion is then obtained using equation 3-4.

$$Slope = \frac{M}{2 * A\sqrt{\pi E_x}} \qquad \textbf{3-3}$$

Where;

M	Mass of salt	[kg]
A	Cross sectional area	[m^2]
E_x	Longitudinal dispersion	[m^2/s]

c. The cross section of the river was subdivided into three main channels as indicated in the figure 3-4 below. The cross sectional areas of each of these sections were measured. In the derivation of dispersion during the first and second injections, these sub-cross sectional areas were used. However, in third and fourth injections were loggers were placed at 40m, 80m and 120m; the sum of these cross sectional areas was used. This is because; this was representative for each logger placed in the middle of the river at their respective distances from the point of injection.

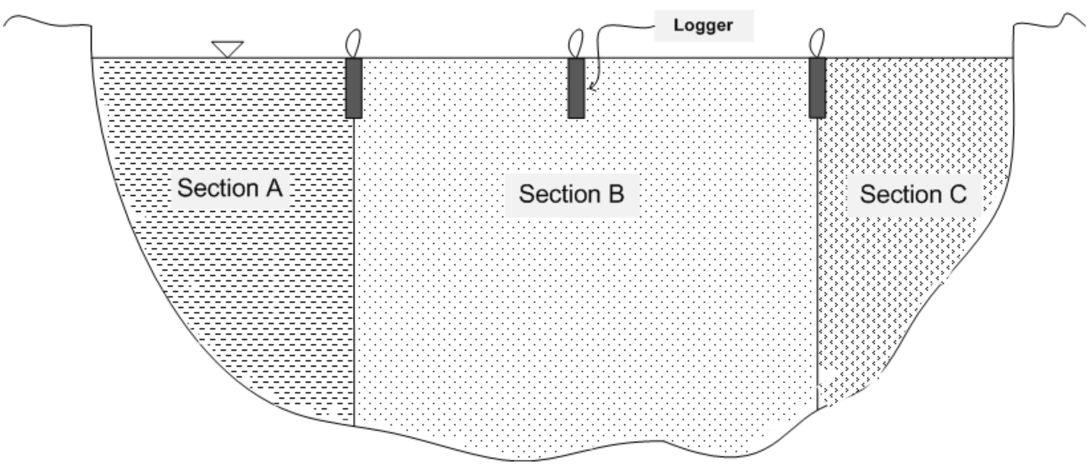


Figure 3-4 Sketch of cross section of river

d. OTIS requires initial parameter setting before it runs. Therefore information on cross sectional area, storage zone area, dispersion and storage zone coefficient were needed. For this initiation purposes, the storage zone area and cross sectional area were assumed to be equal. Hence, the cross sectional area obtained from experimental data was used. Also dispersion was derived from experiment data. The difficult parameter to estimate was the storage zone coefficient. The storage zone coefficient (α) was estimated using an approach developed by Wörman (2000). Wörman (2000) coupled first-order mass transfer (FOT) model and impermeable surface model (IS) to obtain a relationship for transient zone storage coefficient, α, as

$$\frac{5}{2}\frac{A_s D_s}{AL^2} \qquad \textbf{3-4}$$

Where;

D_s	Lateral mixing coefficient	[m^2/s]
L	River reach length	[m]
A_s	Storage zone area	[m^2]
A	Cross sectional area	[m^2]

3.2.4. Calibration of model

OTIS requires five input files for the calibration of the model (*control.inp, params.inp, star.inp, q.inp, data.inp*). For detailed description of these format types, the reader is refered to Runkel (1998). The *data.inp* and *star.inp* are the observation data file and the statistical file respectively. The *star.inp* is almost a default file. Therefore, the files to be modified to fit the study included the *params.inp, data.inp* and *q.inp*. The files were prepared following the steps below:

- After a successful run of OTIS, the other file name params.inp was obtained. This file contains the estimated parameters of dispersion, storage zone area, cross sectional area and storage rate coefficient that would yield the best fit for subsequent run of OTIS.

- The obtained modelled results were then compensated for in the original files of OTIS and again, the OTIS was run. This process was repeated until there was a close match between modelled concentrations and observed concentrations.
- A step wise approach to this has been provided in figure 3-4 below. The steps involved conversion of field EC measurements into concentrations in grams per litres, derivation of in-stream parameters, preparation of OTIS input files for calibration and general run of OTIS model.

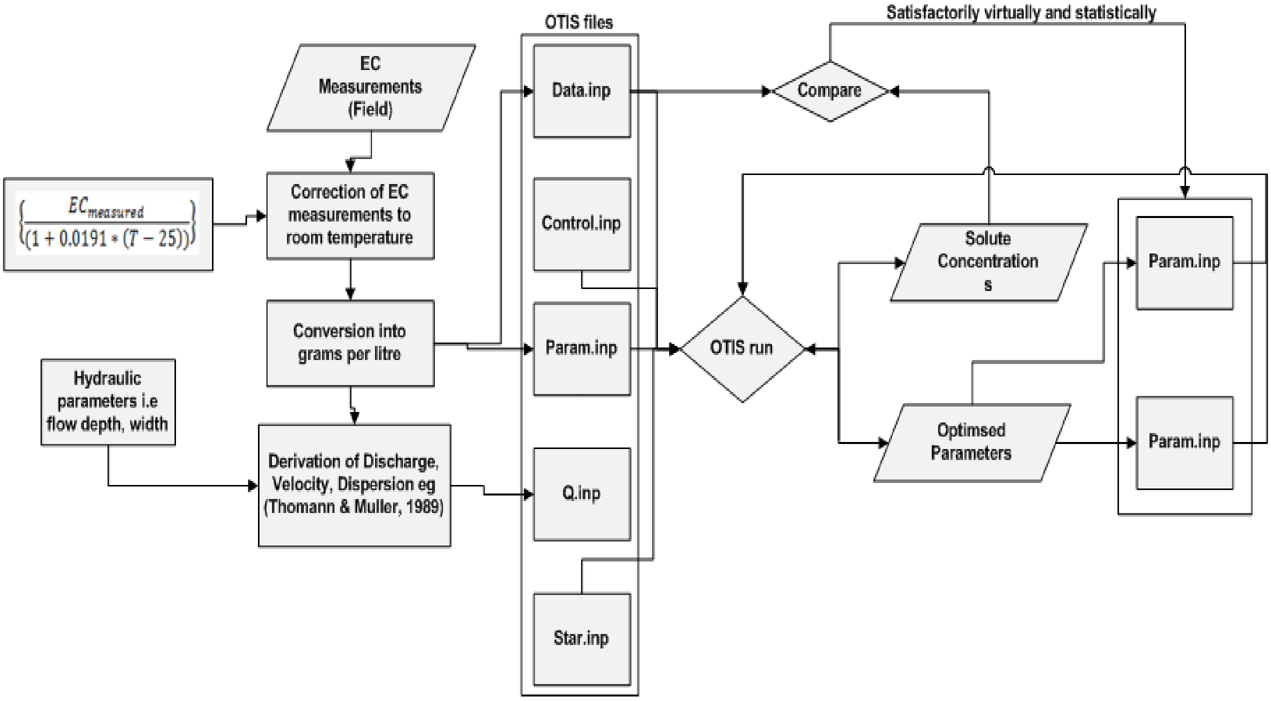


Figure 3-5 Preparation of OTIS files and calibration process

3.2.5. Validation of Model

Since a total of four (4) measurements were taken by each logger at 40m, 80m and 120m. The first two measurements of each section were used for the calibration and the two other datasets used for the validation of results for that section. The calibrated results of each section were also compared with the observed measurements of the entire section to determine the predictability of the model. The Damkohler number (DaI) was computed to provide insight about the reliability of the calibrated model parameters (Scordo et al., 2009; Wagner and Harvey, 1997). DaI is given by:

$$DaI = \frac{\alpha\left(1 + \frac{A}{A_s}\right).L}{u} \quad \textbf{3-5}$$

3.2.6. Integrating OTIS model with ILWIS Open

The hydrologic flow model that physically represents the hydrological network and flow conditions of the Dinkel river is integrated with OTIS model. This hydraulic flow model is the Full Equations (FEQ) model handled completely by a separate thesis work (Zun, 2010). Therefore, OTIS can get some its parameters such as cross sectional area and volumetric flow from this model. It should however be noted that the integration of the OTIS and FEQ is to compensate for the difficult in preparing input files for unsteady flow in OTIS. Since FEQ is an appropriate model in handling hydraulic unsteady flow, its results are easily transformed for use in OTIS.

Identification numbers (IDs) for specific branches (reaches) in FEQ model is also considered to be same in OTIS model. Therefore, for any specific branch definition in FEQ, the corresponding water quality parameters such as dispersion per reach, storage zone coefficient and storage zone cross sectional area are subsequently defined for OTIS. However, other specific details such as the definition of a pollutant plug are defined at the nodes. Each of these definitions specified in the FEQ and OTIS user windows are subsequently converted to the required input file format for running the model. This means that the user can easily get information about the fate of a pollutant at a specified node of the river network created in ILWIS Open. Figure 3-4 illustrates this in more picturesque form. Here, the FEQ model describes the physical hydrological network of the river. The OTIS model in turn gets information from the FEQ model; and then combines with other important details for water quality modelling. Together, these parameters both from FEQ and OTIS are converted into the right input files for OTIS run. A run from OTIS then gives tables and graphs at the various nodes specified by the user.

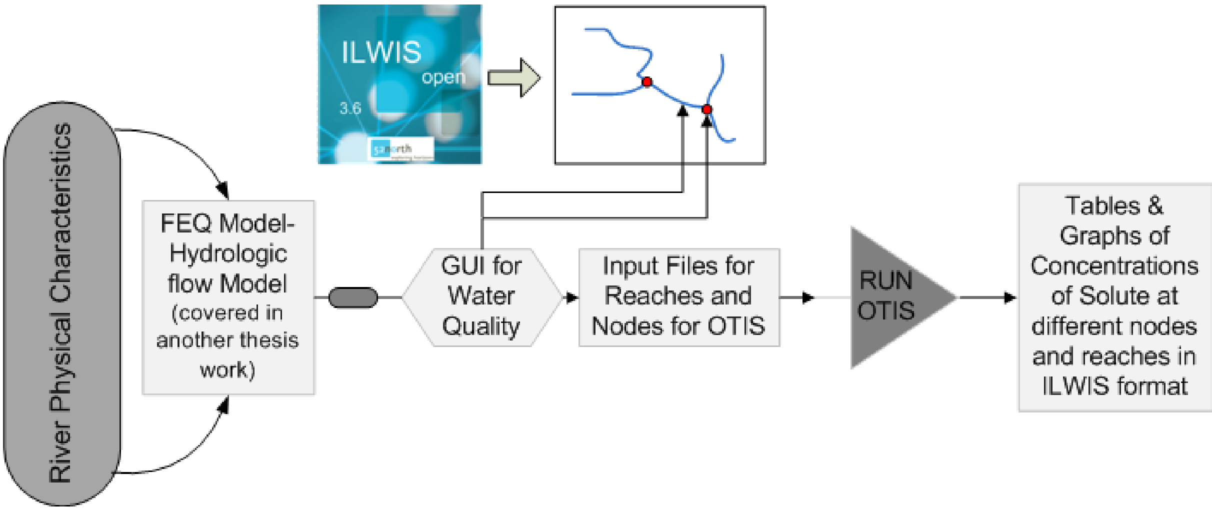


Figure 3-6 Summarised setup for integrating OTIS with ILWIS Open

However, under the current study, the user can obtain from the tracer experiment, all the required information necessary information to run OTIS. Therefore in this singular case, the user does not need to start with FEQ model but rather to prepare all the required input files for OTIS and simply run the model.

3.3. Summary

A non-reactive tracer (NaCl) was used in conducting the experiment in the study area. The data obtained from this experiment was used to characterise the hydrological and in-stream processes in the Dinkel river. The calibration of the model was done using observed data at recorded at 13:00hrs. The validation was also done using observed data at 13:00hrs. The reason for this timescale selection was due to the fact that three measurements were recorded simultaneously at 40m, 80m and 120m. In addition to this, the OTIS model was coupled to a hydraulic flow model –FEQ using a GUI. The integrated GUI would be further coupled to ILWIS Open for spatio-temporal data analysis of both OTIS and FEQ outputs.

4. Results & Analysis

4.1. Background

This section presents the results from the field campaign, model initial outputs, calibration and validation outputs. In the initial experiment setup, three measurements were done at 80m for two timescales. This was done to help distinguish the possible contribution of the transient storage to the overall transport of the tracer along the river. The calibration was done for every reach that is at 40m, 80m and 120m. Reach used here refers to a selected river length from the point of injection of the tracer. Two measurements each at 11:59hrs and 12:15hrs respectively were recorded for each of the three loggers. Since loggers were spaced out at near the banks and middle of the river, calibration was done for each logger for recordings taken at 13:00hrs. The reason for this selection was due to fact that measurement at 13:00hrs and 13:10hrs measurements were taken at 40m, 80m and 120m. The 13:10hrs measurements taken were used for the validation of the all results at each reach. However, measurements at 11:59hrs and 12:15hrs were used to illustrate the behaviour of the solute profile across the river width.

The last section discusses the integration of the OTIS model with FEQ model using a GUI. This GUI facilitates the processing of the input files and the running the two models. The GUI would later be integrated as a plug-in in the ILWIS Open in separate work according Kabo-bah and Zun (2009).

4.2. Field Measurements

The measurements obtained from the field were transformed into concentrations (g/l) as discussed in the previous chapter. For simplicity, this section has been subdivided into reaches. Therefore, analysis and results for each reach are presented. However, it should be noted that the order presented here also follow the order in which the experiment was performed during the field campaign/survey.

4.2.1. 80m Reach

Measurements were recorded in two phases under this reach. The first two sets of measurements were taken with the three loggers installed across the river at 80m from the point of injection. For details of arrangement and spacing of loggers across the river, please refer to figure 3-2(a). In the second phase, only one logger (Diver 38330) was used to record measurements at this reach. The computations therefore for dispersion were based on rapid estimate method (Fischer et al., 1979) for the first and second injections.

4.2.1.1. Measurements across the river at 80m

Figure 4-1 illustrates the recordings made by the three loggers at first injection (11:59hrs). The figure indicates a general rise in concentration after about 3mins after injection. The recordings are also in decreasing order of magnitude (0.14g/l, 0.08g/l and 0.04g/l) respectively for divers 38330, 61815 and 87851. The tailing of recordings of diver 38330 and 87851 are similar with a difference in the magnitudes. The temperature of the water also increases slightly with time reaching a peak of 9.36^{o}C. The discharge measurements estimated were 0.214m^3/s, 0.981m^3/s and 0.980m^3/s respectively for divers 61815, 38330 and 87851.

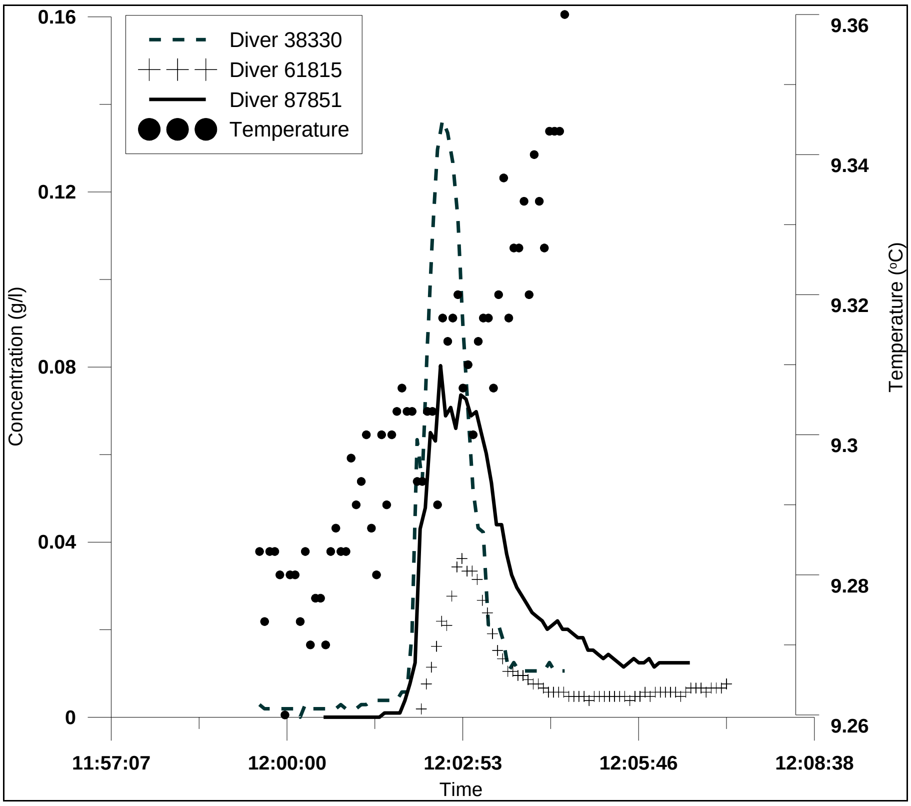


Figure 4-1 Observed Concentrations at 80m during first Injection

This means that, the concentration profile in the middle of the river was relatively higher than at the left bank (diver -61815) of the river. This was realised during field campaign that more flow was concentrated in the middle and right banks than at the left bank. It is also realised from figure 4-1 that the tailoring of the concentration profile after 12:02hrs is more gradual than compared to the middle. This means that while the left and right banks gradually loose their concentrations the middle bank continuously receive retarded solute mass. As a result the tailoring of the concentration profile appears to be more constant after 12:02hrs. Similar observations are seen with a plot at 12:15hrs (see figure 4-2). In this case, the interpretation of the condition at 12:15hrs is comparable to 11:59hrs. There is however some small differences in terms of quantitative values. For instance for discharge, 0.144m^3/s, 0.691m^3/s and 0.674m^3/s were recorded for respectively divers 61815, 38330, and 87851.

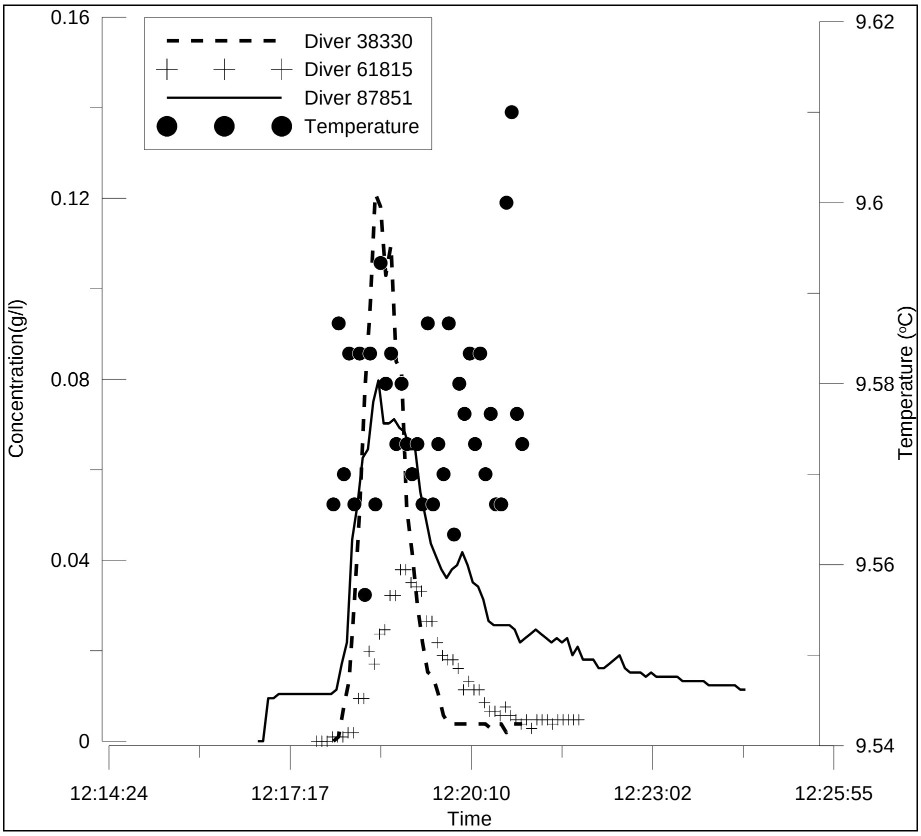


Figure 4-2 Observed concentrations at 80m during second injection

The lateral dispersion estimates were estimated in two parts – the consideration of one central logger in the section and the three loggers placed in the section. The comparison of the results was done to investigate the possibility of efficiency of using just one logger or three loggers. It should be noted that, the dispersion coefficient measurements were done in two ways – one point method (considering one central logger) and three-point method (considering three lateral loggers). The average of the measurements of the three lateral loggers is then compared the measurements of one central logger. In table 4-1 given below, the difference between the one-point method and the three-point method is very small. However, in table 4-2, there is a significant difference in the measurements of the two methods. The high sensitive of (Fischer et al., 1979) method to velocity measurements could be a contributory factor.

Table 4-1 Dispersion estimates for injection at 11:59hrs

	One-Point Method (One central logger)	Three –Point Method (Three lateral loggers)			
Divers	38330	**61815**	**38330**	**87851**	**Average**
Dispersion (m^2/s)	**1.685**	**0.223**	**1.912**	**3.338**	**1.824**

Table 4-2 Dispersion estimates for injection at 12:15hrs

	One-Point Method (One Central Logger)	Three-Point Method (Three lateral loggers)			
Divers	38330	61815	38330	87851	Average
Dispersion (m^2/s)	**8.341**	**0.101**	**0.946**	**1.583**	**0.877**

4.2.1.2.Measurements during second and third injections

This measurement took place at respectively 13.00hrs and 13:10hrs with diver 38330 when the other two loggers (61815 and 87851) were repositioned at 40m and 120m. Figure 4-2 illustrates the concentration profile at both 13:00hrs and 13:10hrs. The concentration peaks at about 13:03hrs for 13:00hrs injection with a value of 0.8g/l. The recorded discharges are 1.642m^3/s and 1.613m^3/s for 40m and 120m respectively. The dispersion coefficient for this period is 0.0642m^2/s. The temperature varies slightly within this period.

At 13:10, the concentration profile peaks slightly higher than at 13:00hrs (1.0g/l compared to 0.8g/l). The temperature variation within this period is also more rapid compared to 13:00hrs. However, temperature recordings are also lesser than at 13.00hrs. The estimated discharges too for this period are 1.490m^3/s and 1.560m^3/s for 40m and 120m respectively. The dispersion coefficient estimated is 0.087m^2/s. The discharge and dispersion coefficient measurements are comparable at both time scales.

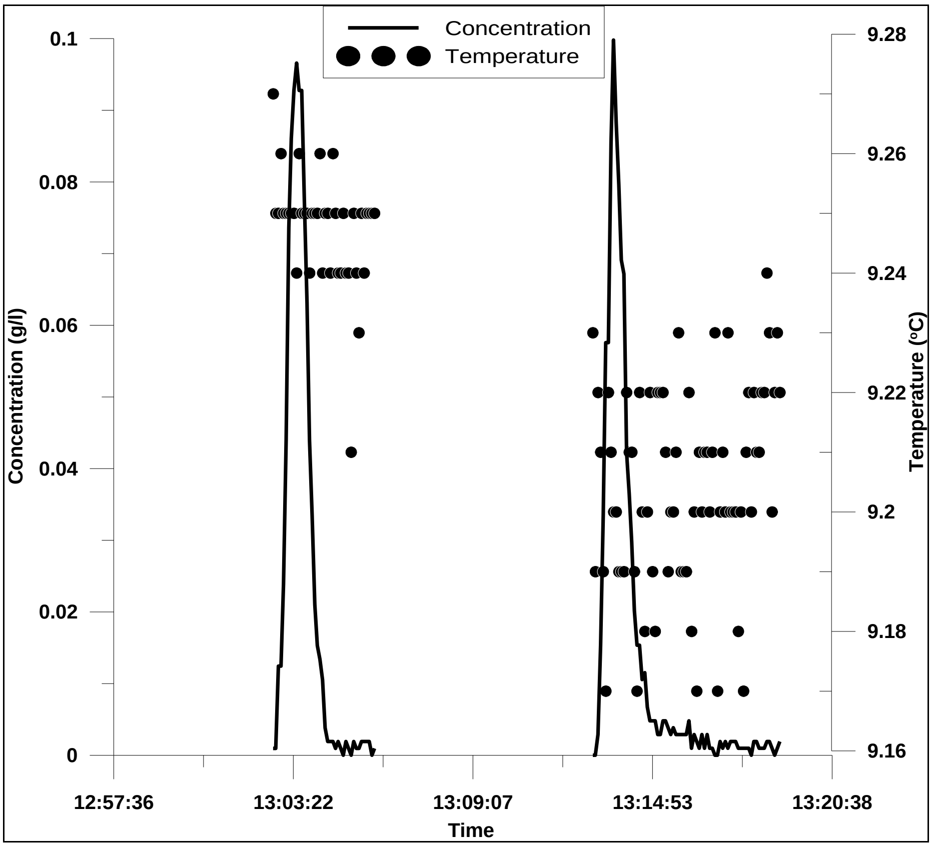


Figure 4-3 Observed concentrations at 13:00hrs and 13:10hrs at 80m reach

4.2.2. 40m Reach

Two recordings were made with diver 61815 at this reach. The measurements took place respectively at 13:00hrs and 13:10. Figure 4-4 shows the concentration profile at these timescales. The figure indicates that peaking of concentration at 13:01:25 with a value of 0.15g/l. Temperature recordings are between 9.39°C and 9.45°C. The discharge and dispersion coefficient are discussed in *section 4.2.2.2.*

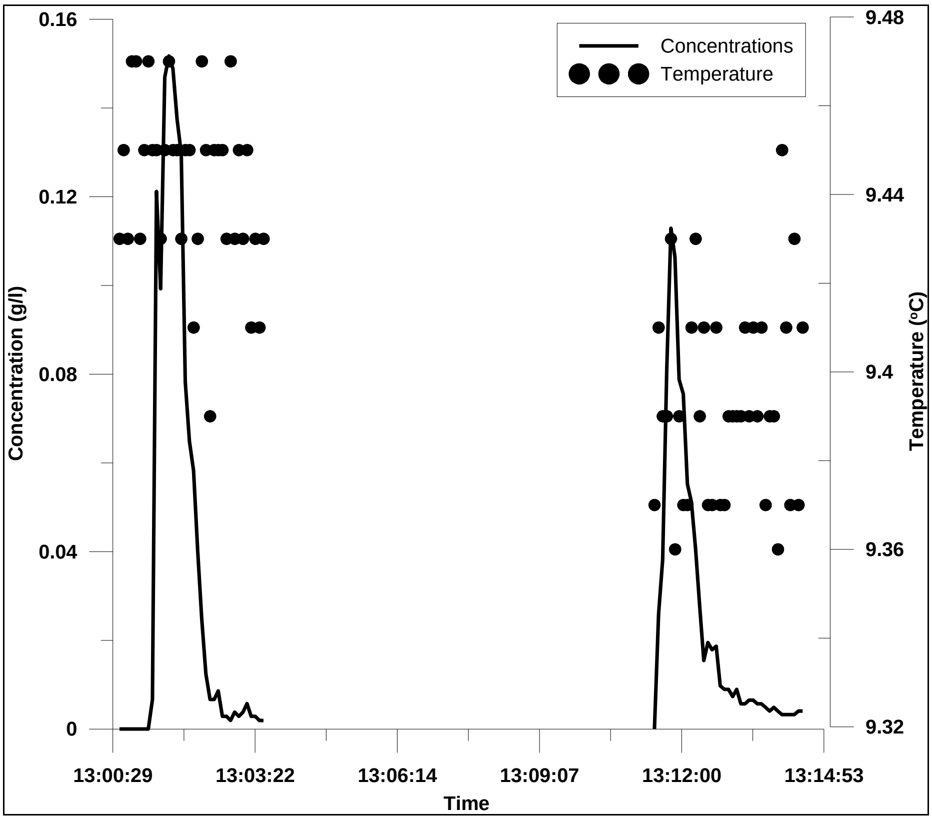


Figure 4-4 Observed concentration profile at 13:00hrs and 13:10hrs for 40m reach

4.2.3. 120m Reach

Figure 4-6 shows the concentration profile at 13:00hrs and 13:10hrs for measurements at taken at this reach. This figure indicates a rapid variation of temperature between 9.38°C and 9.42°C. The concentration peaks with a value of 0.09g/l after about four minutes after injection. On the other hand, the concentration profile at 13:10 peaks with a value of 0.075g/l. Concentration values here are slightly lower than at 13:00hrs. Temperature decreases slightly towards the end of the tail of the concentration profile. The discharge and dispersion coefficient measurements are discussed in *section 4.2.2.2.*

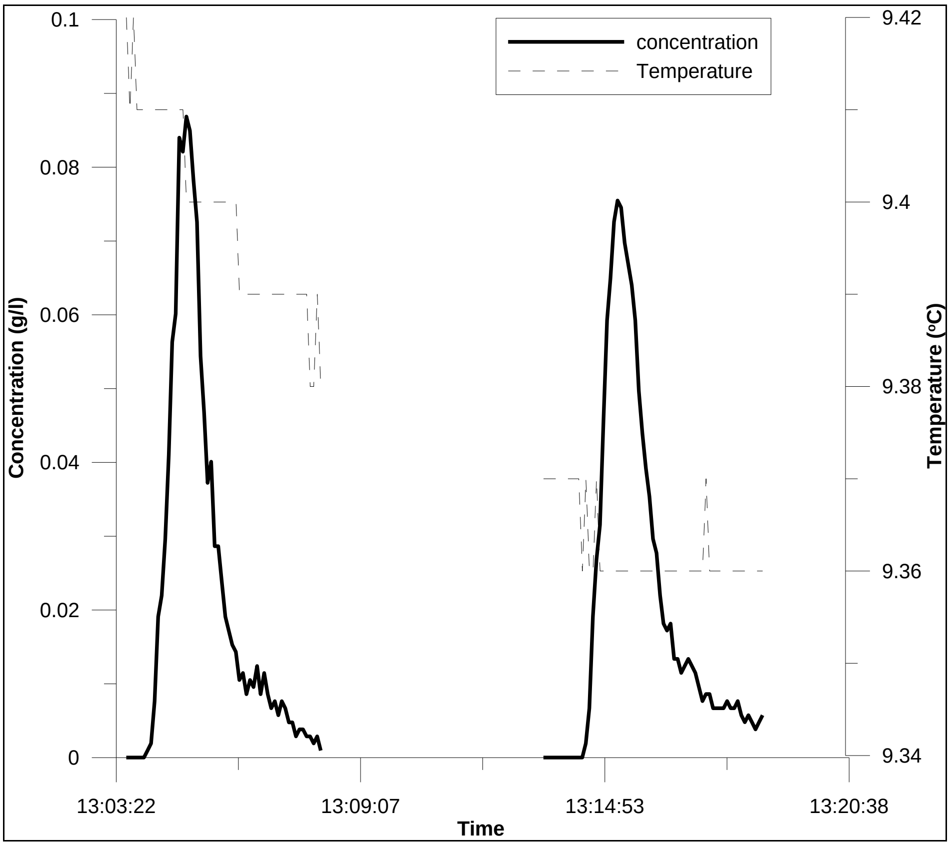


Figure 4-5 Observed concentration at 13:00hrs and 13:10hrs for 120m reach

4.3. Calibration

The model was calibrated at 13:00hrs for each of the reaches (40m, 80m & 120m). Since the model required some initial parameters, parameters such as storage zone coefficient, this was estimated using Wörman (2000) method given in equation 3-4. The storage zone area was assumed to be one-tenth of cross sectional area of the river. This was only an approximation to enable initiation for the model. For each of the cases, the model was run to obtain a good match between modelled and observed data. Model parameters were therefore optimised for the cross sectional area of reach, storage zone coefficient, storage zone area and longitudinal dispersion. The first initial run gave a reasonable behaviour of tracer's fate in figure 4-7. However, the concentration profile at 40m and 120m reaches deviates slightly from measurements at 80m, the model estimates are smaller than observed and also there is a shift to the right. On one hand, the model prediction at 80m closely matches the behaviour of the observed data. Also, there is a general decline in the concentration peaks from shortest to longest reach. This could be attributed to transport and chemical processes at each of these reaches. Apart from this, the cross sectional area at 80m was assumed to be the same for 40m and 120m, and would have contributed also to this variation.

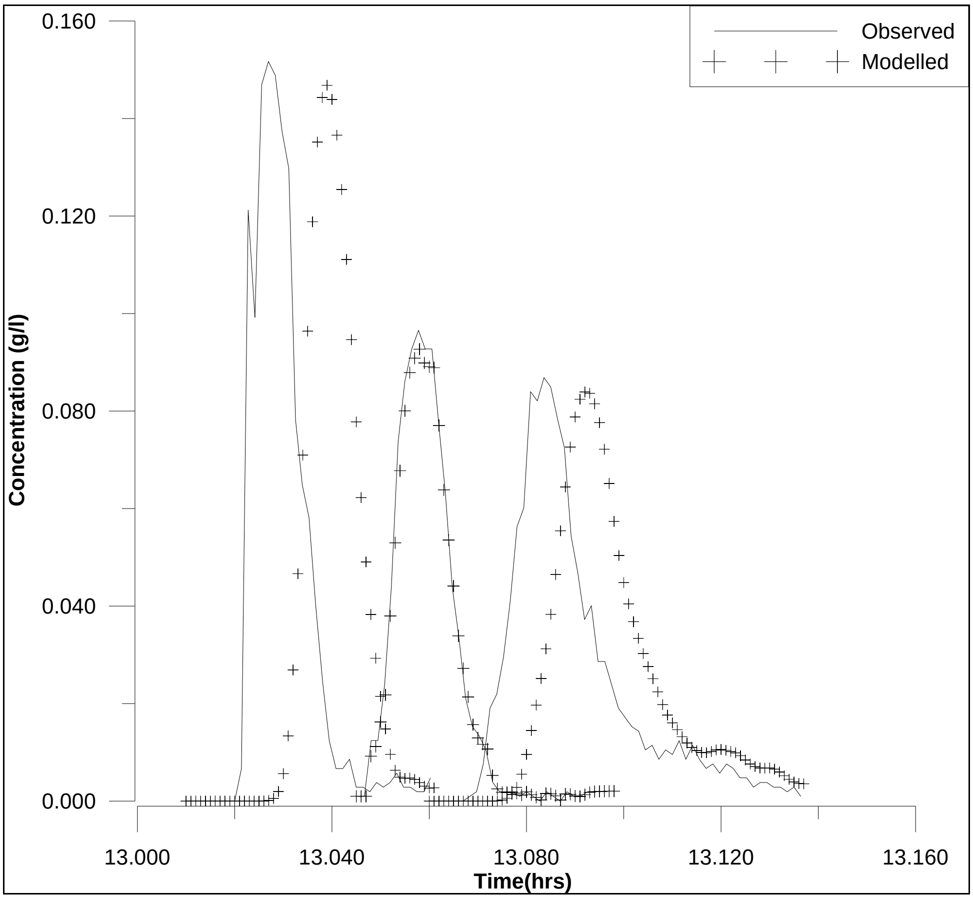


Figure 4-6 Calibration results after first run of OTIS

The model was then run until best fit to observed data was obtained. The result of this is shown in figure 4-7. The figure shows a very close match between observed and modelled data. Interesting, the model predicts precisely the behaviour of the observed data. This is also evident in the R^2 values of 0.986, 0.988 and 0.982 for 40m, 80m and 120m respectively.

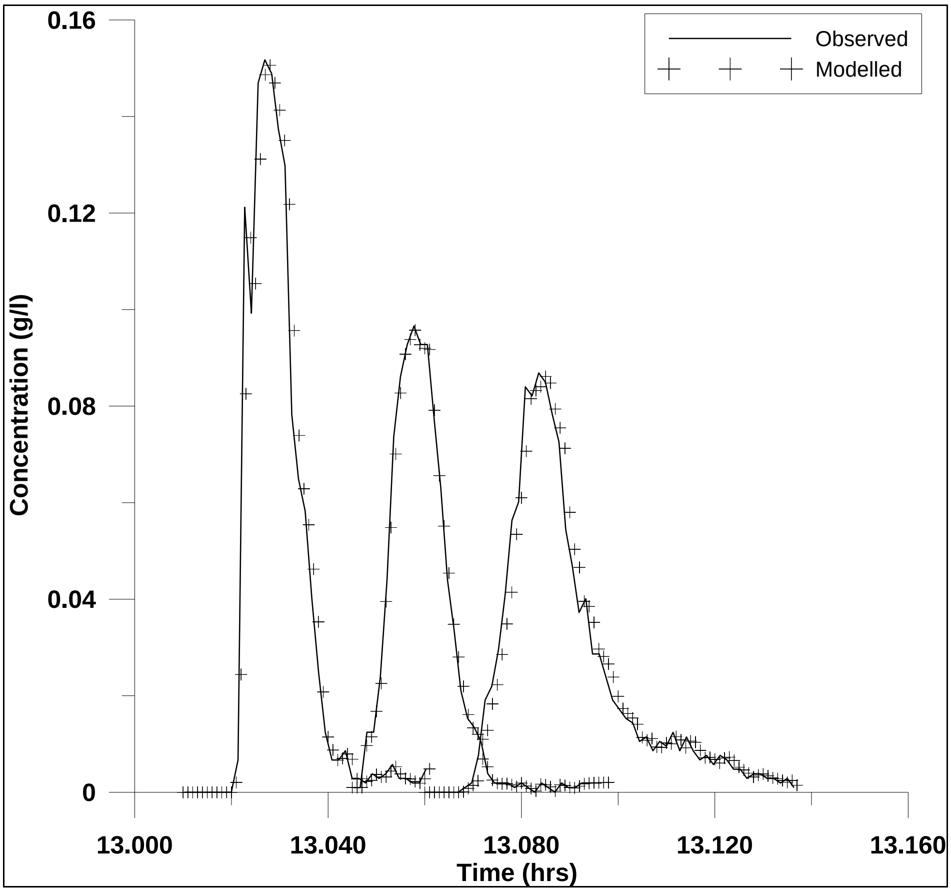


Figure 4-7 Calibrated results of OTIS for reaches

The obtained parameter results as shown in table 4-2. The cross sectional and storage zone areas, storage zone area and dispersion are shown for each reach. Also, the DaI was computed and the values indicated against each reach. Wagner and Harvey (1997) showed that when the DaI deviates from 1.0, the uncertainty in the modelled parameters increases. High values may occur because the exchange with the streambed is relatively fast compared with the water velocity or reach may be too long. Also, small values of DaI (<0.1) could result from 1) high river velocity, 2) long exchange time scale as indicated by a low α and As/A ratio or too short a reach. In this particular study, the DaI was less than 0.1 in all cases, the possible reason is the use of the relatively short reaches.

Table 4-3 Computed parameters of calibration results

Reaches(m)	A(m^2)	A_s(m^2)	D (m^2/s), model	α	DaI
40	4.104	0.4104	0.0642	7.813E-10	8.59E-07
80	4.104	0.4104	0.0642	1.950E-10	4.51E-07
120	4.104	0.4104	0.0642	8.680E-11	2.92E-07

A, Cross sectional of river; A_s, Storage zone area; D, Longitudinal dispersion; α, Storage zone coefficient

4.4. Validation

The model was validated for each reach using observed data taken at 13:10hrs. Figure 4-8 indicates very good prediction of the modelled data and observed data. For instance, there is a very good match of observed and modelled data for all reaches. The computed statistics are shown in table 4-4. There is a significant deviation of 120m results compared to the others. It appears that, the closer the observations from the point of injection, the better the validation results.

Table 4-4 Computed statistics for validation results

	40m	80m	120m
R – square	**0.991**	**0.979**	**0.966**
RMSE	**0.003**	**0.004**	**0.019**

It was also interesting to find out what happens if one had only measurements of concentrations at 120m, was it possible to obtain good results from reaches at 40m and 80m. This resulted in the figure 4-10. The figure shows 120m reach calibrated information is used to predict results at 40m and 120m. The results here are comparable previous work by Bencala (1983) that OTIS can not be used as a predictive engineering tool. This is because there are too many empirically determined parameters used in the application to speculate predictive capabilities in other systems. The other possible reason is that, it is sharp variation in in-stream processes such as dispersion, discharges and transient storage which greatly affect the model to be a predictive tool. This therefore means that, the model gives comparably similar results to the calibrated reach used other than the specific different reach specified. It should also be noted that, OTIS can be predict results beyond the specified reach distance. For example, for a given reach of 120m, OTIS can not predict at 121m or more.

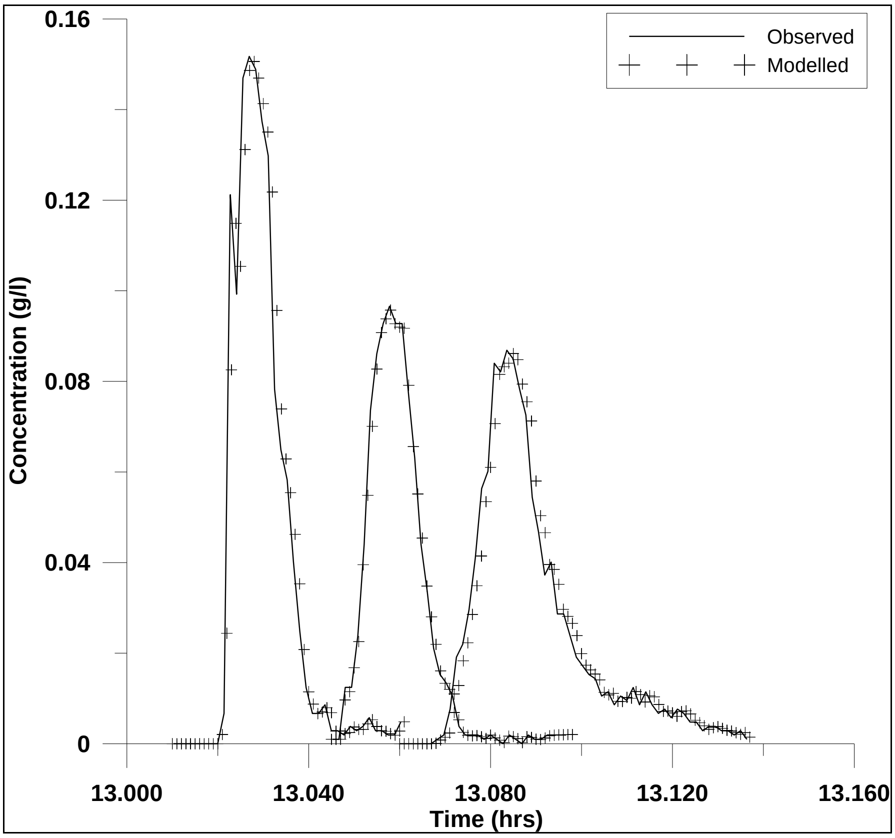


Figure 4-8 Validated results of OTIS using data at 13:10hrs

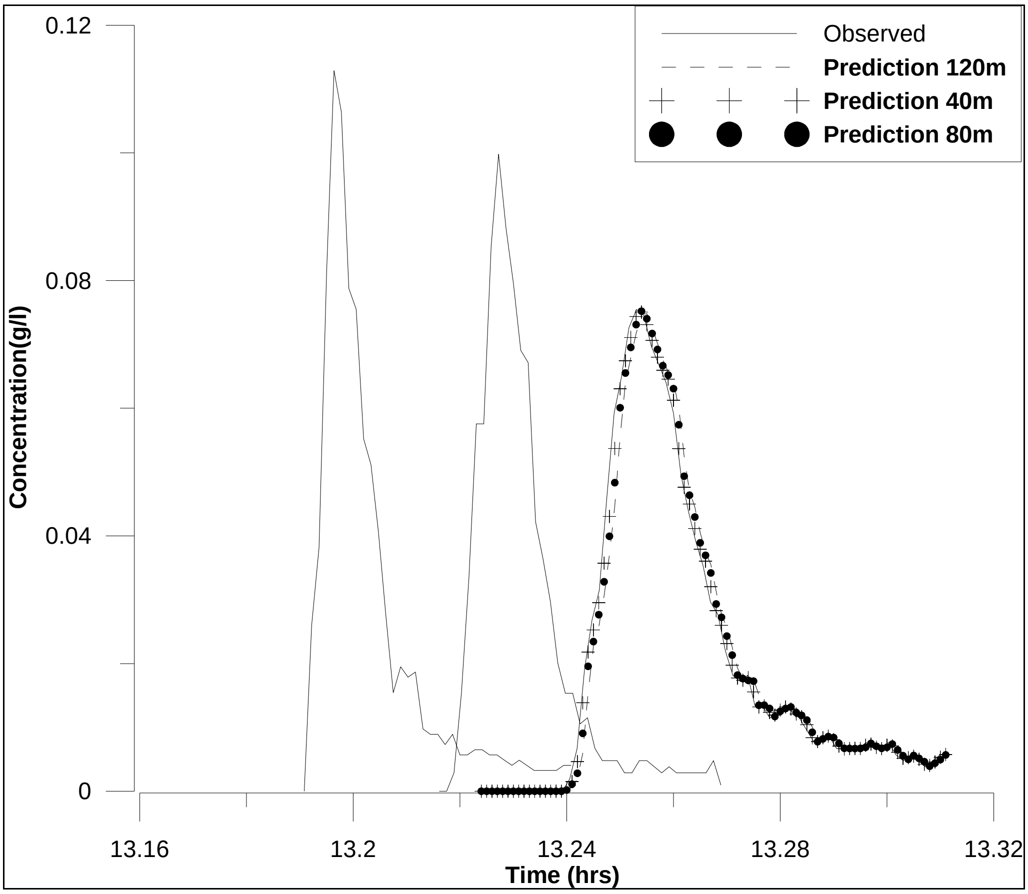


Figure 4-9 Predicting dispersion at 40m and 80m using the observed data of 120m

4.5. GUI for OTIS

4.5.1. Why GUI?

There are three fundamental reasons for the development of the GUI for OTIS. They include:

- OTIS input file formats is complicated and usually require a lot of manual editing and because the code was written in FORTRAN, error in file formats lead to problems with running of OTIS. The GUI therefore is supposed to lessen the burden of the user in editing these files manually.
- The ultimate idea is to have OTIS obtaining unsteady flow information from FEQ in the future, there was the need to develop together some platform where these two models could be interact together and hence the need for the integrated GUI
- The goal of having a stream flow and water quality modelling in ILWIS Open using FEQ and OTIS respectively also means integrating the two models in one platform.

This integrated platform could then be easily implemented as a plug-in in ILWIS Open.

However, for the time being, the OTIS model was calibrated and validated independent set data obtained from field campaign. Therefore, information from FEQ has not been tried yet with OTIS in this instance. Also, the integration of this package to ILWIS Open is underway and would be handled separate work according to Kabo-bah and Zun (2009).

4.5.2. Fundamental framework of GUI

The GUI was written and developed in C++ program using Microsoft Visual Studio 2008 with full support from Mr Yin Zun, author of *'Hydrological transport model calibration and integration by GUI in 52 North/ILWIS OS for the Dinkel river for supporting water quality studies'*. Therefore, a more detailed derivation of the code and explanation on how to use the integrated can be found in this thesis. The GUI is operational under Windows XP and does not work properly under Windows Vista. However, this was not tested in older Windows versions and other operating systems. The GUI is an integrated package of both FEQ and OTIS. The processes of each of these programmes can be run independent of the other.

4.5.3. Main steps in operating OTIS GUI

There are two main processes involve in the operation of the OTIS GUI. They are:

- Entering branch information
- Entering node information

The branch file contains information as shown in figure 4-10. Here, information on the longitudinal dispersion, storage zone area and storage zone coefficient (alpha) are provided. To do this, an existing format for branch in text format is available. This file is first imported. The required parameters for OTIS are then edited and save, and then the branch text file is automatically updated. The steps provided below make an example of using the GUI to run the OTIS model for measurements taken at 80m at 13:00hrs.

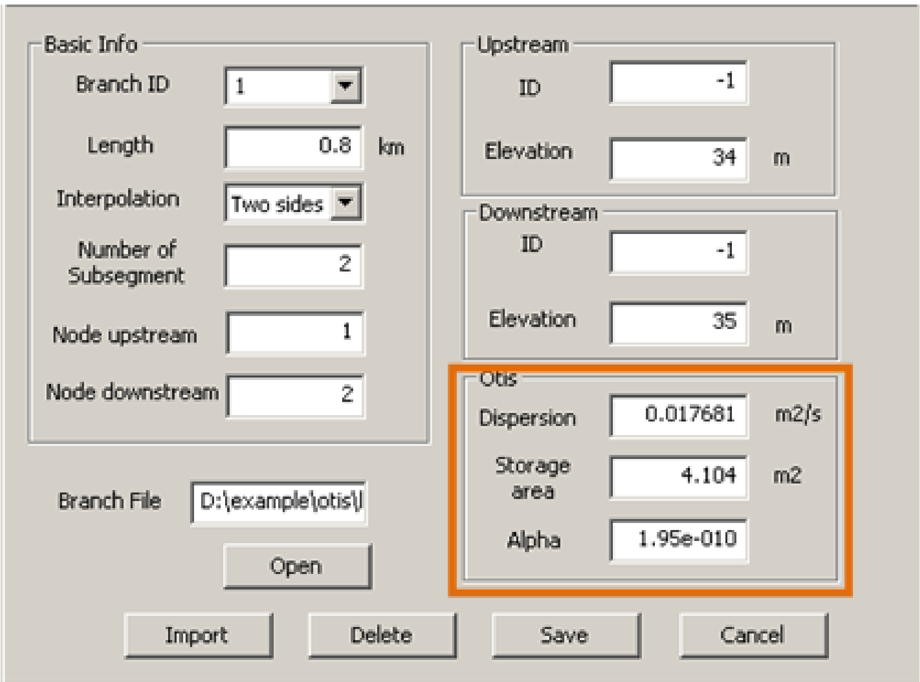


Figure 4-10 Branch information for OTIS (highlighted red)

The next step after this is updating the node file (see figure 4-11). First the node text file provided by the program is first imported. The required parameters for OTIS are then edited and save to file. This automatically updates the node file.

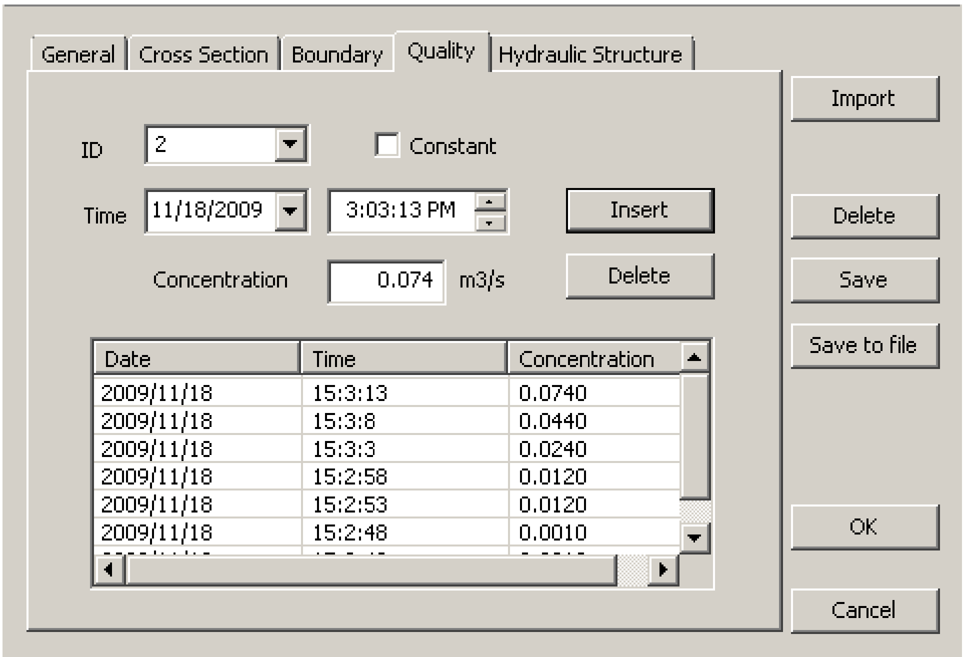


Figure 4-11 Node information for OTIS

After the successful preparation of the branch and node files, the next step is the running of the OTIS model. To do this, in FEQ model mode, the branch, node and output files are loaded. The output file is empty text file and is loaded for technical reasons. Also these files must be loaded before the OTIS model can be run. Else, this would give an error message “no branch file”.

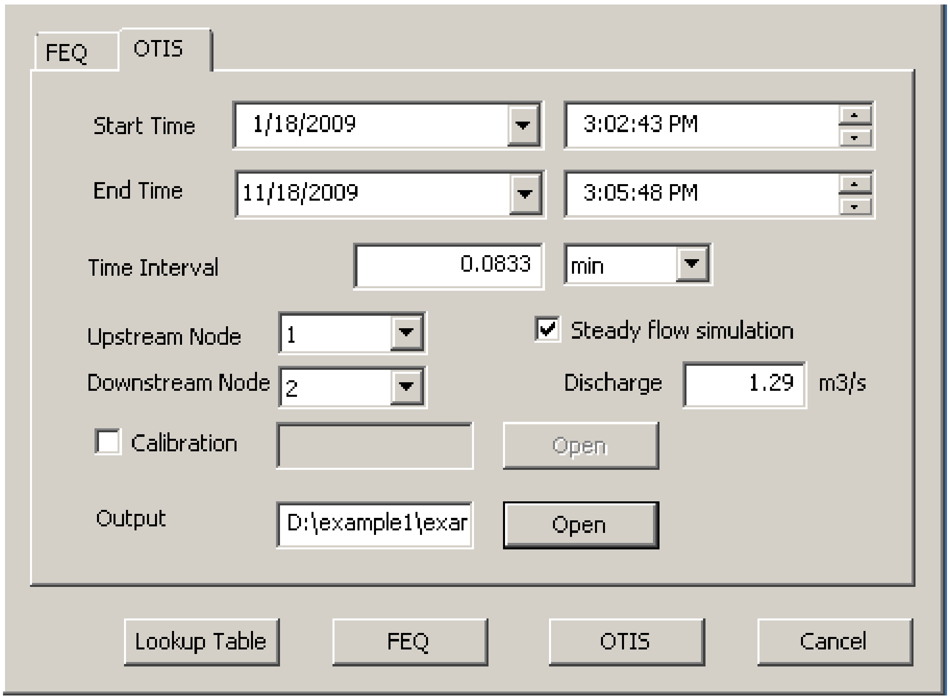


Figure 4-12 Input parameter information at reach 80m for OTIS model

To run the OTIS model, the lookup table is first run. This prepares some input parameters for FEQ model. But for technical reasons, it is advised to be run first before the running the OTIS model.

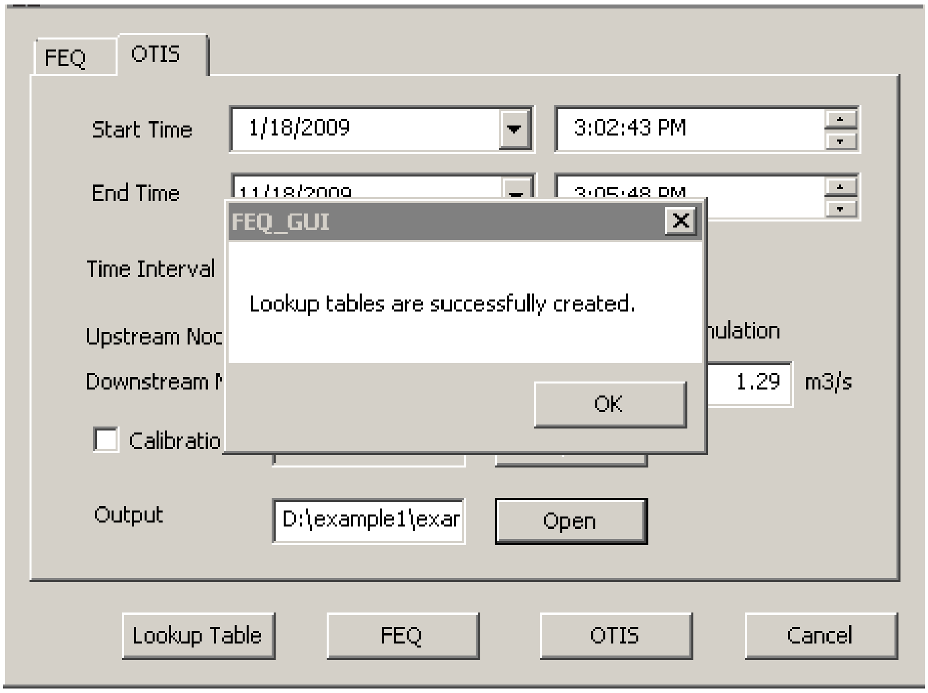


Figure 4-13 Preliminary OTIS run

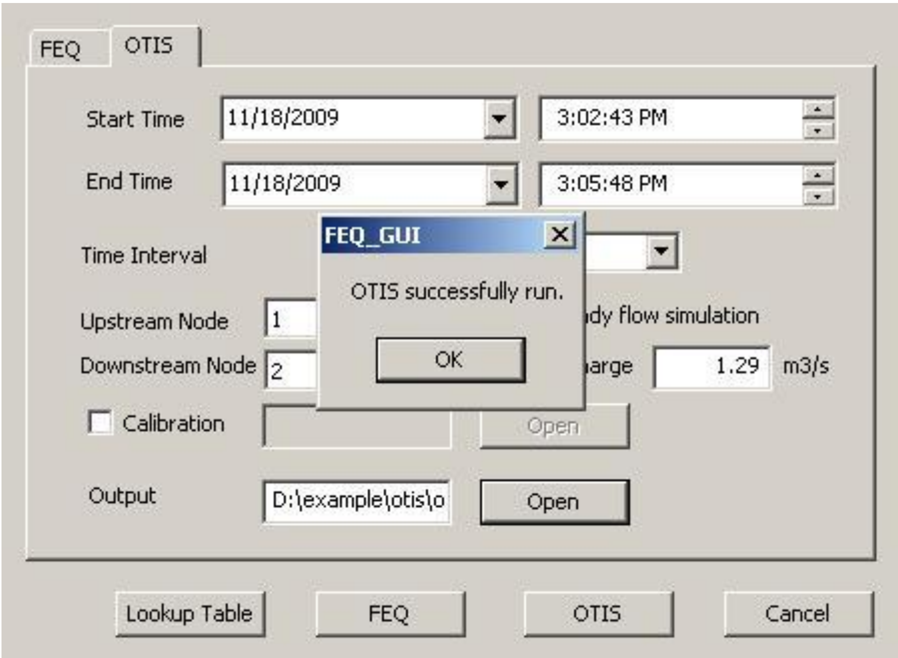


Figure 4-14 Successful OTIS run

In case, calibration is needed, all one need to do is follow the same provided, just that calibration is checked and required calibration file loaded. The OTIS is then run normally.

4.6. Summary

The model was calibrated for each reach at 13:00hrs. The model shows perfect calibration results for each of the reaches. The validation of the model was done using observed data at 13:10hrs. The model shows perfect results for 80m reach. The model is however not a good predictive tool. This was also detected in previous works by Bencala (1983). According to him, there are too many empirically determined parameters used in the model to predict reliably conditions in other systems. The GUI successfully prepares input files and run the OTIS model in the background. The integrated GUI of OTIS and FEQ would be integrated as a plug-in as indicated in the proposal of Kabo-bah and Zun (2009).

5. Discussions

The migration of solute in streams and rivers are subject to advection and dispersion, and in most instances retarded by transient storage processes. The use of OTIS model to quantify solute concentrations as a result of transport and chemical transformations in the streams and rivers becomes crucial. However, the model requires a number of empirically parameters that need to be determined. These parameters are very difficult to determine experimentally. So what usually happens is the use of trial and error approach to determine the parameters which gives the best fit to the observed data. Fortunately with the use of OTIS-P, a non-linear regression package for optimising the parameters of the OTIS, the difficult with the trial and error method is minimised. The only thing needed is to provide initial parameters for the model. Since it is not clear in previous studies how this has been done, there is still need to find a better way of handling this situation.

Studies conducted by Wörman (2000) through the *comparison of models for transient storage of solutes in small streams* provides an important step in the estimation of storage zone coefficient. This coefficient is the most difficult to estimate. The formula derived by Wörman (2000) requires another important parameter, the lateral mixing coefficient (D_s) (refer to equation 3-4). Previous works also by Wörman (1998) indicated that the lateral mixing coefficient varies under different stream conditions in the order of $0.1 \times 10^{-6} < Ds < 10 \times 10^{-6}$ (m^2/s). Wörman (2000) estimated that for an drainage ditch in an agricultural farmland, D_s is approximately $5 \times 10^{-7} m^2/s$. The selected site for this study within the Dinkel river basin is characterised by farmlands. Therefore, the D_s value of 5×10^{-7} was used to estimate storage zone coefficient (α). The α values for reaches 40m, 80m and 120m were estimated as 7.8×10^{-10}, 2.0×10^{-10} and 8.7×10^{-11} respectively.

The measured concentrations at 11:59hrs and 12:15hrs showed bigger peak at the middles than at the side banks with the left bank (diver -61815) being the lowest. There is also similar tailoring of left and right banks compared to the middle bank. One reason is that the delayed solute mass in the side banks flows into the middle of the stream considering the river bed profile (deepest at middle). Discharge and dispersion measurements also vary for the two timescales. It was generally observed on the day of the field campaign that, the weather was characterised by rapid changing environmental conditions with a lot of wind activity. The rapid changing windspeed and direction obviously could have affected these values in this short time. In the subsequent measurments taken at 13:00hrs and 13:10hrs, loggers were installed at distances of 40m, 80m and 120m. Observed measurements at 40m reach are comparable at the two timescales. At 80m reach, observed measurements at 13:00hrs are higher than at 13:10hrs. Also, at 120m reach, observed measurements at 13:10hrs are about three times those taken at 13:00hrs. The sharp constrast between measurements at 80m reach and 120m reach could be due to two reasons 1) faster transport of solute mass from this section. This is because from this point, the reach widens and deepens towards 120m reach 2) the fast transport of solute mass from 80m reach contributes to the increase in solute mass at 120m. The temperature measurments at both 80m and 120m reach are comparable but lesser values are recorded for 40m reach.

The calibrated results for all reaches at 13:00hrs give close match between observed and modelled data. These results are similar to works done by Bencala and Walters (1983a) and Runkel (1998). However, the optimised parameters for instance for storage zone coefficient (α) are in the order of 10^{-09} and dispersion in the order of 10^{-2} m^2/s compared to 10^{-4} – 10^{-6} and $10^{-1} m^2/s$ in other studies conducted by (Bencala and Walters, 1983a; Runkel, 1998; Scordo et al., 2009). The difference could be as a result in different physical of streams and climatic conditions under which each of these studies was conducted. For instance, the discharge in this study ranges between 0.725 – $1.642 m^3/s$ compared to 0.0125 – $0.030 m^3/s$ in those studies. In this case, the discharge in this study is about ten or more times other studies conducted using the model. In addition, it is not clear in these previous studies as to the magnitude of the catchment areas for these rivers under which such studies was conducted. What is however clear is that, the reaches studied in these previous works are in the order of 600m compared to 120m of this current study. These vast disparities could obviously also contribute towards the different model parameters obtained. However, the perfect calibration results still indicate the sustainability of the model under the current conditions.The estimated transient storage of all reaches is negligble as a result of the very low storage zone coefficient values.

The model was validated using observed data recorded at 13:10hrs. This was the only option because there was no other independent tracer experiment conducted in the Dinkel river basin. Very close match was obtained for observed and modelled data for all reaches. The 120m reach calibrated model was also used to predict for the solute migration at 40m and 80m. The modelled results obtained were not comparable to 40m and 80m but closely matches the observed data at 120m. This indicates similar observations made by Bencala (1983). Therefore, the model is very good for predicting results at sections that it is calibrated for and can not predict for another section. Also, the model is not capable for predicting results of solute migration greater the length of the reach specificied.

The lateral dispersion coefficient measured by the one-point compared to the three-point method indicates that the latter method shows more consistent approximation for the two timescales (11:59hrs and 12:15hrs). In addition to this, the three lateral loggers take into account variable hydrologic processes across a section of the river compared to just one logger.

The biggest challenge of using this model is the preparation of input files. The model written in FORTRAN language is very sensitive to the file format and structure. Therefore the building of the GUI to prepare input files and run the model makes work with the model easier. In the design of the GUI too, only steady state condition have been considered as a result of the time constraints involved in incorporating all the capabilities of the OTIS model. This GUI package too would further be included in ILWIS Open to enable the spatial display of results of both OTIS and FEQ.

6. Conclusions

Water quality modelling is crucial to understanding the dynamics in water quality monitoring and management of our rivers and lakes. With the recent climate change reports by IPCC and similar works by Royal Netherlands Meteorological Department, it is evident that more efforts are needed in the area of research to understand effects of this on water resources on effective water quality management. One way to address this is to incorporate water quality modelling to the available open source GIS and remote sensing tools. In this way, traditional methods of studying water quality would be extended to understanding this phenomenon in time and space and can be visualised in the form of maps. Since, there is existing open source GIS and remote sensing software in ITC – ILWIS Open, the study therefore made use of this existing advantage to develop a GUI for water quality modelling.

As a partial contribution to the above, the study first identified OTIS as the most appropriate water quality model capable of integrating into ILWIS Open. The OTIS is a one-dimensional transport and inflow with storage. The decision on this model was reached after review of water quality models, roundtable discussions with water quality professionals such as the Regge and Dinkel Waterboard based in the Netherlands and online discussion with one of the authors (Rob Runkel, research hydrologist at the US Geological Survey) of the model. The approval of these parties led to final selection of the OTIS model for this study. On November 18, 2009, a tracer experiment was conducted in the Glane section of the Dinkel River. Measurements of EC at 40m, 80m and 120m were done with automatic loggers. These measurements taken at 13:00hrs and 13:10hrs were used respectively for calibration and validation of the model.

In order to calibrate the model, initialisation of parameters is needed. One of the most difficult parameters to estimate is the storage zone coefficient. Previous studies on this have not clearly shown how this is done. However, works by Wagner and Harvey (1997) indicate that a mathematical relationship exists for this coefficient. This method was applied to estimate the initial storage zone coefficient. The model was calibrated and validated for 40m, 80m and

120m and indicate in all cases R^2 value of more than 96%. The model was also investigated for the ability of the model to predict solute migration for distances lesser or more than the specified length of the reach. The results obtained were poor and comparable to earlier conclusions by Bencala and Walters (1983a) as non-predictive tool.

Another main goal of this research is to contribute in part towards an integration of a stream flow and water quality scheme in ILWIS Open. To do this, the OTIS model was coupled together with a FEQ model using a GUI. The GUI facilitates the preparation of input files for both models and run models in the background. This GUI would be further integrated into ILWIS Open according to Kabo-bah and Zun (Kabo-bah and Zun, 2009).

It is believed that the efforts of this research would in the long run help young researchers and other professionals who are not able to afford expensive models to rely on this package for their water quality monitoring and management. This would give the chance for more researchers to further contribute their knowledge and experience towards the improvement of this package to handle chemical processes in rivers and lakes.

Recommendations

To be able to achieve the overall goal of this research, continuous effort and research are necessary. These areas are below:

1. The use of three lateral loggers to determine the dispersion coefficient at a section gives a better approximation than compared to just one logger. It is suggested that, in subsequent studies of this nature, for every reach, three loggers should be used. This would provide useful information in the characterization of hydrologic and transport processes occurring in the river.
2. Further studies on the OTIS to perform unsteady flow conditions to include Biochemical Oxygen Demand (BOD), eutrophication, decay, and sorption processes. It would be interesting to do more studies on the behavior of OTIS for longer reaches in the upstream of Dinkel and also find out the suitability of OTIS for BOD and sorption processes. The OTIS can also be applied to river systems which are not man-handled so much to understand how the model behaves between natural and man-made river systems.
3. Improvement of the GUI in ILWIS Open to automate processing of flow and water quality with OTIS and unsteady flow conditions. With the hydro-processing tool in ILWIS, and with the capabilities of FEQ model covered in another thesis, it is possible to automate the processes of OTIS in ILWIS Open.
4. Improvement of the visualization of results in ILWIS Open in 3D with an external open source program such as Paraview. This help in the visualization of the results of solute migration in 3D dimension. This is important for informing policy and decision makers who are not interested in all the technical complexities behind the operation of this model.

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Appendices

A- 1 Measurements and estimates of dispersion and discharge at 40m for first and second injections

	1st injection (11:59hrs)			2nd Injection (12:15hrs)		
Discharge(m^3/s)	**0.214**			**0.144**		
Velocity(m/s)	**0.229**			**0.154**		
	Time	**Temp (°C)**	**g/l**	**Time**	**Temp (°C)**	**g/l**
	12:02:12	9.39	0.0019	12:17:42	9.66	0.0000
	12:02:17	9.39	0.0076	12:17:47	9.70	0.0000
	12:02:22	9.39	0.0114	12:17:52	9.66	0.0000
	12:02:27	9.39	0.0162	12:17:57	9.71	0.0009
	12:02:32	9.41	0.0219	12:18:02	9.64	0.0009
	12:02:37	9.32	0.0210	12:18:07	9.71	0.0009
	12:02:42	9.39	0.0277	12:18:12	9.64	0.0019
	12:02:47	9.39	0.0343	12:18:17	9.68	0.0019
	12:02:52	9.36	0.0363	12:18:22	9.64	0.0095
	12:02:57	9.39	0.0334	12:18:27	9.70	0.0095
	12:03:02	9.37	0.0334	12:18:32	9.70	0.0199
	12:03:07	9.39	0.0315	12:18:37	9.68	0.0171
	12:03:12	9.39	0.0267	12:18:42	9.68	0.0237
	12:03:17	9.34	0.0239	12:18:47	9.66	0.0246
	12:03:22	9.41	0.0191	12:18:52	9.66	0.0322
	12:03:27	9.39	0.0153	12:18:57	9.66	0.0322
	12:03:32	9.39	0.0134	12:19:02	9.66	0.0379
	12:03:37	9.41	0.0105	12:19:07	9.64	0.0379
	12:03:42	9.39	0.0105	12:19:12	9.70	0.0351
	12:03:47	9.39	0.0095	12:19:17	9.64	0.0341
	12:03:52	9.39	0.0095	12:19:22	9.64	0.0332
	12:03:57	9.41	0.0086	12:19:27	9.64	0.0265
	12:04:02	9.39	0.0076	12:19:32	9.68	0.0265
	12:04:07	9.37	0.0076	12:19:37	9.62	0.0218
	12:04:12	9.41	0.0067	12:19:42	9.66	0.0189
	12:04:17	9.39	0.0057	12:19:47	9.66	0.0180
	12:04:22	9.41	0.0057	12:19:52	9.68	0.0180
	12:04:27	9.43	0.0057	12:19:57	9.64	0.0161
	12:04:32	9.41	0.0057	12:20:02	9.66	0.0114

12:04:37	9.41	0.0048	12:20:07	9.64	0.0133
12:04:42	9.41	0.0048	12:20:12	9.64	0.0114
12:04:47	9.41	0.0048	12:20:17	9.64	0.0114
12:04:52	9.39	0.0048	12:20:22	9.62	0.0085
12:04:57	9.43	0.0038	12:20:27	9.73	0.0066
12:05:02	9.41	0.0048	12:20:32	9.73	0.0066
12:05:07	9.41	0.0048	12:20:37	9.66	0.0057
12:05:12	9.45	0.0048	12:20:42	9.64	0.0076
12:05:17	9.45	0.0048	12:20:47	9.68	0.0057
12:05:22	9.41	0.0048	12:20:52	9.64	0.0047
12:05:27	9.43	0.0048	12:20:57	9.71	0.0038
12:05:32	9.41	0.0048	12:21:02	9.71	0.0047
12:05:37	9.43	0.0038	12:21:07	9.66	0.0028
12:05:42	9.41	0.0048	12:21:12	9.70	0.0047
12:05:47	9.41	0.0048	12:21:17	9.64	0.0047
12:05:52	9.41	0.0057	12:21:22	9.68	0.0047
12:05:57	9.43	0.0048	12:21:27	9.68	0.0038
12:06:02	9.43	0.0057	12:21:32	9.64	0.0047
12:06:07	9.41	0.0057	12:21:37	9.66	0.0047
12:06:12	9.45	0.0057	12:21:42	9.64	0.0047
12:06:17	9.43	0.0057	12:21:47	9.68	0.0047
12:06:22	9.43	0.0057	12:21:52	9.70	0.0047
12:06:27	9.45	0.0048			
12:06:32	9.45	0.0057			
12:06:37	9.41	0.0067			
12:06:42	9.45	0.0067			
12:06:47	9.45	0.0067			
12:06:52	9.41	0.0057			
12:06:57	9.45	0.0067			
12:07:02	9.47	0.0067			
12:07:07	9.45	0.0067			
12:07:12	9.49	0.0076			

A- 2 Measurements and estimates of dispersion and discharge at 40m for third and forth injections

	3rd injection (13:00hrs)			4th injection (13:10hrs)		
Discharge(m^3/s)		**1.642**			**1.490**	
Velocity(m/s)		**0.400**			**0.363**	
	Time	**Temp (^oC)**	**g/l**	**Time**	**Temp (^oC)**	**g/l**
	13:00:37	9.43	0.0000	13:11:27	9.37	0.0000
	13:00:42	9.45	0.0000	13:11:32	9.41	0.0260
	13:00:47	9.43	0.0000	13:11:37	9.39	0.0382
	13:00:52	9.47	0.0000	13:11:42	9.39	0.0812
	13:00:57	9.47	0.0000	13:11:47	9.43	0.1129
	13:01:02	9.43	0.0000	13:11:52	9.36	0.1064
	13:01:07	9.45	0.0000	13:11:57	9.39	0.0788
	13:01:12	9.47	0.0000	13:12:02	9.37	0.0755
	13:01:17	9.45	0.0067	13:12:07	9.37	0.0552
	13:01:22	9.45	0.1212	13:12:12	9.41	0.0512
	13:01:27	9.43	0.0992	13:12:17	9.43	0.0406
	13:01:32	9.45	0.1469	13:12:22	9.39	0.0276
	13:01:37	9.47	0.1517	13:12:27	9.41	0.0154
	13:01:42	9.45	0.1488	13:12:32	9.37	0.0195
	13:01:47	9.45	0.1374	13:12:37	9.37	0.0179
	13:01:52	9.43	0.1298	13:12:42	9.41	0.0187
	13:01:57	9.45	0.0782	13:12:47	9.37	0.0097
	13:02:02	9.45	0.0649	13:12:52	9.37	0.0089
	13:02:07	9.41	0.0582	13:12:57	9.39	0.0089
	13:02:12	9.43	0.0401	13:13:02	9.39	0.0073
	13:02:17	9.47	0.0248	13:13:07	9.39	0.0089
	13:02:22	9.45	0.0124	13:13:12	9.39	0.0057
	13:02:27	9.39	0.0067	13:13:17	9.41	0.0057
	13:02:32	9.45	0.0067	13:13:22	9.39	0.0065
	13:02:37	9.45	0.0086	13:13:27	9.41	0.0065
	13:02:42	9.45	0.0029	13:13:32	9.39	0.0057
	13:02:47	9.43	0.0029	13:13:37	9.41	0.0057
	13:02:52	9.47	0.0019	13:13:42	9.37	0.0049
	13:02:57	9.43	0.0038	13:13:47	9.39	0.0041
	13:03:02	9.45	0.0029	13:13:52	9.39	0.0049
	13:03:07	9.43	0.0038	13:13:57	9.36	0.0041
	13:03:12	9.45	0.0057	13:14:02	9.45	0.0032

	13:03:17	9.41	0.0029	13:14:07	9.41	0.0032
	13:03:22	9.43	0.0029	13:14:12	9.37	0.0032
	13:03:27	9.41	0.0019	13:14:17	9.43	0.0032
	13:03:32	9.43	0.0019	13:14:22	9.37	0.0041
				13:14:27	9.41	0.0041

A- 3 Measurements and estimates of dispersion and discharge at 80m for first and second injections

	1st injection (11:59hrs)			2nd Injection (12:15hrs)		
Discharge (m^3/s)	**0.982**			**0.691**		
Velocity (m/s)	**0.516**			**0.363**		
	Time	**Temp (°C)**	**g/l**	**Time**	**Temp (°C)**	**g/l**
	11:59:33	9.16	0.0029	12:17:58	9.44	0.0000
	11:59:38	9.13	0.0019	12:18:03	9.46	0.0010
	11:59:43	9.16	0.0019	12:18:08	9.46	0.0076
	11:59:48	9.16	0.0019	12:18:13	9.44	0.0133
	11:59:53	9.13	0.0019	12:18:18	9.46	0.0305
	11:59:58	9.16	0.0019	12:18:23	9.44	0.0505
	12:00:03	9.15	0.0019	12:18:28	9.43	0.0772
	12:00:08	9.15	0.0019	12:18:33	9.46	0.0953
	12:00:13	9.15	0.0000	12:18:38	9.46	0.1210
	12:00:18	9.15	0.0029	12:18:43	9.47	0.1182
	12:00:23	9.13	0.0019	12:18:48	9.43	0.1029
	12:00:28	9.13	0.0019	12:18:53	9.46	0.1096
	12:00:33	9.13	0.0019	12:18:58	9.43	0.0839
	12:00:38	9.16	0.0019	12:19:03	9.47	0.0820
	12:00:43	9.13	0.0019	12:19:08	9.45	0.0515
	12:00:48	9.16	0.0019	12:19:13	9.44	0.0419
	12:00:53	9.15	0.0029	12:19:18	9.45	0.0305
	12:00:58	9.13	0.0019	12:19:23	9.45	0.0219
	12:01:03	9.19	0.0019	12:19:28	9.45	0.0152
	12:01:08	9.16	0.0019	12:19:33	9.45	0.0143
	12:01:13	9.17	0.0029	12:19:38	9.47	0.0105
	12:01:18	9.17	0.0029	12:19:43	9.46	0.0057
	12:01:23	9.15	0.0038	12:19:48	9.47	0.0038
	12:01:28	9.15	0.0038	12:19:53	9.46	0.0038
	12:01:33	9.17	0.0038	12:19:58	9.47	0.0038
	12:01:38	9.16	0.0038	12:20:03	9.46	0.0038
	12:01:43	9.17	0.0038	12:20:08	9.45	0.0038
	12:01:48	9.16	0.0038	12:20:13	9.46	0.0038
	12:01:53	9.19	0.0058	12:20:18	9.47	0.0038
	12:01:58	9.17	0.0058	12:20:23	9.45	0.0038
	12:02:03	9.17	0.0192	12:20:28	9.47	0.0029
	12:02:08	9.15	0.0634	12:20:33	9.44	0.0038

12:02:13	9.16	0.0538	12:20:38	9.46	0.0038
12:02:18	9.15	0.0845	12:20:43	9.45	0.0019
12:02:23	9.17	0.1095	12:20:48	9.48	0.0038
12:02:28	9.13	0.1297	12:20:53	9.45	0.0038
12:02:33	9.17	0.1364	12:20:58	9.46	0.0038
12:02:38	9.15	0.1335			
12:02:43	9.20	0.1268			
12:02:48	9.19	0.1143			
12:02:53	9.17	0.0893			
12:02:58	9.16	0.0701			
12:03:03	9.15	0.0519			
12:03:08	9.19	0.0432			
12:03:13	9.19	0.0423			
12:03:18	9.18	0.0211			
12:03:23	9.15	0.0211			
12:03:28	9.21	0.0211			
12:03:33	9.21	0.0173			
12:03:38	9.17	0.0106			
12:03:43	9.20	0.0125			
12:03:48	9.18	0.0106			
12:03:53	9.19	0.0106			
12:03:58	9.19	0.0106			
12:04:03	9.21	0.0106			
12:04:08	9.19	0.0106			
12:04:13	9.20	0.0106			
12:04:18	9.21	0.0125			
12:04:23	9.19	0.0106			
12:04:28	9.21	0.0106			
12:04:33	9.22	0.0106			

A- 4 Measurements and estimates of dispersion and discharge at 80m for third and fourth injections

	3rd injection			4th injection		
Discharge (m^3/s)		**0.725**			**1.494**	
Velocity (m/s)		**0.381**			**0.364**	
	Time	**Temp (°C)**	**g/l**	**Time**	**Temp (°C)**	**g/l**
	13:02:43	9.27	0.0010	13:12:58	9.23	0.0000
	13:02:48	9.25	0.0010	13:13:03	9.19	0.0000
	13:02:53	9.25	0.0124	13:13:08	9.22	0.0029
	13:02:58	9.26	0.0124	13:13:13	9.21	0.0154
	13:03:03	9.25	0.0239	13:13:18	9.19	0.0336
	13:03:08	9.25	0.0440	13:13:23	9.17	0.0576
	13:03:13	9.25	0.0736	13:13:28	9.22	0.0576
	13:03:18	9.25	0.0861	13:13:33	9.21	0.0854
	13:03:23	9.25	0.0927	13:13:38	9.20	0.0998
	13:03:28	9.24	0.0966	13:13:43	9.20	0.0883
	13:03:33	9.26	0.0927	13:13:48	9.19	0.0796
	13:03:38	9.25	0.0927	13:13:53	9.19	0.0691
	13:03:43	9.25	0.0774	13:13:58	9.19	0.0672
	13:03:48	9.25	0.0631	13:14:03	9.22	0.0422
	13:03:53	9.24	0.0440	13:14:08	9.21	0.0365
	13:03:58	9.25	0.0335	13:14:13	9.21	0.0297
	13:04:03	9.25	0.0210	13:14:18	9.19	0.0201
	13:04:08	9.25	0.0153	13:14:23	9.17	0.0154
	13:04:13	9.26	0.0134	13:14:28	9.22	0.0154
	13:04:18	9.24	0.0105	13:14:33	9.20	0.0106
	13:04:23	9.25	0.0038	13:14:38	9.18	0.0115
	13:04:28	9.25	0.0019	13:14:43	9.20	0.0067
	13:04:33	9.24	0.0019	13:14:48	9.22	0.0048
	13:04:38	9.26	0.0019	13:14:53	9.19	0.0048
	13:04:43	9.25	0.0010	13:14:58	9.18	0.0048
	13:04:48	9.24	0.0019	13:15:03	9.22	0.0029
	13:04:53	9.24	0.0010	13:15:08	9.22	0.0029
	13:04:58	9.25	0.0000	13:15:13	9.22	0.0048
	13:05:03	9.24	0.0019	13:15:18	9.21	0.0048
	13:05:08	9.24	0.0010	13:15:23	9.19	0.0038
	13:05:13	9.21	0.0000	13:15:28	9.20	0.0029
	13:05:18	9.25	0.0019	13:15:33	9.20	0.0038
	13:05:23	9.24	0.0010	13:15:38	9.21	0.0029

	13:05:28	9.23	0.0010	13:15:43	9.23	0.0029
	13:05:33	9.25	0.0019	13:15:48	9.19	0.0029
	13:05:38	9.24	0.0019	13:15:53	9.19	0.0029
	13:05:43	9.25	0.0019	13:15:58	9.19	0.0029
	13:05:48	9.25	0.0019	13:16:03	9.22	0.0048
				13:16:08	9.18	0.0010
				13:16:13	9.20	0.0029
				13:16:18	9.17	0.0019
				13:16:23	9.21	0.0010
				13:16:28	9.20	0.0029
				13:16:33	9.21	0.0010
				13:16:38	9.21	0.0029
				13:16:43	9.20	0.0010
				13:16:48	9.21	0.0010
				13:16:53	9.23	0.0000
				13:16:58	9.17	0.0000
				13:17:03	9.20	0.0019
				13:17:08	9.21	0.0010
				13:17:13	9.20	0.0019
				13:17:18	9.23	0.0010
				13:17:23	9.20	0.0019
				13:17:28	9.20	0.0019

A- 5 Measurements and estimates of dispersion and discharge at 120m for first and second injections

	1st injection			2nd Injection		
Discharge		**0.980**			**0.675**	
Velocity		**0.774**			**0.533**	
	Time	**Temp (°C)**	**g/l**	**Time**	**Temp (°C)**	**g/l**
	12:00:36	9.30	0.0000	12:16:46	9.60	0.0000
	12:00:41	9.30	0.0000	12:16:51	9.60	0.0000
	12:00:46	9.30	0.0000	12:16:56	9.59	0.0095
	12:00:51	9.30	0.0000	12:17:01	9.60	0.0095
	12:00:56	9.30	0.0000	12:17:06	9.60	0.0104
	12:01:01	9.30	0.0000	12:17:11	9.60	0.0104
	12:01:06	9.30	0.0000	12:17:16	9.60	0.0104
	12:01:11	9.30	0.0000	12:17:21	9.61	0.0104
	12:01:16	9.31	0.0000	12:17:26	9.60	0.0104
	12:01:21	9.31	0.0000	12:17:31	9.61	0.0104
	12:01:26	9.31	0.0000	12:17:36	9.61	0.0104
	12:01:31	9.31	0.0000	12:17:41	9.61	0.0104
	12:01:36	9.31	0.0010	12:17:46	9.61	0.0104
	12:01:41	9.31	0.0010	12:17:51	9.61	0.0104
	12:01:46	9.31	0.0010	12:17:56	9.61	0.0104
	12:01:51	9.31	0.0010	12:18:01	9.61	0.0114
	12:01:56	9.31	0.0038	12:18:06	9.61	0.0171
	12:02:01	9.31	0.0076	12:18:11	9.61	0.0218
	12:02:06	9.31	0.0124	12:18:16	9.61	0.0446
	12:02:11	9.32	0.0430	12:18:21	9.61	0.0522
	12:02:16	9.32	0.0478	12:18:26	9.61	0.0626
	12:02:21	9.32	0.0650	12:18:31	9.61	0.0645
	12:02:26	9.32	0.0631	12:18:36	9.61	0.0750
	12:02:31	9.32	0.0803	12:18:41	9.61	0.0797
	12:02:36	9.32	0.0688	12:18:46	9.61	0.0702
	12:02:41	9.32	0.0707	12:18:51	9.61	0.0702
	12:02:46	9.32	0.0660	12:18:56	9.62	0.0712
	12:02:51	9.32	0.0736	12:19:01	9.62	0.0693
	12:02:56	9.32	0.0727	12:19:06	9.62	0.0683
	12:03:01	9.33	0.0688	12:19:11	9.62	0.0645
	12:03:06	9.33	0.0698	12:19:16	9.62	0.0645
	12:03:11	9.32	0.0650	12:19:21	9.62	0.0550

12:03:16	9.33	0.0602	12:19:26	9.62	0.0493
12:03:21	9.33	0.0535	12:19:31	9.62	0.0436
12:03:26	9.33	0.0440	12:19:36	9.62	0.0408
12:03:31	9.33	0.0440	12:19:41	9.62	0.0380
12:03:36	9.33	0.0373	12:19:46	9.62	0.0361
12:03:41	9.34	0.0325	12:19:51	9.62	0.0380
12:03:46	9.34	0.0296	12:19:56	9.62	0.0389
12:03:51	9.34	0.0277	12:20:01	9.62	0.0417
12:03:56	9.34	0.0258	12:20:06	9.62	0.0389
12:04:01	9.34	0.0239	12:20:11	9.62	0.0351
12:04:06	9.34	0.0229	12:20:16	9.62	0.0342
12:04:11	9.34	0.0220	12:20:21	9.62	0.0313
12:04:16	9.35	0.0201	12:20:26	9.62	0.0266
12:04:21	9.34	0.0210	12:20:31	9.62	0.0256
12:04:26	9.34	0.0220	12:20:36	9.62	0.0256
12:04:31	9.34	0.0201	12:20:41	9.62	0.0256
12:04:36	9.35	0.0201	12:20:46	9.62	0.0256
12:04:41	9.35	0.0191	12:20:51	9.62	0.0247
12:04:46	9.35	0.0182	12:20:56	9.62	0.0218
12:04:51	9.35	0.0182	12:21:01	9.62	0.0228
12:04:56	9.36	0.0153	12:21:06	9.62	0.0237
12:05:01	9.36	0.0153	12:21:11	9.62	0.0247
12:05:06	9.36	0.0143	12:21:16	9.62	0.0237
12:05:11	9.36	0.0134	12:21:21	9.62	0.0228
12:05:16	9.37	0.0143	12:21:26	9.62	0.0218
12:05:21	9.37	0.0134	12:21:31	9.62	0.0228
12:05:26	9.37	0.0124	12:21:36	9.62	0.0218
12:05:31	9.37	0.0115	12:21:41	9.62	0.0228
12:05:36	9.37	0.0124	12:21:46	9.62	0.0190
12:05:41	9.37	0.0134	12:21:51	9.62	0.0209
12:05:46	9.37	0.0124	12:21:56	9.62	0.0180
12:05:51	9.38	0.0124	12:22:01	9.62	0.0180
12:05:56	9.38	0.0134	12:22:06	9.62	0.0180
12:06:01	9.38	0.0115	12:22:11	9.62	0.0161
12:06:06	9.38	0.0124	12:22:16	9.62	0.0161
12:06:11	9.39	0.0124	12:22:21	9.62	0.0171
12:06:16	9.39	0.0124	12:22:26	9.62	0.0180
12:06:21	9.39	0.0124	12:22:31	9.62	0.0190
12:06:26	9.39	0.0124	12:22:36	9.62	0.0161

	12:06:31	9.39	0.0124	12:22:41	9.62	0.0152
	12:06:36	9.39	0.0124	12:22:46	9.62	0.0152
				12:22:51	9.62	0.0152
				12:22:56	9.62	0.0142
				12:23:01	9.62	0.0152
				12:23:06	9.62	0.0142
				12:23:11	9.62	0.0142
				12:23:16	9.62	0.0142
				12:23:21	9.62	0.0142
				12:23:26	9.62	0.0142
				12:23:31	9.62	0.0133
				12:23:36	9.62	0.0133
				12:23:41	9.62	0.0133
				12:23:46	9.62	0.0133
				12:23:51	9.62	0.0133
				12:23:56	9.62	0.0123

A- 6 Measurements and estimates of dispersion and discharge at 120m for third and fourth injections

	3rd injection (13:00hrs)			4th injection (13:10hrs)		
Discharge		**1.613**			**1.560**	
Velocity		**0.393**			**0.380**	
	Time	**Temp (°C)**	**g/l**	**Time**	**Temp (°C)**	**g/l**
	13:03:36	9.42	0.0000	13:13:26	9.37	0.00000
	13:03:41	9.41	0.0000	13:13:31	9.37	0.00000
	13:03:46	9.42	0.0000	13:13:36	9.37	0.00000
	13:03:51	9.41	0.0000	13:13:41	9.37	0.00000
	13:03:56	9.41	0.0000	13:13:46	9.37	0.00000
	13:04:01	9.41	0.0000	13:13:51	9.37	0.00000
	13:04:06	9.41	0.0010	13:13:56	9.37	0.00000
	13:04:11	9.41	0.0019	13:14:01	9.37	0.00000
	13:04:16	9.41	0.0076	13:14:06	9.37	0.00000
	13:04:21	9.41	0.0191	13:14:11	9.37	0.00000
	13:04:26	9.41	0.0220	13:14:16	9.37	0.00000
	13:04:31	9.41	0.0296	13:14:21	9.36	0.00000
	13:04:36	9.41	0.0410	13:14:26	9.37	0.00191
	13:04:41	9.41	0.0563	13:14:31	9.36	0.00669
	13:04:46	9.41	0.0601	13:14:36	9.36	0.01911
	13:04:51	9.41	0.0840	13:14:41	9.37	0.02675
	13:04:56	9.41	0.0821	13:14:46	9.36	0.03153
	13:05:01	9.40	0.0868	13:14:51	9.36	0.04586
	13:05:06	9.40	0.0849	13:14:56	9.36	0.05923
	13:05:11	9.40	0.0783	13:15:01	9.36	0.06496
	13:05:16	9.40	0.0725	13:15:06	9.36	0.07261
	13:05:21	9.40	0.0544	13:15:11	9.36	0.07547
	13:05:26	9.40	0.0468	13:15:16	9.36	0.07452
	13:05:31	9.40	0.0372	13:15:21	9.36	0.06974
	13:05:36	9.40	0.0401	13:15:26	9.36	0.06687
	13:05:41	9.40	0.0286	13:15:31	9.36	0.06401
	13:05:46	9.40	0.0286	13:15:36	9.36	0.05923
	13:05:51	9.40	0.0239	13:15:41	9.36	0.04968
	13:05:56	9.40	0.0191	13:15:46	9.36	0.04395
	13:06:01	9.40	0.0172	13:15:51	9.36	0.03917
	13:06:06	9.40	0.0153	13:15:56	9.36	0.03535
	13:06:11	9.40	0.0143	13:16:01	9.36	0.02962

13:06:16	9.39	0.0105	13:16:06	9.36	0.02770
13:06:21	9.39	0.0115	13:16:11	9.36	0.02197
13:06:26	9.39	0.0086	13:16:16	9.36	0.01815
13:06:31	9.39	0.0105	13:16:21	9.36	0.01720
13:06:36	9.39	0.0095	13:16:26	9.36	0.01815
13:06:41	9.39	0.0124	13:16:31	9.36	0.01337
13:06:46	9.39	0.0086	13:16:36	9.36	0.01337
13:06:51	9.39	0.0115	13:16:41	9.36	0.01146
13:06:56	9.39	0.0086	13:16:46	9.36	0.01242
13:07:01	9.39	0.0067	13:16:51	9.36	0.01337
13:07:06	9.39	0.0076	13:16:56	9.36	0.01242
13:07:11	9.39	0.0057	13:17:01	9.36	0.01146
13:07:16	9.39	0.0076	13:17:06	9.36	0.00955
13:07:21	9.39	0.0067	13:17:11	9.36	0.00764
13:07:26	9.39	0.0048	13:17:16	9.37	0.00860
13:07:31	9.39	0.0048	13:17:21	9.36	0.00860
13:07:36	9.39	0.0029	13:17:26	9.36	0.00669
13:07:41	9.39	0.0038	13:17:31	9.36	0.00669
13:07:46	9.39	0.0038	13:17:36	9.36	0.00669
13:07:51	9.39	0.0029	13:17:41	9.36	0.00669
13:07:56	9.38	0.0029	13:17:46	9.36	0.00764
13:08:01	9.38	0.0019	13:17:51	9.36	0.00669
13:08:06	9.39	0.0029	13:17:56	9.36	0.00669
13:08:11	9.38	0.0010	13:18:01	9.36	0.00764
			13:18:06	9.36	0.00573
			13:18:11	9.36	0.00478
			13:18:16	9.36	0.00573
			13:18:21	9.36	0.00478
			13:18:26	9.36	0.00382
			13:18:31	9.36	0.00478
			13:18:36	9.36	0.00573