1. WRA

China – UK, WRDMAP
Integrated Water Resources Management Document Series

Example 1.5: Water Quality Modelling in Chaoyang, Liaoning Province

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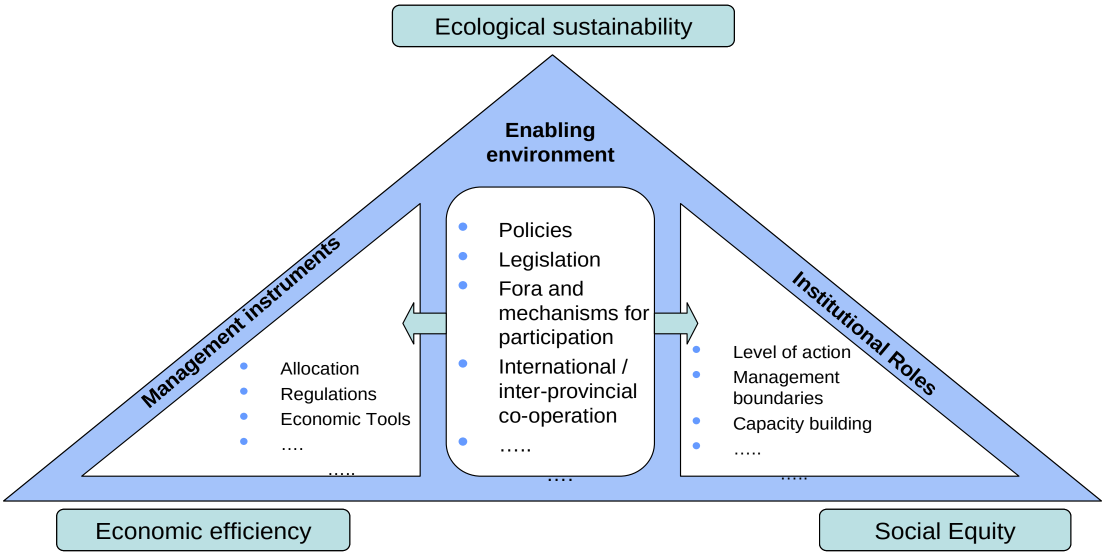
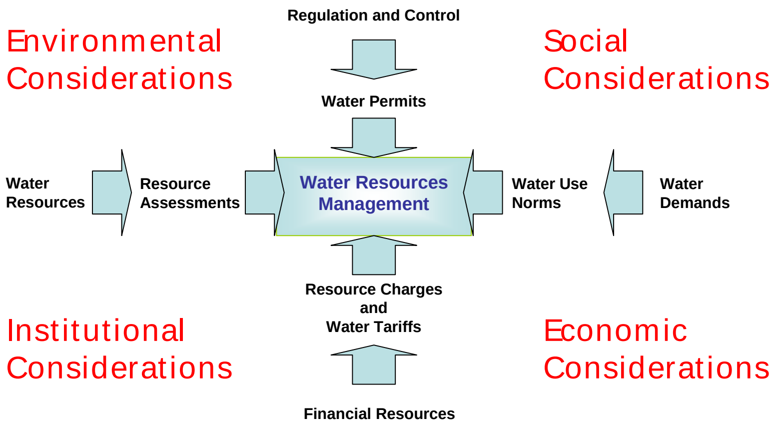
Integrated Water Resources Management (IWRM)

(Basics after Global Water Partnership)



Driving Elements of Integrated Water Resources Management



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Summary: This document describes the water quality modelling undertaken in Chaoyang, Liaoning Province. The modelling was used to investigate the water quality in the Daling River and some of its tributaries. The purpose was to better understand the sources of pollution, with the longer term aim of improving the river water quality.

This document covers the following topics:

- Purpose of modelling
- Choice of modelling software
- Data requirements and availability
- Data processing and estimation
- Model development
- Training and support required for local staff
- Summary of findings

This document is part of a series addressing aspects of integrated water resources management (IWRM) under which water quality is increasingly viewed as a critical component. It should be read in conjunction with Thematic Paper 1.5 'Use of Water Quality Modelling for Water Protection' and Advisory Note 1.5 'Use of QUAL2K Water Quality Model in IWRM Planning'.

The Ministry of Water Resources have supported the Water Resources Demand Management Assistance Project (WRDMAP) to develop this series to support WRD/WAB at provincial, municipal and county levels in their efforts to achieve sustainable water use.

1 Introduction

Water pollution is a health hazard to people, and can be damaging to the environment. In the Daling River Basin, Liaoning Province, water quality modelling has been used to better understand the local sources of pollution with the longer term aim of improving the local water quality.

1.1 Chaoyang City and the Daling River

Chaoyang City is located in the province of Liaoning in north east China, approximately 390 km from Beijing. The city has a growing population which presently totals approximately 300 000 people.

The Daling River is 434 km long and its basin covers an area of 23 837 km^2.

1.2 Overview of modelling

The purpose of this water quality modelling is to inform improvements to the abstraction and discharge permitting systems in the Chaoyang area, operated by the Water Affairs Bureau (WAB) and the Environmental Protection Bureau (EPB) respectively.

A water quality model was initially developed for a pilot reach: a stretch of approximately 60 km of the Daling River in the vicinity of Chaoyang from the Yanwangbizi (YWBZ) Reservoir to the Baishi Reservoir.

This model was later extended, following an extensive data collection and monitoring programme, to cover a greater part of the Daling River and some of its tributaries.

The modelling work was undertaken by a team of local staff from the Chaoyang WAB, the Chaoyang EPB, consultants from the Shenyang Hydrology Bureau and with assistance from an international consultant.

2 Purpose of Modelling

The purpose of this modelling was to inform improvements to the abstraction and discharge permitting systems in the Chaoyang area, operated by the Chaoyang Municipal WAB and EPB respectively.

Water quality modelling can be used to assist in the setting of abstraction and discharge permitting. A model can be used to test “what if?” scenarios which can demonstrate the effect on the water quality in the river due to changes in abstractions and discharges, or changes in flow volumes (e.g. drought conditions). Conversely, appropriate discharge and abstraction limits to achieve specific river water quality targets can be investigated using a water quality model.

Daling River Basin

Baishi Reservoir in the Daling River Basin

3 Choice of Modelling Software

Several different modelling options were considered for this case study including a bespoke spreadsheet model (based in Excel), the Mike Basin model from DHI, and the Qual2K model from the US Environmental Protection Agency (USEPA).

The cost and ease of use of each model were considered, bearing in mind that this modelling process should be suitable for use throughout China.

Qual2K is a hydraulic and water quality model available as a free download from the United States Environmental Protection Agency (USEPA). The model is supported by a user manual (Chapra *et al*, 2006). Development is ongoing and regular updates are issued on the website， making this model particularly appropriate in the context of using the case study model throughout China.

Due to the considerations of both cost and ease of use, it was decided to proceed with the Qual2K model.

4 Data Requirements and Availability

4.1 Data requirements

Qual2K requires water quality, hydraulic and climatic data and parameters for its calculations.

Additional information can be found in the Qual2k user manual (Chapra *et al*, 2006) and the accompanying Advisory Note on Water Quality Modelling.

> It is possible to use estimates of many data values if measured values are not available - the effect of this is to reduce the accuracy of the model output.

Hydraulic and hydrological data required:

- Flow rates (m^3/s) at headwaters, point discharges / abstractions, and diffuse discharges / abstractions;
- Dimensions for each river reach (reach length, bed width, bank slopes and bed slope);
- Locations for upstream and downstream ends of each reach;
- Height, width and shape of any weirs, dams and waterfalls;
- Rating curve parameters where available (e.g. at gauging stations);
- Manning's *n* for river reaches.
- Rainfall runoff data

Water quality data required (at headwaters, point sources, and diffuse sources):

- Temperature (^{O}C)
- Nitrate, NO_3 (µg/l of N)
- Conductivity (µsiemens)
- Organic Phosphorus (µg/l of P)
- Inorganic Solids (mg/l, dry weight)
- Inorganic Phosphorus (µg/l of P)
- Dissolved Oxygen (mg/l of O_2)
- Phytoplankton (µg/l)
- CBODslow (mg/l of O_2)
- Detritus (POM) (mg/l, dry weight)
- CBODfast (mg/l of O_2)
- Pathogens (cfu/100 ml)
- Organic Nitrogen (µg/l of N)
- Alkalinity (mg/l of $CaCO_3$)
- Ammonia, NH_4 (µg/l of N)
- pH

Water quality and flow measurements are also required at locations throughout the model for calibration.

The reaction rates and settling velocities for the water quality parameters are typically user defined parameters. Default values for the reaction rates and settling velocities are provided in Qual2K but may be adjusted during calibration.

Climatic data required:

- Air temperature
- Wind speed
- Dew point temperature
- Percentage cloud cover
- Percentage shade

4.2 Data availability in Chaoyang

Data from Chaoyang EPB and WAB was used in the model and was shared freely between the two agencies (see Advisory Note 8.4 'Inter-agency Agreements for Collaborative Water Quality Management').

Routing data collection and monitoring is undertaken by both EPB and WAB. During the extension of the model to a larger part of the Daling River, additional monitoring was undertaken as part of an extensive data collection programme.

Hydraulic and hydrological data available:

- Daily flow rates at gauging stations (only one gauging station in the pilot reach).
- Specially collected flow data (for use in extending the model).
- Cross-sections at gauging stations.
- Specially collected cross-section data.
- Dimensions of dams.
- Flow and level data (used to create a rating curve) for gauging stations.
- Locations of monitoring locations and gauging stations.
- Specially collected location data using GPS.
- Monthly average rainfall-runoff volumes.
- Abstraction and discharge volumes for enterprises (collected by WAB and EPB respectively).

Water quality data available:

Monthly water quality monitoring is undertaken by Chaoyang Municipal EPB and WAB at a number of locations along the pilot study reach.

When the model was extended to cover more of the Daling River Basin, water quality data was obtained from County level EPB and WAB agencies and by specially commissioned monitoring.

Data for point discharges (such as individual enterprises) is collected by EPB.

No data was available for diffuse pollution sources.

The available water quality parameters did not exactly match the suite of water quality determinands used by Qual2K. Estimation procedures used to cope with this are described in the next section.

Climatic data available (collected by EPB):

- Annual average wind speed
- Annual average air temperature
- Average hours of sunshine per annum.

Polluted reach of Daling River

5 Data Processing and Estimation

Qual2K has specific data requirements for water quality and hydraulic parameters. There is not a perfect match between the available data and the data required by Qual2K. The available data was used directly in the model where possible. Other model parameters were estimated as described below.

5.1 Water quality data

For the pilot study, the water quality data used in the model was a three-year median of the data from the beginning of 2004 to the end of 2006. (A first attempt used the three-year mean of the data, however, the skewness of this data due to some extreme values meant that satisfactory calibration was not possible.)

Qual2K allows data input for each hour over a 24 hour period as part of the diurnal simulation. However, as no such data was available for this study, the same average value was entered for each hour.

The data available for the study area did not precisely match the data requirements for Qual2K. The measured data was used directly where possible. For other parameters, where there was no data available, a value was estimated, or the value was excluded if appropriate; see explanations in Table 1.

Table 1 Comparison of Available Data and Requirements for Qual2K

Qual2K water quality parameters	**Nearest available measured parameter**	**Comments on estimation / conversion**
Water temperature	Water temperature	✓
Conductivity	×	Not included (limited impact on other parameters)
Dissolved Oxygen	Dissolved Oxygen	✓
$CBOD_{slow}$ and $CBOD_{fast}$	BOD and COD	See explanation in the text below.
Ammonia	Ammonia	✓
Organic Nitrogen	Total Nitrogen (TN)	Only one TN measurement available, so too early for inclusion into the model
Nitrate		
Organic Phosphorus (OP)	Total Phosphorus (TP)	TP value used for OP as OP is likely to account for the majority of the TP measurement
Inorganic Phosphorus (IP)		IP value set to zero
Inorganic Solids	×	Not included (limited impact on other parameters)
Phytoplankton	×	
Detritus	×	
Pathogens	×	
Alkalinity	×	Default value of 200 mg/l of $CaCO_3$ used
pH	pH	✓
	Volatile Phenol	Model adapted to remove pathogens and replace with volatile phenol.

× = no data available; ✓ = data used directly in the model

The Qual2K model uses ultimate carbonaceous biochemical oxygen demand ($CBOD_{ultimate}$); the available water quality data for this study was five-day biochemical oxygen demand (BOD5) and chemical oxygen demand using potassium dichromate (CODcr).

An extensive literature review was conducted to attempt to reconcile the differences between BOD_5, COD_{cr} and $CBOD_{ultimate}$, and thereby estimate an appropriate value for $CBOD_{ultimate}$ to use in the model.

Section 7.5 of the World Health Organisation's water quality monitoring manual (Bartram & Balance, 1996) states that:

"Where wastes contain only readily available organic bacterial nutrients and no toxic matter, the results can be used to obtain an approximate estimate of the ultimate carbonaceous BOD values."

COD_{cr} values are readily available, so this compromise was adopted.

5.2 Hydraulic data

The reservoir dams and rubber dams in Chaoyang City were included in the model as weirs. The model requires the weir height, width, and coefficients to represent its shape (estimated from information in the user guide, Chapra *et al*, 2006).

Although the dimensions of the dams could be measured or obtained from designs, the actual part that the water flows over should be used as the weir in the model. This was different under different flows and operating conditions so required careful thought.

Sufficient data was available for Chaoyang gauging station to create rating curves for insertion into the Qual2K model. The rating curves were derived by creating "best fit" curves for the data which fit the models prescribed format for rating curves.

Qual2K requires a simplified cross-section that is defined by the bed width and the slope of each bank. This information was estimated from the surveyed cross sections. Different estimated cross-sections were required for different flow regimes – for example, at low flows, only a small amount of the cross-section was under water and so a different cross-section had to be used at low flows, compared with high flows.

The estimation of Manning's *n* was based on local knowledge, photographic evidence and site visits. Tabulated descriptions in the Qual2K user guide (Chapra et al, 2006) were used as guidance.

A rubber dam in Chaoyang City

5.3 Hydrological data

The catchment for the study area was divided into sub-catchments to enable the calculation of an estimated run-off flow into the Daling River based on rainfall runoff data. A sub-catchment was created for each river reach to represent the area from which rainfall runoff would enter that reach.

The sub-catchments were created using GIS and a digital elevation model (DEM). The edges of each sub-catchment were identified using the DEM to find the high points separating the sub-catchments. The area of each sub-catchment was calculated using the GIS software.

The average rainfall runoff values for the Daling Basin were multiplied by each sub-catchment area, and converted into m^3/s to calculate the diffuse runoff flow to each reach. Each catchment flow was input to the model as a diffuse source and was assumed to enter the river along the entire length of each reach.

Insufficient land use data was available to calculate the water quality of the runoff, so these values were estimated using local knowledge to guess a typical value for each parameter for the Daling Basin.

5.4 Climatic data

Table 2 shows the required climatic data for Qual2K, and whether it was directly available as data, or how it was estimated.

Although Qual2K allows different climatic data to be entered for each model reach, the catchment was considered to be sufficiently small for any local variation to be insignificant.

Qual2K allows different data to be input for each hour over a 24 hour period as part of a diurnal simulation. However, as no such water quality data was available for this study, the same value was entered for each hour for all parameters; this resulted in a typical daily condition.

Table 2 Sources of Climatic Data and Estimations

Climatic data required by Qual2K	**Obtained from…**
Air temperature (^{O}C)	Available data (EPB)
Wind speed (m/s)	Available data (EPB)
Dew point temperature (^{O}C)	Estimated using an online calculator: http://www.srh.noaa.gov/elp/wxcalc/rh.shtml The calculator requires input values for temperature, relative humidity and air pressure – relative humidity and air pressure values estimated based on local knowledge.
Cloud cover (%)	Estimated from the average hours of sunshine per annum data (from EPB), assuming that there are an average of 12 hours of daylight per day: % cloud cover = hours of sunshine per annum / (365 x 12)
Shade (%)	Estimated from local knowledge as 10%.

6 Model Development

6.1 Phase 1

The objective in Phase 1 (Sept 2007) was to create a simple water quality model of a pilot study area. This model used a very simple dataset reflecting the annual average conditions.

Data use

The water quality and flow data used in Phase 1 were average (mean) values based on three years' data from the beginning of 2004 to the end of 2006.

Data from both EPB and WAB was included in the model.

Suitable flow data was only available at Chaoyang Gauging Station.

The catchment average rainfall runoff value of 79 mm/year was used to estimate the diffuse inflows

Only one measured cross-section was available; other cross-sections were estimated during site visits.

Model calibration

The model agreed well with the observed data upstream of Chaoyang City; however just downstream of the Chaoyang central sewer and Shijia inflows, the model could not simulate the observed high pollution levels.

Learning points

Discrepancies between the model results and the observed values were thought to be due in part to the use of average data values. A median value can be more appropriate than a mean value because median values are less influenced by extreme data points.

Using annual average data may not be the appropriate in an area with such extremes of rainfall. The simplified cross-sections used in Qual2K should be dramatically different for small flows compared with large flows. It was therefore decided to split the data into different flow regimes in Phase 2.

Figure 1 The model pilot reach and monitoring locations

6.2 Phase 2

Model development

In Phase 2 (December 2007) the modelling team made the following improvements to the water quality model:

1. New cross section data for the Daling River was incorporated;

2. The data was divided into "small flows", "medium flows" and "large flows" and a separate model was created for each case;

3. Median values of the data were used as model inputs, instead of the mean values that had been used in Phase 1.

4. Seasonal data on the rainfall runoff was incorporated.

In addition, the model was extended to include the Shijia River, a heavily polluted stream that joins the Daling River just downstream of Chaoyang City. Individual enterprises that discharge into the Shijia were included as "point discharges" if data was available.

> Inclusion of individual enterprise discharges in the model allows use of the model for developing effective discharge permitting. The model can be used to predict future water quality based on changes to the individual discharges.

Calibration

The hydraulic model was calibrated to the flow at Chaoyang gauging station. (The limited flow data at the upstream YWBZ reservoir was found to be incompatible and was therefore abandoned.)

Calibration for the water quality parameters was achieved by adjusting the reaction rates in the model.

The results for each flow regime showed reasonable agreement with the median of the observed data for each water quality parameter. Some discrepancies were observed in the region of the heavily polluted outfalls just downstream of Chaoyang City.

It should be noted that the data for individual enterprises was taken from 2003, whereas the other water quality data used in the model is from 2004 to 2006. Some discrepancy between the data from the two different time periods is expected.

Scenarios

New scenarios may be modelled with the Qual2K water quality model. This involves using a model that is already calibrated to a particular situation (i.e. the annual average data), making a change to some input data (e.g. the water quality of a discharge) and comparing the new model result with the calibrated model result.

The hypothetical scenario of a reduction in pollutant load from individual enterprises discharging to the Shijia River was trialled with the model.

The model demonstrated that a reduction in pollution from one particular enterprise had a dramatic impact on the water quality in the Shijia, whereas the others did not have much effect. This was due to dilution effects and the size of the discharges.

6.3 Phase 3 – Model extension

Phase 3 of the modelling work was undertaken in May 2009 and followed an extensive data collection and monitoring programme.

The purpose of the additional work was to extend the water quality model to other areas in the Daling River Basin that suffer from large point or diffuse sources of pollution, such as industrial sites and agricultural areas.

Model calibration

Model calibration in phase 3 focussed on three main points:

- Rainfall runoff estimates
- Groundwater infiltration
- Unknown pollution sources

Rainfall runoff volumes were estimated using seasonal runoff averages scaled by sub-catchment areas. Model results showed that this was a clear over-estimate. The runoff estimates were then scaled down (using the same factor at all locations) until a reasonable match was achieved.

During calibration it also became clear that large amounts of water are lost along some reaches of the main river. These losses were determined to be due to groundwater infiltration, which is exacerbated by local groundwater abstraction for irrigation. An estimate of this infiltration was included in the Qual2K model as a diffuse abstraction to match the flows observed in the river. The results of this rough calibration are shown in Figure 2.

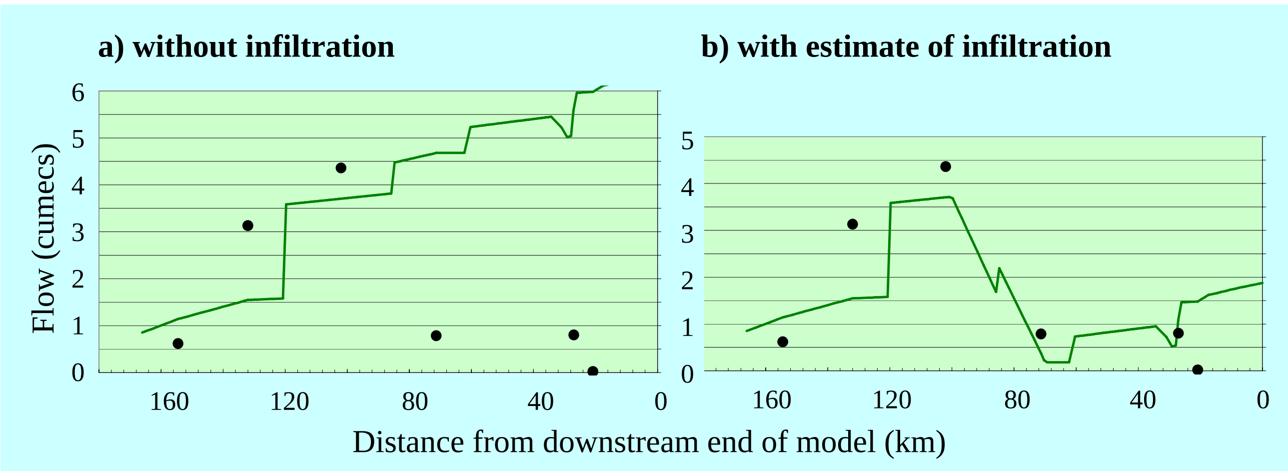
At some locations there was a clear discrepancy between the observed data and the model results; it was assumed that this was due to unknown abstractions and discharges. These were included as “dummy” point sources in the model.

Conclusions from modelling

Model results generally indicated the scale of the unavailable information such as ungauged pollution discharges or groundwater infiltration.

> The main success of this modelling was determining the approximate size and scale of the unknowns (e.g. ungauged pollution discharges); EPB and WAB can now see which areas they should target for better data.

Figure 2 Effect of infiltration estimate on model predicted flows



7 Training

Local staff in the Chaoyang Municipal WAB and EPB had no previous experience of water quality modelling prior to this project. They were knowledgeable in a variety of subjects in the area of water and environmental management. They were university educated in relevant subjects such as Environmental Science, and Water Resources, but detailed knowledge of water chemistry, hydrology and hydraulics could not be assumed.

Training of municipal level staff focussed on water quality modelling, with other subjects being explained as and when necessary. They were involved throughout the project so that they developed a thorough understanding of the processes involved.

Training of provincial level staff from the Shenyang Hydrological Bureau involved familiarisation with the Qual2K model and explanations of data treatment. They had previous experience of modelling and were more familiar with the technical background.

Everyone involved in the project required training in estimating and approximating values where no measured value was available.

While workshops were found to be valuable for initial explanations and discussion, the best way for people to learn how to use the model was found to be through practical experience; "playing" with the model is the most effective way to learn how it behaves.

Water quality modelling workshop in Chaoyang, Liaoning

8 Summary of Findings

8.1 Conclusions on introducing modelling at municipal level

A steady state water quality model, such as Qual2K, may be employed to predict the long term response of a river system's water quality to changes in conditions; for example, changes in the water quality of discharges to the river system.

In predicting changes to the water quality of a river system, a water quality model may assist with permitting for abstractions and discharges.

8.2 Data

There is data available from both WAB and EPB agencies. Combining these data sets is worthwhile for improving model accuracy.

In Chaoyang, data is now shared between the WAB and EPB (see Advisory Note 8.4 'Inter-agency Agreements for Collaborative Water Quality Management'). This cooperation has been invaluable in obtaining sufficient data to create the model.

The extension of the model to other reaches of the Daling Basin required additional monitoring work to cover areas where data was sparse. In the case of the YWBZ reservoir there was no information for cross sections within the reservoir which compromised the ability to achieve reliable calibration downstream. It is only possible to extend the model to areas where data is available.

The primary data limitation in this project was the availability of water quality and quantity monitoring for individual enterprise discharges. Without such data, the impact of permitting strategies cannot be predicted.

8.3 The use of water quality modelling

A water quality model can be used to inform permitting strategies to achieve a desired river water quality by limiting discharges and abstractions.

The most effective use of a model is likely to be a shared-use model which is informed by the discharge and abstraction data of both EPB and WAB. Joint targets in water quality for EPB and WAB, in association with the modelling, could indicate suitable permitting limits for both abstractions and discharges to river systems.

The type of water quality modelling undertaken in this study can predict the long-term impacts of a change in the water quality inputs to the study area.

It is important to note that there are some things that a model of this type cannot do:

- Predict the spread of a pollutant spill in a river;
- Give an indication of the timescales necessary to reach the predicted water quality;
- Back-calculate the necessary water quality permits from a desired river water quality.

Document Reference Sheet

Glossary:

Boundaries	The edges of a model – for a 1D model, upstream and downstream boundaries are required. Data is required to establish conditions at the boundaries.
Cross-section	Profile of the river bed and banks, perpendicular to flow direction.
Headwater	The upstream end of a watercourse. Model headwaters may be located in the middle of a river; in this case it is the upstream boundary of the model.
Node	Many models use "nodes" which are point locations at which the hydraulic and/or water quality calculations are made. Some models are cell based instead, and calculate values at cell centres.
Numerical	Numerical models use equations without an exact solution. Numerical (typically computational) methods are used to solve the equations.
Rating curve	A relationship between flow and water depth at a specific location.
Reach	A length of river, usually between two nodes.

Bibliography:

Bartram, J. and Ballance, R. (1996), *Water quality monitoring*, Spon, London, UK. http://www.who.int/water_sanitation_health/resourcesquality/wqmonitor/en/index.html

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Related materials from the MWR IWRM Document Series:

Thematic Paper 1.5	Use of Water Quality Modelling for Water Protection
Advisory Note 1.5	Use of QUAL2K Water Quality Model in IWRM Planning
Advisory Note 1.7	Designing a Monitoring Programme for Water Quality Modelling
Advisory Note 8.4	Inter-agency Agreements for Collaborative Water Quality Management

Where to find more information on IWRM – recommended websites:

Ministry of Water Resources: www.mwr.gov.cn

Global Water Partnership: www.gwpforum.org

WRDMAP Project Website: www.wrdmap.com

China – UK, WRDMAP

1. WRA

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Advisory Services by : Mott MacDonald (UK) leading a consultancy team comprising DHI (Water and Environment), HTSPE (UK), IWHR, IECCO (Comprehensive Bureau), CIAD (China Agricultural University), Tsinghua University, CAAS-IEDA, CAS-CWRR, Gansu WRHB and Liaoning WRHB.

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