Water Quality
Simulation Model
for the
King Abdullah Canal in Jordan

Prepared for
CESAR by
Dr. Michael T. Brett,
Dr. Richard N. Palmer and
Jae Hyun Ryu
University of Washington
Dept. of Civil and Environmental Engineering
Seattle, Washington, USA

February 2002

UNIVERSITY OF WASHINGTON

TABLE OF CONTENTS

INTRODUCTION ---------- 1
Background Information ---------- 1
Description of the King Abdullah Canal ---------- 1
Problems ---------- 1
Objective and Approach ---------- 2

WATER QUALITY MODELLING ---------- 2
Review of QUAL2E and MIKE 11 ---------- 2
History of Models ---------- 2
Model Formulation ---------- 4
Model Setup and Run ---------- 8
Comparison of runs ------------ ---------- 12
Uncertainty Analysis ---------- 15
Model Selection ---------- 8
Modeling Management Alternatives ---------- 17

ALTERNATIVES ---------- 19
Alternative 1: flow control ---------- 19
Alternative 2: nutrient control ---------- 20
Alternative 3: light control ---------- 22
Alternative 4: changing resistance to flow ---------- 23

SCENARIO ANALYSIS ---------- 24
Scenario 1 ---------- 24
Scenario 2 ---------- 25
Scenario 3 ---------- 25
Scenario 4 ---------- 25
Scenario 5 ---------- 25
Scenario 6 ---------- 25
Scenario 7 ---------- 25
Scenario 8 ---------- 26

COST EFFECTIVENESS ---------- 31
Estimated Cost ---------- 32
Unit Cost ---------- 32

NUTRIENT MASS BALANCE -- **34**
CONCLUSION AND RECOMMENDATION --- **38**
REPLY TO INTERCONSULT COMMENTS -- **40**
REFERENCES -- **44**
APPENDICES --- **A-1**
APPENDIX A: Model Parameters and Coefficient ------------------------------- A-1
APPENDIX B: Parameter Table for Sensitivity Analysis ------------------------ B-1
APPENDIX C: Statistic Analysis for Model Parameter Sensitivity ------------ C-1
APPENDIX D: QUAL2E Panel for the King Abdullah Canal ------------------ D-1
APPENDIX E: Scenario Table --- E-1

LIST OF TABLES

Table	Title	Page
Table 1.	Maximum and Minimum values of model basic parameters for QUAL2E based on literature review	16
Table 2.	Maximum and Minimum values of model basic parameters for MIKE11 based on literature review	16
Table 3.	Comparison of Basic-Variable Sensitivity Ranks for QUAL2E and MIKE 11	17
Table 4.	Basic Model Assumptions	18
Table 5.	Flow Control Alternative	20
Table 6.	Nutrient Control Alternative	21
Table 7.	Light Control Alternative	22
Table 8.	Change of Manning Roughness n	22
Table 9.	Direct comparison of components in each scenario	24
Table 10.	Scenario 1 for the King Abdullah Canal	27
Table 11.	Scenario 2 for the King Abdullah Canal	27
Table 12.	Scenario 3 for the King Abdullah Canal	27
Table 13.	Scenario 4 for the King Abdullah Canal	28
Table 14.	Scenario 5 for the King Abdullah Canal	28
Table 15.	Scenario 6 for the King Abdullah Canal	28
Table 16.	Scenario 7 for the King Abdullah Canal	29
Table 17.	Scenario 6 for the King Abdullah Canal	29
Table 18.	Water Management Scenarios for the King Abdullah Canal	30
Table 19.	Summary of Construction Costs for Scenarios	31
Table 20.	Estimated cost for covering the top of the canal	32
Table 21.	Estimated cost for removing vegetation option	33
Table 22.	A mass balance for the King Abdullah Canal	34
Table 23.	Predicted chlorophyll-a for the King Abdullah Canal	36

APPENDICES

Table A1.	The monthly average flow of water at the Yarmouk, Taberia and Mukhebeh	A-1
Table A2.	Model parameters and coefficients for QUAL2E	A-2
Table A3.	Eutrophication module parameters and coefficients for MIKE 11	A-3
Table A4.	Model parameters and coefficients of QUAL2E for Status Quo	A-6

Table B1. Parameter table of 2^k factorial Design for MIKE 11 B-1
Table B2. Parameter table of 2^k factorial Design for QUAL2E B-3
Table C1. Statistic Analysis for MIKE 11 Sensitivity C-1
Table C2. Statistic Analysis for QUAL2E Sensitivity C-2
Table E1. Water Management Scenarios for the King Abdullah Canal using QUAL2E Model E-1

LIST OF FIGURES

Figures	Title	Page
Figure 1.	Conceptualized Canal System	5
Figure 2.	The King Abdullah Canal Water Flow	6
Figure 3.	The King Abdullah Canal Water Quality Monitoring System location map	8
Figure 4.	Water depth along the King Abdullah Canal	10
Figure 5.	State variable and process in the Eutrophication module of MIKE 11	11
Figure 6.	Concentration of Chlorophyll-a from QUAL2E and MIKE 11	14
Figure 7.	Relationship between concentration of Chlorophyll-a and retention time	20
Figure 8.	Relationship between concentration of Chlorophyll-a and total phosphorous corresponding to different initial condition	21
Figure 9.	Relationship between concentration of Chlorophyll-a and light control	23

APPENDICES

Figure D1.	QUAL2E Simulation	D-1
Figure D2.	The King Abdullah Canal System	D-1
Figure D3.	Computational Element	D-2
Figure D4.	Water Quality Simulation	D-2
Figure D5.	Geographical and climatologic Data	D-3
Figure D6.	Global Kinetics	D-3
Figure D7.	Temperature Correction Factors	D-4
Figure D8.	Hydraulic Data	D-4
Figure D9.	BOD and DO Reaction Rate Constants	D-5
Figure D10.	N, P, and Algae Coefficients	D-5
Figure D11.	Initial Condition of the King Abdullah Canal	D-6
Figure D12.	Incremental Flow	D-6
Figure D13.	Headwater Source Data	D-7
Figure D14.	Global Value of the Climatologic Data	D-7

Water Quality Simulation Model for the King Abdullah Canal in Jordan

1. INTRODUCTION

Water is a severely limited resource in the Middle East. More than half of Israel, Jordan and Syria receive less than 250 millimeters (10 inches) of precipitation per year. The lack of sufficient rainfall presents great challenges to the management of water, which have been exacerbated by the rapid rate of population growth throughout the region in recent decades. Since the mid-1950s, there have been major plans to develop an extensive water infrastructure in Jordan. In 1958 the Government of Jordan decided to divert a portion of the Yarmouk River into a canal providing water for irrigation and municipal supply further south. The King Abdullah Canal (KAC), as this project came to be known (Elhance 1999), represents a significant source of water for the country's interior. Approximately 0.3 km^3 of water are diverted annually and that water irrigates 12,200 ha of agricultural land along the eastern slope of the Jordan Valley. The remainder of the water is used as a drinking water supply for the City of Amman, the capital of Jordan. The canal was about 66 km when it was first constructed in 1961 and stretched to Swallha. The KAC was extended three times between 1969 and 1987, and now has a total length of 110.5 kilometers.

During the past three years, water in the King Abdullah Canal has had severe taste and odor problems when it reached the Zai drinking water treatment facility near Amman. Eutrophication is the likely source of these problems. Eutrophication is caused by excessive nutrient loading to bodies of water and associated planktonic and/or periphytic algal blooms. Since the King Abdullah Canal is the main municipal, industrial, and agricultural water supply for the Kingdom of Jordan, it is imperative that the causes and potential solutions for the eutrophication problem in the King Abdullah Canal be identified.

This research describes the development of two water quality simulation models to evaluate the impacts of water management alternatives on water quality in the King Abdullah Canal. Such a model is necessary to improve water quality management in the King Abdullah Canal, as well as for providing useful insights to potential cooperation between management and the upstream riparian users of the King Abdullah Canal.

The basic approach to evaluate the water quality problems and their solution is as follows: two water quality software tools were selected to model the King Abdullah Canal. The two models are QUAL2E and MIKE 11. The models are first described briefly. Next, the basic assumption used by both models to describe the eutrophication process is presented along with a discussion of their implementation. Next, a sensitivity analysis is presented to identify the most important parameters in the models related to eutrophication. A description of potential management alternatives that reduce the algal levels in the canal is then presented. This is followed by an analysis of the cost-effectiveness of each alternative for lowering algal biomass (modeled as chlorophyll-a) in the canal. Next, combinations of these alternatives are tested, and the most promising management scenarios identified.

2. Water Quality Modeling

2.1. REVIEW of QUAL2E and MIKE 11

Two widely used and accepted water quality models, QUAL2E and MIKE 11, were reviewed for potential application to evaluating eutrophication in the King Abdullah Canal. Both models have been in general use for many years and have been successfully applied for evaluating water quality management alternatives. In 1972 the original QUAL-II model was introduced by the U.S. Environmental Protection Agency based on QUAL-I, a stream water quality model, developed by F. D. Masch and Associates and the Texas Water Development Board (1970). The enhanced QUAL-II model was renamed QUAL2E (Brown and Barnwell, 1985). The current release of QUAL2E (Version 3.0) is distributed by the US Environmental Protection Agency CEAMS (Center for Exposure Assessment Modeling, Athens GA and Exposure Assessment Branch, Washington, DC).

It has been applied to diverse water quality problems including waste load allocation (WLA) studies and total maximum daily load (TMDL) studies.

QUAL2E simulates as many as 15 water quality state variables, including temperature; dissolved oxygen (DO), biological oxygen demand (BOD), algae (as chlorophyll-a), the phosphorus cycle (organic and inorganic), the nitrogen cycle (organic-N, ammonia, nitrate, and nitrate); and conservative constituents. The model is appropriate for river systems and can be used to monitor multiple point sources and withdrawal, riparian river flows, and external non-point source loading. In addition, QUAL2E can accommodate time-varying local boundary conditions associated with climatologic data including wind, solar radiation, and air temperature to dynamically simulate the diurnal variation in algal growth due to the variation of nutrients, temperature and solar radiation. In addition the uncertainty analysis tools (sensitivity analysis, first order error analysis, and Monte Carlo simulation) built into QUAL2E provide estimates of model output error (US EPA website http://www.epa.gov/docs/QUAL2E_WINDOWS/metadata.txt.html).

MIKE 11 was developed by Danish Hydraulic Institute (DHI) in 1985. MIKE 11 is a software tool for the simulation of a wide range of engineering fields including hydrology, hydraulics, water quality and sediment transport in estuaries and river systems. MIKE 11 consists of several modules including the following modules: river network, cross section, hydrodynamic, advection-dispersion, sediment transport, water quality, rainfall-runoff, and flood forecast. The river network module provides a common link to MIKE 11’s other modules including cross section modules and the boundary conditions built into the advection-dispersion module. It also conceptualizes the system with river networks and branch connections, and defines the hydraulic structures (dam, weirs, culverts, etc.) located in the systems.

The cross section module, which is dynamically linked to the network module, is also a powerful component of MIKE 11. It displays all model cross section information including flow depth, width, area, and hydraulic radius. Each boundary condition is defined by the boundary module, which assigns a time series associated with hydrodynamic data and external nutrient loading. It is also dynamically linked to a hydrodynamic module, advection-dispersion module, and water quality module that contains the eutrophication component. Boundary conditions for the hydrodynamic module (HD) are defined by hydraulic characteristics of the system including initial conditions of flow rate, bed resistance (Manning coefficient), flow celerity and wind. To define a boundary condition for the advection-dispersion (AD) module, a set of parameters is applied that considers water quality and sediment interactions.

The water quality module is an important module for this project. It is composed of twelve state variables describing biotic and abiotic components. It includes variables that account for nutrient cycling (nitrogen and phosphorous), the growth of phytoplankton and zooplankton, and the elements of oxygen balance. In particular phytoplankton and zooplankton dynamics are well modeled. Since the advection-dispersion and water quality (Eutrophication) modules are dynamically linked, they are solved simultaneously using an integration routine after carrying out the first order differential equations which define the eutrophication process (MIKE 11 User's Manual, 1995).

2.2. MODEL FORMULATION

The primary objective of this study is to create a water quality management model for the King Abdullah Canal that simulates the behavior of the hydrologic and eutrophication components of the systems and to identify cost-effective approaches to canal eutrophication.

The KAC is a concrete trapezoidal canal with a base-width of 3 meters and an average surface-width that varies from 10 to 11 meters. The lower portions of the canal are narrower than at its beginning. The height of the canal ranges from 2.3 to 3.0 meters. The average slope of the canal is 0.00018 (meters/meters). The canal contains many operational components such as gates, siphons and pump stations. The average velocity of canal is 1.52 km/hour. The average monthly flow rates provided by the Jordan Valley Authority are provided in Table A1 in the Appendix A.

Figure 1 presents a simple conceptualization of the canal with a number of computational elements to represent the system. The King Abdullah Canal has four major nutrient sources: 1) Lake Tiberius, 2) Yarmouk River, 3) Mukhiba wells, and 4) agricultural return water. Throughout the canal's length, there are a series of inputs and outputs as illustrated in Figure 2.

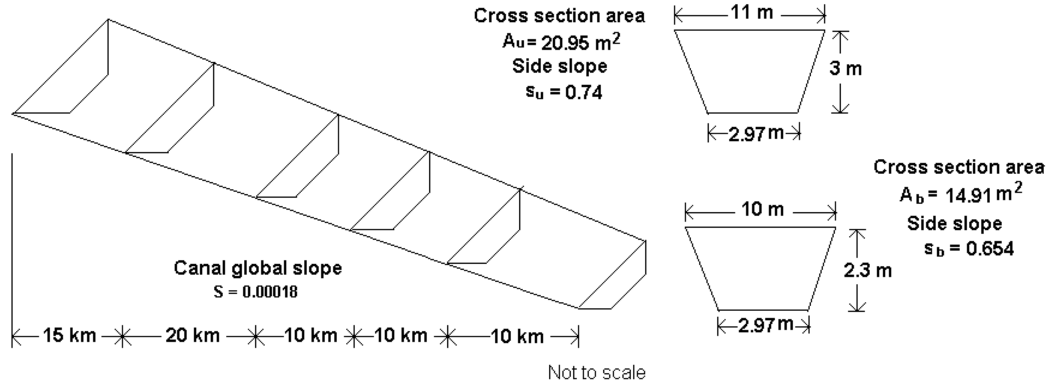


Figure 1. Conceptualized Canal System

The basic equation describing the nutrient mass balance for King Abdullah Canal (Equation 1) is for the phosphorus (the nutrient which most likely limits algal production in this system) and nitrogen loading to the canal.

$$\text{INPUTS} = Q_{LT}*C_{LT} + Q_{YR}*C_{YR} + Q_{NW}*Q_{MW} + Q_{AR}*C_{AR} \qquad (1)$$

where,

Q_{LT} = water flow rate from Lake Tiberius (m^3/s)

C_{LT} = nutrient concentration in Lake Tiberius (mg/L)

Q_{YR} = water flow rate from the Yarmouk River (m^3/s)

C_{YR} = nutrient concentration in Yarmouk River (mg/L)

Q_{MW} = water flow rate from the Mukheiba wells (m^3/s)

C_{MW} = nutrient concentration in the Mukheiba wells (mg/L)

Q_{AR} = net water flow rate from agricultural return flows (m^3/s)

C_{AR} = nutrient concentration from agricultural return flows (mg/L)

$$\text{OUPUTS} = Q_O*C_O \tag{2}$$

where,

Q_O = the outflow water flow rate from the King Abdullah Canal to the Zai drinking water treatment plant (m^3/s)

C_O = nutrient concentration in the King Abdullah Canal outflow (mg/L)

These inputs and outputs provide the primary mass balance to the system and the nutrient loadings.

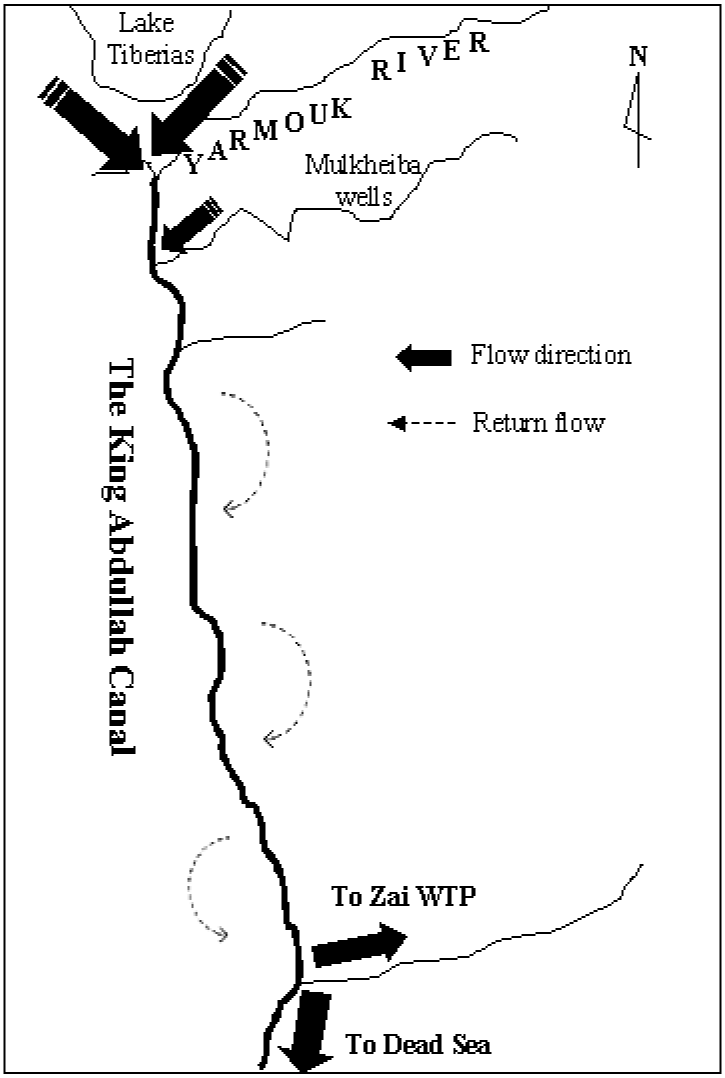


Figure 2. The King Abdullah Canal water flow

Algal Dynamics

As previously stated, the most likely cause of excessive algal growth in KAC is high nutrient loading. Algal dynamics can be defined simply as:

$$Pnet = Pg - Ps - Zg \qquad (3)$$

where,

Pnet = phytoplankton net growth rate (day^{-1})
Pg = phytoplankton growth rate (day^{-1})
Ps = phytoplankton settling rate (day^{-1})
Zg = zooplankton grazing rate (day^{-1})

Phytoplankton growth rate depends on three major components: light, nutrient and temperature. These components influence the algal growth rate.

$$Pg = Umax * f(\theta_I) * f(\theta_N) * f(\theta_T) \qquad (4)$$

Where, Umax = maximum growth rate
θ_I = light coefficient
θ_N = nutrient coefficient
θ_T = temperature coefficient

Based on these functional relationships, eutrophication was modeled using both QUAL2E and MIKE 11. As will be noted, both models are capable of simulating the system. It is valuable, however, to evaluate two approaches to illustrate the sensitivity of each to model to inputs and to determine sensitivity of management alternatives to model choice. Available data were reviewed and used as general inputs to the model. Data are described in Table A2 and Table A3 in the Appendix A.

2.3. MODEL SETUP AND RUN

Six monitoring sites exist along the canal system. Figure 3 shows the locations of this site.

Figure 3. The King Abdullah Canal water quality monitoring system, location map

Although the canal is modeled along its entire length, the Abu Sidu area (M4) was selected as the critical location for the water quality assessment. It was chosen as the furthest location at which the most extreme effects of algal blooms would be experienced. The models simulate 10 days (Aug. 1st ~ Aug. 10th in 2001) during summer season. The models use a 30 minutes time-step for their simulation of water quality. The period August 1st – August 10th was chosen as the critical water quality period. This August period typically has warm temperatures and high light intensity, encouraging algae growth in the canal. This is also the time of year when past taste and odor problems in this water supply have occurred.

1) Formulating QUAL2E

In QUAL2E, the KAC is conceptualized as a series of five sequential, completely mixed reaches. It is assumed that the reach is mixed horizontally and vertically (throughout the water column and across the canal reach) but not longitudinally. Each reach is divided into 10 to 15 computational elements, each 1 km long. The hydraulic, geometric, and biological rate constants for the first three reaches are assumed identical, as are the last two reaches. Input parameters and coefficients for QUAL2E are listed in Table A4 in the Appendix A.

> The output from QUAL2E includes flow rates and the concentration of DO, nitrogen, phosphorous, and chlorophyll-a at a time-step of 30 minutes for 10 days during the summer season. Chlorophyll-a was selected as the primary output for analysis and comparison. Because the two models simulate water quality differently, some model parameters and coefficients are not identical. In some cases different conceptual representations of the key processes are used, so direct comparisons of certain model inputs and parameters cannot be made.

2) Formulating MIKE 11

MIKE 11 consists of three crucial modules including the hydrodynamic module, the advection-dispersion module, and the water quality module. Each module is coupled with the river network module and the cross section module.

Hydrodynamic Module (HD) Set up

The hydrodynamic module represents the physical boundary conditions associated with flow routing including flow, wind, and bed resistance (Manning’s coefficient). A consistent flow of 10 m^3/s (provided by Jordan Valley Authority) was used in the model as the default flow rate. The canal was simulated for the first 10 days of August on a 30 minutes time step. The Manning coefficient was adjusted to generate the average water depth provided by Jordan Valley Authority.

Figure 4. Water depth along the King Abdullah Canal

The advection-dispersion module is based on the mass balance of dissolved and suspended material including nutrients and oxygen. The module requires two external forcing values that are utilized in the eutrophication module, solar radiation and water temperature. The discharge and water level components used in hydrodynamic module are utilized in the advection-dispersion module. The eutrophication module is integrated with the advection-dispersion module and is composed of diverse parameters and coefficient associated with algae dynamics. The module describes the dynamic behavior of phytoplankton, zooplankton, benthic vegetation, and nutrients, as well as external forcing (light intensity and water temperature). Figure 5 shows the biological and chemical interactions within the canal system.

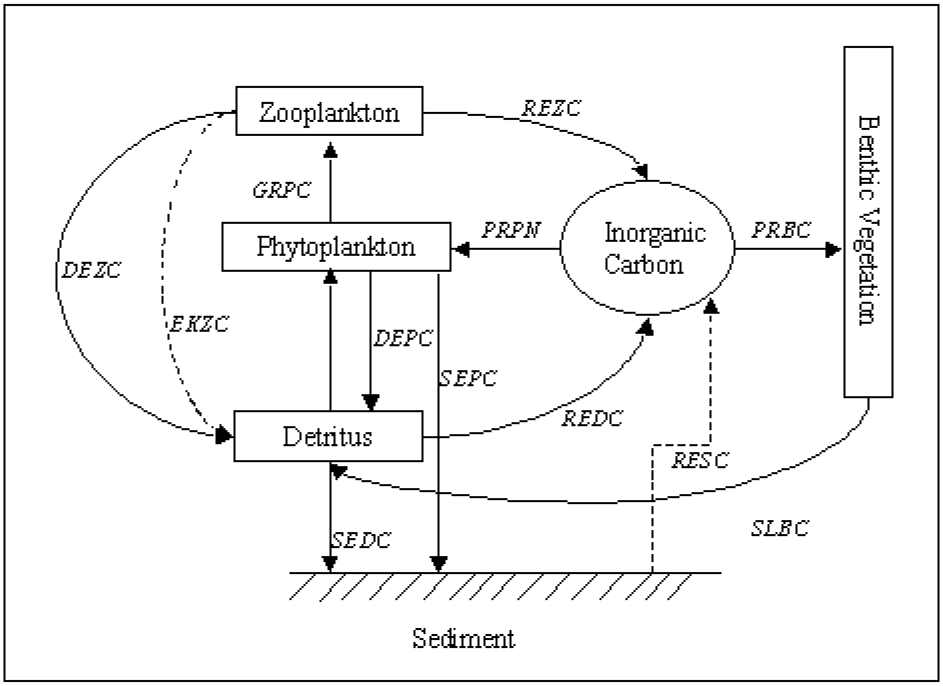


Figure 5. State variable and process in the eutrophication module (EU) of MIKE 11

The abbreviation used in the Figure 5 are defined as follows:

PRPN: production of phytoplankton
SEPC: sedimentation of phytoplankton
GRPC: grazing by zooplankton
DEPC: death of phytoplankton
DEZC: death of zooplankton
EKZC: excretion of zooplankton
REZC: respiration of zooplankton
REDC: mineralization of detritus
SEDC: sedimentation of detritus
RESC: mineralization of sediment
PRBC: production of benthic vegetation
SLBC: death of benthic vegetation

All input parameters for hydrodynamic, advection-dispersion and eutrophication modules are listed in Table A3 in the Appendix A.

3) Comparison of runs

Figure 6 and Figure 7 present concentration of chlorophyll-a for M4 (Abu Sidu) from QUAL2E and MIKE 11, respectively. Although both models predict essentially the same concentration at Abu Sidu, the shape of the growth curves are significantly different. Chlorophyll-a concentration increased exponentially in QUAL2E, while chlorophyll-a concentrations in MIKE 11 increase asymptotically. For the QUAL2E model, model results suggest that the limiting factor is time of travel whereas the MIKE 11 model suggests that growth is beginning to be limited by some other factor.

This difference results from the relationship between chlorophyll-a and phytoplankton biomass of each model. Chlorophyll-a is considered to be directly proportional to the concentration of phytoplanktonic algal biomass in QUAL2E.

$$\text{Chl-a} = \alpha o * A \qquad (5)$$

where

Chl-a = chlorophyll-a concentration (μg/L)
A = algal biomass concentration (μg/L)
αo = a conversion factor (μg Chl-a/μg Algae)

Unlike QUAL2E, MIKE 11 estimates chlorophyll-a concentration as a complicated function of phytoplankton intracellular nutrient concentration accordingly:

$$PRCH = \left[\frac{CHMI}{IK} * \exp(CHMA * \mu_N) \right] * PRPC \qquad (6)$$

where

PRCH = chlorophyll-a concentration (μg/L)
CHMI = a coefficient related to minimum chlorophyll-a production

CHMA = a coefficient related to maximal chlorophyll-a production

PRPC = algal biomass concentration (μg/L)

μ_N = a factor related to the intracellular nitrogen-carbon ratio

IK = light saturation coefficient,

$$\mu_N = \frac{PN/PC - PNMI}{PNMA - PNMI} \tag{7}$$

where

PN = intracellular nitrogen concentration of phytoplankton

PC = intracellular carbon concentration of phytoplankton

PNMI = the minimum intracellular concentration of phosphorous in phytoplankton

PNMA = the maximum intracellular concentration of phosphorous in phytoplankton

The differences in the results arise from the differences in how the growth of algae is conceptualized in the models.

Figure 6. Concentration of chlorophyll-a from QUAL2E and MIKE 11

2.4. UNCERTAINTY ANALYSIS

Because there is significant uncertainty associated with a variety of components in the KAC, it is appropriate to explore which variables have the greatest impact on model results. Uncertainty analysis methods are commonly used to determine model sensitivity. The basic variables may include model coefficients, parameters, boundary conditions, input variables, and other factors that are considered in the model (Melching and Bauwens 1982).

A 2^k factorial design is used to evaluate sensitivity. A 2^k factorial design implies that K variables are evaluated between a maximum and minimum value. The most important aspect of applying sensitivity analysis for assessment of model-output uncertainty is to determine the uncertainty in important input variables. Table 1 and 2 show the range of uncertainties of eleven basic parameters. S-Plus®, a statistical package developed by

Mathsoft, was used to generate the sets of random values for each basic variable corresponding to the 2^k factorial designs (Appendix C and D). Having obtained estimates of all the main effects and interaction effects, an analysis of variance (ANOVA) is used to determine the sensitivity of the basic parameters (Appendix C and D).

Among the eleven basic parameters utilized in QUAL2E and MIKE 11, three parameters impacted model results significantly: Manning's n coefficient, the light extinction coefficient, and the maximum growth rate of phytoplankton. Table 3 shows that these parameters account for 48% of the uncertainty in the mean of chlorophyll-a concentration for QUAL2E and 80% of the uncertainty in the mean of chlorophyll-a concentration for MIKE 11, respectively. Appendix C and D describe this process. Therefore, management alternatives that addressed these three parameters were developed and evaluated.

Table 1. Maximum and Minimum values of model basic parameters for QUAL2E based on literature review

Parameter	Definition	Max. value	Min. Value	Notes
α_3	Oxygen production by algae (mg-O/mg-A)	1.8	1.4	1
α_4	Oxygen uptake by algae (mg-O/mg-A)	2.3	1.6	1
U_{max}	Maximum growth rate (1/day)	3	1	1
ρ	Respiration of algae (1/day)	0.4	0.05	4
K_N	Half saturation constant for nitrogen (mg-N/L)	0.2	0.04	1
K_P	Half saturation constant for phosphorous (mg-P/L)	0.06	0.015	2
λ_1	Linear algal self shading coefficient (1/(m(µg-chla/L)))	0.009	0.002	2
K_L	Half saturation constant for light (Langley/min)	0.007	0.001	2
N	Manning's n coefficient	0.05	0.0125	3
$\sigma 1$	Settling rate for algae (m/day)	0.5	0.1	2
λ_2	Non-algae light extinction coefficient (1/m)	30	0.2	2

1 = based on the typical range for the coefficient of parameters built in QUAL2E
2= based on the typical range for the coefficient for such parameters reported by Brown and Barnwell (1987, p. 54)
3= Manning coefficient for concrete (Linsley, Kohler and Paulhus 1982 , p484)
4= based on the typical range for the coefficient of respiration rate by Jorgensen and Nielsen (1983, page 83)

Table 2. Maximum and Minimum values of model basic parameters for MIKE11 based on literature review

Parameter	Definition	Max value	Min value	Notes
PLA	Light extinction constant for phytoplankton (1/m)	24	6	1
VEFO	Zooplankton growth efficiency	0.3	0.1	1
N	Manning coefficient	0.05	0.0125	2
MYMG	Maximum growth rate for algae (1/day)	2.5	1	1
KNI	Dependency of N uptake rate on N availability	100	50	1
KC	Half saturation constant for phytoplankton	0.02	0.005	1
KDMA	Maximum death rate for starving phytoplankton (1/day)	0.2	0.005	1
KGRB	Maximum grazing rate at 20 degree Celsius (1/day)	1.8	0.45	1
FAC	Correction for dark reaction	10	5	1
VM	Fraction of nutrients released under decay	0.7	0.175	1
KMDM	Maximum death rate for starving phytoplankton (1/day)	0.06	0.015	1

1 = based on the typical range for the coefficient of parameters built in MIKE11
2= Manning coefficient for concrete (Linsley, Kohler and Paulhus, 1982, page 484)

Table 3. Comparison of Basic-Variable Sensitivity Ranks for QUAL2E and MIKE 11

	QUAL2E	Rank	MIKE 11	Rank
Maximum growth rate of Algae	21%	1	15%	2
Light extinction coefficient	20%	2	62%	1
Manning coefficient n	7%	3	3%	3
Total	48 %		80 %	

2.5. MODEL SELECTION

Having applied both models to the King Abdullah Canal and having tested their response to a wide range of parameter values, it was appropriate to select one for the alternative evaluation process. As previously noted, both models can simulate the growth pattern of phytoplankton. The results of the sensitivity analysis indicated extreme sensitivity of MIKE 11 to light intensity. The light coefficient in MIKE 11 is coupled with light extinction coefficient of chlorophyll-a and light extinction coefficients of detritus and water. There was insufficient filed data to provide all of the values needed for this analysis. MIKE 11 was unable to simulate water quality values extremely low nutrient concentrations. Both of these factors resulted in concern over the values generated when model inputs were varied.

One of the most important aspects of the model selection is model reliability. If sufficient data are available, more complicated models are appropriate. However, considering the scarcity of algal physiology data for the King Abdullah Canal, QUAL2E is more appropriate.

2.6. MODELING MANAGEMENT ALTERNATIVE

In this section the process of alternative evaluation is described. First, the Status Quo, or the current condition, is defined. Next, four specific management alternatives are identified. Finally, combinations of these alternatives are tested.

2.6.1 STATUS QUO

The King Abdullah Canal has experienced eutrophication that is typically associated with nitrogen levels in excess of 5 mg/l and phosphorous levels in excess of 0.1-0.2 mg/l. In all likelihood, the poor taste and odor problems that have been experienced are due to eutrophication. Since the King Abdullah Canal delivers 10 m^3/s of water for drinking and irrigation purposes, it is imperative that the key sources of eutrophication and management alternatives be identified. For the initial condition, a chlorophyll-a concentration of 20 µg/L was assumed. The current environmental conditions that regulate algal growth coupled with nutrient, light, temperature, and zooplankton are also included in the water quality model. All inputs for the current system are listed in Table A4 in appendix A. During the course of a normal year, short-term simulation (August 1 through August 10) of algal dynamics were assessed. Earlier Figure 6 suggests the environmental conditions in the King Abdullah Canal are likely to result in severe algal blooms. In brief these data alone indicate the necessity for immediate action.

Table 4. Basic Model Assumptions

Assumption	Description
Data availability	Used typical data for the region
Boundary Condition	External flow and nutrient loading into the canal caused by rainfall are negligible.
Internal loading	The internal nutrient loading from sediment was assumed and accumulated into average nutrient value

3. *ALTERNATIVES*

A series of water management alternatives are posed as a means of addressing the elevated values of chlorophyll-a in the King Abdullah Canal. These are described below.

1. Alternative 1: Flow Control

One cause of eutrophication could be the operation of the canal, that is, allowing the flow rate to decrease, increasing the travel time and creating ideal conditions of eutrophication. This can have a major impact because longer canal retention times (caused by lower flow rates) provide more time for the phytoplankton community to produce larger blooms. To test the impact of flow rate on maximum algae levels, 10 different flow rates were tested at head of the canal. As Table 5 indicates that the flow rate significantly impacts algal growth. Consistent flow and frequent flushing could help suppress phytoplankton blooms in the canal. The results of these simulations clearly indicate that low flow rates tend to chlorophyll-a concentrations.

Table 5. Flow Control

WATER MANAGEMENT ALTERNATIVES FOR THE KING ABDULLAH CANAL USING QUAL2E MODEL														
									Manning				AVERAGE	
RUN #	FLOW	N (mg/l	P (mg/l	N ppb	P ppb	LIGHT	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	%change	Chlorophyll	%change
0	10	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	0%	97.30	
1) FLOW CHANGE														
11	19.5	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	95%	70.08	-28%
12	18	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	80%	72.63	-25%
13	16	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	60%	76.69	-21%
14	14	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	40%	81.79	-16%
15	12	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	20%	88.43	-9%
16	10	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	0%	97.30	0%
17	8	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	20%	111.01	14%
18	6	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	40%	133.20	37%
19	4	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	60%	177.53	82%
20	2	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	80%	304.98	213%

The flow rate is inversely correlated to retention time. Figure 7 presents the chlorophyll-a concentration at Abu Sidu associated with different retention times. For reference, a retention time of 1 day is associated with a flow rate of 11.6 m^3/s whereas a retention time of 4 days is associated with a flow rate of 3.2 m^3/s.

Figure 7. Relationship between concentration of chlorophyll-a and retention time

6. Alternative 2: Nutrient Control

Since algal growth is very sensitive to nutrient levels, low nutrient levels would significantly lower chlorophyll-a levels. Low concentrations of nutrients reduce the rate of eutrophication. In this evaluation both nitrogen and phosphorus were reduced by a specific percentage. This could be accomplished by treating all or portions of the flows with alum or treating irrigation return flows with high nutrient content. As the results indicated, a 20 % nutrient removal resulted in a 4% decrease in chlorophyll-a, and a 95 % nutrient removal resulted in a 75% decrease of chlorophyll-a concentrations at Abu Sidu.

Table 6. Nutrient Control Alternative

WATER MANAGEMENT ALTERNATIVES FOR THE KING ABDULLAH CANAL USING QUAL2E MODEL														
									Manning				AVERAGE	
RUN #	FLOW	N (mg/l)	P (mg/l)	N ppb	P ppb	LIGHT	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	%change	Chlorophyll	%change
0	10	7.230	1.00	13014	1800	400	0.035	0.035	0.022	0.022	0.035	0%	97.30	
2) NUTRIENT CONTROL														
24	10	**8.676**	**1.200**	8676	1200	400	0.035	0.035	0.022	0.022	0.035	20%	100.21	3%
25	10	**7.230**	**1.000**	7230	1000	400	0.035	0.035	0.022	0.022	0.035	0%	97.30	0%
26	10	**5.784**	**0.800**	5784	800	400	0.035	0.035	0.022	0.022	0.035	20%	93.76	-4
27	10	**4.338**	**0.600**	4338	600	400	0.035	0.035	0.022	0.022	0.035	40%	87.93	-10
28	10	**2.892**	**0.400**	2892	400	400	0.035	0.035	0.022	0.022	0.035	60%	77.88	-20
29	10	**1.446**	**0.200**	1446	200	400	0.035	0.035	0.022	0.022	0.035	80%	57.25	-41
30	10	**0.362**	**0.050**	362	50	400	0.035	0.035	0.022	0.022	0.035	95%	24.68	-75

Figure 8 presents the sensitivity of chlorophyll-a concentration as a function of its initial concentration and as a function of the total phosphorous concentration in the waters in the canal.

Figure 8. Relationship between concentration of chlorophyll-a and total phosphorous corresponding to different initial condition

3. Alternative 3: Light Control

Another approach is to limit the light reaching the water to reduce the rate of eutrophication. Placing a cover over the canal would prevent light from penetrating into the water column. This effect reduces the concentration of chlorophyll-a by reducing light availability. As noted previously, light intensity influences algae growth. If it were possible to cover all or a large portion of the canal, light could be limited, reducing the rate of algal production. The results indicate that even reducing the light intensity by 60% would only reduce chlorophyll-a levels by 20%. Figure 9 shows that concentration of chlorophyll-a decreases as light intensity decreases at Abu Sidu.

Table 7. Light Control Alternative

WATER MANAGEMENT ALTERNATIVES FOR THE KING ABDULLAH CANAL USING QUAL2E MODEL														
									Manning				AVERAGE	
RUN #	FLOW	N (mg/l)	P (mg/l)	N ppb	P ppb	LIGHT	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	%change	Chlorophyll	%change
0	10	7.230	1.00	13014	1800	400.0	0.035	0.035	0.022	0.022	0.035	0%	97.30	
3) LIGHT CONTROL														
31	10	7.230	1.00	13014	1800	20	0.035	0.035	0.022	0.022	0.035	95%	28.74	-70%
32	10	7.230	1.00	13014	1800	40	0.035	0.035	0.022	0.022	0.035	90%	40.86	-58%
33	10	7.230	1.00	13014	1800	80	0.035	0.035	0.022	0.022	0.035	80%	57.72	-41%
34	10	7.230	1.00	13014	1800	120	0.035	0.035	0.022	0.022	0.035	70%	68.72	-29%
35	10	7.230	1.00	13014	1800	160	0.035	0.035	0.022	0.022	0.035	60%	76.44	-21%
36	10	7.230	1.00	13014	1800	200	0.035	0.035	0.022	0.022	0.035	50%	82.15	-16%
37	10	7.230	1.00	13014	1800	240	0.035	0.035	0.022	0.022	0.035	40%	86.56	-11%
38	10	7.230	1.00	13014	1800	280	0.035	0.035	0.022	0.022	0.035	30%	90.07	-7%
39	10	7.230	1.00	13014	1800	320	0.035	0.035	0.022	0.022	0.035	20%	92.92	-4%
40	10	7.230	1.00	13014	1800	360	0.035	0.035	0.022	0.022	0.035	10%	95.30	-2%
41	10	7.230	1.00	13014	1800	400	0.035	0.035	0.022	0.022	0.035	0%	97.30	0%

Table 8. Change of Manning Roughness n

WATER MANAGEMENT ALTERNATIVES FOR THE KING ABDULLAH CANAL USING QUAL2E MODEL														
									Manning				AVERAGE	
RUN #	FLOW	N (mg/l)	P (mg/l)	N ppb	P ppb	LIGHT	Sec 1	Sec 2	Sec 3	Sec 4	Sec 5	%change	Chlorophyll	%change
0	10	7.230	1.00	0	0	400.	0.035	0.035	0.022	0.022	0.035	0%	97.30	
4) MANNING COEFFICIENT														
44	10	7.230	1.00	13014	1800	400.	0.042	0.042	0.026	0.026	0.042	20%	118.53	22%
45	10	7.230	1.00	13014	1800	400.	0.035	0.035	0.022	0.022	0.035	0%	97.30	0%
46	10	7.230	1.00	13014	1800	400.	0.028	0.028	0.018	0.018	0.028	20%	78.28	-20%
47	10	7.230	1.00	13014	1800	400.	0.021	0.021	0.013	0.013	0.021	40%	60.55	-38%
48	10	7.230	1.00	13014	1800	400.	0.014	0.014	0.009	0.009	0.014	60%	46.02	-53%
49	10	7.230	1.00	13014	1800	400.	0.007	0.007	0.004	0.004	0.007	80%	32.34	-67%
50	10	7.230	1.00	13014	1800	400.	0.002	0.002	0.001	0.001	0.002	95%	23.15	-76%

Figure 9. Relationship between concentration of chlorophyll-a and light control

4. Alternative 4: Changing Resistance to Flow

Because the flow rate is controlled by the bed resistance (Manning's n coefficient), cleaning the canal of attached vegetation, dredging sediment, or removing other flow obstructions would also be helpful. A percentage change above 50% for the Manning’s coefficient is not feasible since n values below 0.012 for concrete are not realistic. The hydraulic travel time through the system is extremely important. The time of travel can be controlled by either increasing the flow rate (Alternative 1) or by creating conditions that allow the flow to pass much faster. Changing the roughness by 20% results in a 20% decrease in chlorophyll-a.

3.1. SENARIO ANALYSES

The previously defined alternatives for decreasing algal growth in the King Abdullah Canal were combined to create eight scenarios to meet a hypothetical water quality standard (arbitrarily set at 50 μg/L of chlorophyll-a). Each scenario has primary management options, such as additional flow or covering the canal some type of cover. The results of Section 3.0 indicate that no single alternative applied at an appropriate level provides water quality that will meet the 50 μg/L target. The eight scenarios were analyzed with QUAL2E. The goal of this analysis is to identify combinations of alternatives that could be cost-effectively applied and that do not significantly impact the quantity of water delivered. The flow rate was limited to no more than 16 m^3/s and the Manning's n coefficient to 0.012.

The individual options were evaluated for the 10 day, critical summer season with regard to the phytoplankton concentration. The first four scenarios consider higher flow rates and the later four scenarios used a constant flow rate of 10 m^3/s.

Table 9. Direct comparison of components in each scenario

The King Abdullah Canal Scenarios	Flow rate increase (m3/s)	Nutrient		LC. (1/m)	Manning Coeff
		N (mg/L)	P (mg/L)		
Scenario 1	20 – 60 %	Constant	Constant	Constant	20 – 50 %
Scenario 2	20 – 60 %	Constant	Constant	20 – 95 %	Constant
Scenario 3	20 – 60 %	20 – 80 %	20 – 80 %	Constant	Constant
Scenario 4	20 – 60 %	20 – 80 %	20 – 80 %	20 – 95 %	20 – 50 %
Scenario 5	Constant	Constant	Constant	20 – 95 %	20 – 50 %
Scenario 6	Constant	20 – 80 %	20 – 80 %	Constant	20 – 50 %
Scenario 7	Constant	20 – 80 %	20 – 80 %	20 – 95 %	Constant
Scenario 8	Constant	20 – 80 %	20 – 80 %	20 – 95 %	20 – 50 %

1. Scenario 1

Scenario 1 includes a higher flow rate and clearing vegetation from the canal (Alternative 4) to decrease flow retention time. The combination of increasing the flow rate and decreasing the resistance to flow results in meeting the 50 μg/L standard. One of these combinations meets the standard with a flow rate of 12 m^3/s.

2. Scenario 2

Scenario 2 combines additional flow and light control. Four combinations were considered in this scenario. The feasibility of providing shade along the canal or of creating a barrier to light entering the canal has not been investigated. However, the results indicate that this could be an effective approach for reducing algal levels.

3. Scenario 3

Scenario 3 combines additional flow and nutrient control using input water treatment. The scenario calls for removing a large percentage of the nutrients, therefore a treatment plant of sufficient size to remove these nutrients before the water enters the canal would be necessary. This would likely be one of the more expensive alternatives. As the results indicate, even with increased flows, a reduction in nutrients meets the 50 μg/L level, but only barely.

4. Scenario 4

Scenario 4 combines an increase in flow rate, nutrient removal, light control, and removing vegetation.

5. Scenario 5

Scenario 5 combines removing vegetation, and light control. The flow rate in this scenario is 10 m^3/s, the minimum flow rate allowed.

6. Scenario 6

Scenario 6 combines nutrient control and vegetation removal. This scenario has high initial construction and high operations costs due to periodically removing the vegetation.

7. Scenario 7

Scenario 7 combines light control and nutrient control. This scenario has a high initial construction cost for the treatment facility and canal cover, and moderate operations cost maintaining the treatment facility.

8. Scenario 8

Scenario 8 would involve multiple options including vegetation removal, and light and nutrient control.

Figure 18 presents direct comparison of components in each scenario.

Table 10. Scenario 1 for the King Abdullah Canal

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning's n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	n		
Scenario 1	A	16	7.230	1.00	400	0.012	60	-	-	50	40.5	58%
	B	14	7.230	1.00	400	0.012	40	-	-	50	41.8	57%
	C	12	7.230	1.00	400	0.012	20	-	-	50	43.4	55%

Abbreviations are as follow: N, nitrogen; P, phosphorous; LC, light coefficient (Langley); F, percentage change of flow rate; NU, percentage change of nutrient; LC, percentage change of light intensity; n, percentage change of Manning roughness; Chl, concentration of chlorophyll-a at station M4 (µg/L)

Table 11. Scenario 2 for the King Abdullah Canal

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning's n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	n		
Scenario 2	A	16	7.230	1.00	20	0.035	60	-	95	-	**26.9**	**72%**
	B	14	7.230	1.00	20	0.035	40	-	95	-	**27.4**	**72%**
	C	12	7.230	1.00	20	0.035	20	-	95	-	**28.0**	**71%**
	D	16	7.230	1.00	80	0.035	60	-	80	-	**48.1**	**51%**

Scenario 3	A	16	7.230	1.00	400	0.035	60	80	-	-	49.5	49%

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning's n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	N		

Table 12. Scenario 3 for the King Abdullah Canal

Table 13. Scenario 4 for the King Abdullah Canal

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning's n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	N		
Scenario 4	A	12	0.362	0.05	20	0.012	20	80	95	50	18.0	82%
	B	14	1.446	0.20	80	0.021	40	80	80	40	30.87	68
	C	14	5.784	0.80	320	0.012	40	20	20	50	40.29	59
	D	16	5.784	0.80	320	0.021	60	20	20	40	49.09	50

Table 14. Scenario 5 for the King Abdullah Canal

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning's n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	N		
Scenario 5	A	10	7.230	1.00	20	0.012	-	-	95	50	23.90	75
	B	10	7.230	1.00	80	0.012	-	-	80	50	35.21	64
	C	10	7.230	1.00	80	0.021	-	-	80	40	42.69	56
	D	10	7.230	1.00	80	0.028	-	-	80	20	50.42	48

Table 15. Scenario 6 for the King Abdullah Canal

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning’s n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	n		
Scenario 6	A	10	1.446	0.2	400	0.012	-	80	-	50	34.2	65
	B	10	4.338	0.6	400	0.012	-	40	-	50	43.0	56
	C	10	1.446	0.2	400	0.028	-	80	-	20	49.4	49

Table 16. Scenario 7 for the King Abdullah Canal

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning’s n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	N		
Scenario 7	A	10	1.446	0.2	20	0.035	-	80	95	-	23.74	76
	B	10	5.784	0.8	20	0.035	-	20	95	-	28.33	71
	C	10	2.892	0.4	80	0.035	-	60	80	-	49.28	49

Table 17. Scenario 8 for the King Abdullah Canal

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC (Langley)	Manning's n	%changes				Chl (µg/L)	- % change Chl
			N (mg/L)	P (mg/L)			F	NU	LC	N		
Scenario 8	A	10	1.446	0.2	20	0.012	-	80	95	50	21.31	78
	B	10	1.446	0.2	160	0.012	-	80	60	50	31.48	68
	C	10	4.338	0.6	80	0.021	-	40	80	40	40.42	58
	D	10	2.892	0.4	320	0.021	-	60	20	40	50.29	48

Table 18. Water Management Scenarios for The King Abdullah Canal Using QUAL2E Model

The King Abdullah Canal Scenarios		Flow rate (m3/s)	Nutrient		LC. (Langley)	Manning Coeff. n					%changes				Chl (mg/L)	- % change Chl
			N (mg/L)	P (mg/L)		S1	S 2	S3	S4	S 5	F	NU	LC	n		
Scenario 1	A	16	7.230	1.00	400	0.012	0.012	0.012	0.012	0.012	60	-	-	50	40.54	58
	B	14	7.230	1.00	400	0.012	0.012	0.012	0.012	0.012	40	-	-	50	41.82	57
	C	12	7.230	1.00	400	0.012	0.012	0.012	0.012	0.012	20	-	-	50	43.40	55
Scenario 2	A	16	7.230	1.00	20	0.035	0.035	0.022	0.022	0.035	60	-	95	-	26.87	72
	B	14	7.230	1.00	20	0.035	0.035	0.022	0.022	0.035	40	-	95	-	27.39	72
	C	12	7.230	1.00	20	0.035	0.035	0.022	0.022	0.035	20	-	95	-	28.00	71
	D	16	7.230	1.00	80	0.035	0.035	0.022	0.022	0.035	60	-	80	-	48.12	51
Scenario 3	A	16	1.446	0.20	400	0.035	0.035	0.022	0.022	0.035	60	80	-	-	49.54	49
Scenario 4	A	12	1.446	0.20	20	0.012	0.012	0.012	0.012	0.012	20	80	95	50	21.41	78
	B	14	1.446	0.20	80	0.021	0.021	0.013	0.013	0.021	40	80	80	40	30.87	68
	C	14	5.784	0.80	320	0.012	0.012	0.012	0.012	0.012	40	20	20	50	40.29	59
	D	16	5.784	0.80	320	0.021	0.021	0.013	0.013	0.021	60	20	20	40	49.09	50
Scenario 5	A	10	7.230	1.00	20	0.012	0.012	0.012	0.012	0.012	-	-	95	50	23.90	75
	B	10	7.230	1.00	80	0.012	0.012	0.012	0.012	0.012	-	-	80	50	35.21	64
	C	10	7.230	1.00	80	0.021	0.021	0.013	0.013	0.021	-	-	80	40	42.69	56
	D	10	7.230	1.00	80	0.028	0.028	0.018	0.018	0.028	-	-	80	20	50.42	48
Scenario 6	A	10	1.446	0.2	400	0.012	0.012	0.012	0.012	0.012	-	80	-	50	34.2	65
	B	10	4.338	0.6	400	0.012	0.012	0.012	0.012	0.012	-	40	-	50	43.0	56
	C	10	1.446	0.2	400	0.028	0.028	0.018	0.018	0.028	-	80	-	20	49.4	49
Scenario 7	A	10	1.446	0.2	20	0.035	0.035	0.022	0.022	0.035	-	80	95	-	23.74	76
	B	10	5.784	0.8	20	0.035	0.035	0.022	0.022	0.035	-	20	95	-	28.33	71
	C	10	2.892	0.4	80	0.035	0.035	0.022	0.022	0.035	-	60	80	-	49.28	49
Scenario 8	A	10	1.446	0.2	20	0.012	0.012	0.012	0.012	0.012	-	80	95	50	21.31	78
	B	10	1.446	0.2	160	0.012	0.012	0.012	0.012	0.012	-	80	60	50	31.48	68
	C	10	4.338	0.6	80	0.021	0.021	0.013	0.013	0.021	-	40	80	40	40.42	58
	D	10	2.892	0.4	320	0.021	0.021	0.013	0.013	0.021	-	60	20	40	50.29	48

Abbreviations are as follow: N, nitrogen; P, phosphorous; LC, light coefficient (Langley); S1, Manning roughness of cross section 1; S2, Manning roughness of cross section 2; S3, Manning roughness of cross section 3; S4, Manning roughness of cross section 4; S5, Manning roughness of cross section 5; F, percentage change of flow rate; NU, percentage change of nutrient; LC, percentage change of light intensity; n, percentage change of Manning roughness; Chl, concentration of chlorophyll-a at station M4 (mg/L)

4.COST-EFFECTIVENESS

A summary of construction cost for each scenario including 1) building new municipal wastewater treatment plant (WWTP), 2) covering the top of the canal, and 3) removing and dredging sediment is given (Table 19). Annual operation and maintenance (O&M) costs are not included due to assuming O&M cost is relatively small in comparison with construction cost. Cost was estimated based on references (Helyar1978, RSMeans 2002) and engineering judgment. In general, unlike building new WWTP, the cost of both covering and clearing options are similar, although material and construction equipment would differ. Estimated process for covering and clearing options are provided in Appendix D. In terms of the cost of building WWTP, the unit cost would be $1,000 to $1,100 per cubic meters based on average daily flow. The total cost would be $864 million based on average daily flow 864000 cubic meter per day. The cost of covering and clearing option ranges from 6.7 million to 6.8 million.

Table 19. Summary of Construction Costs for Scenarios

	Flow rate increase (m^3/s)	Nutrient Control	Light Control	Manning's n Control	Cost $ ($\times10^6$)	Unit Cost ($\$/m^3$)	Construction Period (Year)
Scenario 1	20 – 60 %	Constant	Constant	20 – 50 %	6.8	7.8	1
Scenario 2	20 – 60 %	Constant	20 – 95 %	Constant	6.7	7.7	1
Scenario 3	20 – 60 %	20 – 80 %	Constant	Constant	864	1,000	2
Scenario 4	20 – 60 %	20 – 80 %	20 – 95 %	20 – 50 %	877	1,015	2
Scenario 5	Constant	Constant	20 – 95 %	20 – 50 %	13.5	15.6	1
Scenario 6	Constant	20 – 80 %	Constant	20 – 50 %	870.8	1,007	2
Scenario 7	Constant	20 – 80 %	20 – 95 %	Constant	870.7	1,006	2
Scenario 8	Constant	20 – 80 %	20 – 95 %	20 – 50 %	877	1,015	2

Table 20. Estimated cost for covering the top of the canal

	Material	Labor	Equipment	Total	Estimated Construction Period
Site Preparation	Metal Anchor with bolt: 65000 meter × 4 each/2 meter × $2/each = $130,000 (2.5 cm diameter × 30 cm long) ***Subtotal: $390,000***	1. Marking crew (2 × $187/day = $374/day) 2. Driller (2 × $ 190/day = $380/day) 3. Bolt fastening crew (2 × $187/day = $374/day) ***Subtotal: $1128/day***	$33.5/day (80lb Drills, hand(jackhammer) 65lb) ***Subtotal: $33.5/day***	$390,000 + ($1128/day +33.5/day) × 270days = ***$703,605***	270 days (4 × 65000 meter/2 meter × 0.1(productive rate: labor-hours/each) / 2 persons /24 hrs = 270 days (9 month)
Site Construction	Black Plastic Sheet: 65000 meter × 5 × $16/each = ***$5.2 million*** Side walk bridge: 2 × $3,000/each = ***$6,000*** Crossover Rod: 65000 meter /2 meter × 2 × $10/each = ***$650,000*** ***Subtotal: $5.85 million***	Workers 4 × $187/day = $***748 /day*** ***Subtotal:$748/day***		$5.85 million + $748/day × 447 days = ***$6.2 million***	32500 (65000 meters ÷2 meters) × 0.33 (productive rate: 4 labors-hour/each 2 meter) ÷ 24 = 446.87 days
				Total Construction Cost:	

				<u>$6.8 million</u>	

Table 21. Estimated cost for removing vegetation option

	Material	Labor	Equipment	Total	Estimated Construction Period
Site Preparation	Special Designed movable Iron Blockage that can sustain water pressure 2 × $3,000/each = ***$6,000*** Hosepipes	Four Carpenters: 4 × $398.4/day × 65 times = ***$103,584***	1. Backhoe-loader ($415/day, 112HP) = 65 times × $415/day = ***$26,975*** 2. Water Pumps (10 m^3/s = 2,642 gallon/s, and also 600 m^3/min = 158,000 gallon/min) 528 × $4,650/each = ***$2.4 million*** (if siphon is available, this cost would be tremendously decrease, or if more big pump is available, or if we rent pump, the cost would be changed)	$6,000 + $103,584 + $26975 + $2.4 million = ***$2.6 million***	15 days /each × 65 times = 975 days
Site Construction		Assistant Workers (Add hole in bottom or wall of canal with cement: finish work) 4 × $187/day = $***748 /day*** × 10 times/1km ***Subtotal:$7480***	1. Backhoe-loader ($415/day, 112HP) 2. Grader ($420/day, 25,000lb) 1. Brush-chipper ($208/day, 130HP) 2. Dump Trucks $1,050 /day (35 ton Capacity) × 3 = $3150/day Subtotal: ($415/day+$420/day+$208/day+$3150/day) × 975 days = ***$ 4 million***	$7480 + $4.09 million = ***$4.1 million***	
				Total: ***$6.7 million***	

5. NUTRIENT MASS BALANCE FOR THE KING ABDULLAH CANAL

A mass balance analysis of nutrient, sediment, algal and hydrologic inputs into the King Abdullah Canal suggests Yarmouk River is the most important source of nutrients and sediments, Lake Tiberias is the most important source of algae, and despite being a relatively small source of water the Mukeiba Wells are an important source of BOD (see Table 22). These calculations assume that water quality data collected from station M2 represent water coming from Lake Tiberias, however, the phosphate concentrations reported for M2 (i.e. mean = 0.076 mg/l or 76 µg/l) are substantially higher that what has recently been reported for Lake Tiberias surface waters (≈ 10 µg/l) by scientists at the Kinneret Limnological Laboratory (Hadas et al. 1999). This suggests one of three scenarios: 1) Lake Tiberias water is not discharged from the relatively nutrient poor epilimnion (which is probably about 10 m deep) and is instead discharged from more nutrient rich metalimnetic or hypolimnetic waters; 2) the waters discharged from Lake Tiberias pick up additional nutrients before they are discharged to the King Abdullah Canal (for example via agricultural return flows); and/or 3) the water quality data reported from station M2 does not represent pure Lake Tiberias water.

Table 22. A mass balance and volume weighted input constituent concentrations for the King Abdullah Canal.

				% mass loading	
Parameter	Units	Vol. Wt. input conc.	Yarmouk R.	Lake Tiberias	Mukeiba Wells
DIN (NH_4 +NO_3)	(mg/l)	5.3	65.1%	28.7%	6.2%
PO4	(mg/l)	0.143	66.5%	28.8%	4.6%
TP	(mg/l)	0.214	47.5%	40.8%	11.7%
TOC	(mg/l)	2.8	25.5%	65.6%	9.0%
Chl	(µg/l)	4.4	18.1%	74.7%	7.2%
Algae Count	(Unit/ml)	410	8.0%	91.7%	0.3%
Turbidity	(NTU)	167	67.6%	32.4%	0.0%
TSS	(mg/l)	36	50.2%	30.8%	19.0%
BOD	(mg/l)	2.8	30.0%	29.9%	40.0%
Flow	(m^3/s)	3.35	29.3%	54.0%	16.7%

The source mass balance for the King Abdullah Canal suggests the Yarmouk River supplies the nutrient and Lake Tiberias the phytoplankton that subsequently leads to eutrophication in the King Abdullah Canal. However, it should be pointed out that it may not be this simple. Because phytoplankton are able to increase their biomass at very fast a rates (i.e. many species can quadruple their biomass each day when nutrients, light and temperature are at ideal levels) algal inputs from the Yarmouk River and the Mukeiba Wells are more than sufficient to provide the phytoplankton inoculum for a severe algal bloom by the time King Abdullah Canal water reaches station M5 (Deir-Alla). It should also be pointed out that the water quality data for station M2 suggests the water originating from Lake Tiberias is highly nutrient enriched and even these nutrient levels are more than sufficient to result in severe eutrophication in the King Abdullah Canal. The water quality data available for the King Abdullah Canal also suggest substantial water quality degradation occurs along the course of the King Abdullah Canal (which is most likely due to agricultural return flows). For example, from the point were the King Abdullah Canal has received inputs from the Yarmouk River, Lake Tiberias, and the Mukeiba Wells to station M4 (Abu-Seedo) average dissolved nitrogen concentrations have increased by 36% (from 5.3 to 7.2 mg/l) and average phosphate concentrations have increased by 200% (from 0.143 to 0.424 mg/l). In sum, all the sources to the King Abdullah Canal have poor water quality especially for nutrients.

The volume weighted nutrient input concentrations calculated for the King Abdullah Canal (see Table 22) suggest this system is highly eutrophic (actually hypertrophic) with extremely high total and especially soluble phosphorus concentrations. For example, according to Welch (1992, page 169) lake water is typically classified as eutrophic when TP exceeds 0.025-0.030 mg/l which is far lower than observed in the King Abdullah Canal. The incoming nitrogen concentrations are also extremely high, in fact the nitrate concentrations reported for the Yarmouk River (mean = 11.5 mg/l) exceed the level normally considered safe for human consumption (i.e. 10 mg/l). Given these very high nutrient concentrations it will be very difficult to control algal blooms in the King Abdullah Canal under most circumstances, and especially when warm and sunny conditions prevail. In fact, the generally very nutrient rich, warm and sunny conditions that usually exist for the King Abdullah Canal are ideal for supporting massive algal blooms.

Table 23. Standard regression equations relating phytoplankton concentrations (as chlorophyll-a) to total phosphorus supplies and their predicted chlorophyll concentration for the King Abdullah Canal based on a TP concentration of 0.271 mg/l.

Source	Equation	Estimated conc.
Dillon (1974)	$Chl = 0.0724*TP^{1.45}$	244
Megard (1978)	Chl = -7.3 + 1.19*TP	315
Schindler et al (1978)	Chl = 4.2 + 0.58*TP	161
Berge (1980)	Chl = -0.93 + 0.42*TP	113
Edmondson (1981)	Chl = -4.8 + 0.55*TP	144
Mean		196
Standard deviation		83

Given the very high nutrient concentrations reported in the King Abdullah Canal it is quite surprising that much higher chlorophyll concentrations were not in fact reported by the scientists studying water quality there. According to the water quality data for the King Abdullah Canal which was made available to us, station M5 had an average chlorophyll concentration of 13.1 µg/l. We used five regression equations which predicted chlorophyll concentrations as a function of phosphorus supply (Ahlgren et al. 1988) to estimate predicted chlorophyll concentrations at M5 in the King Abdullah Canal (see Table 23). These calculations show much higher chlorophyll concentrations (i.e. 196 ± 83, ± 1 SD) are typically observed in aquatic systems with on average 271 µg TP/l. These expected concentrations are also similar to those predicted for the King Abdullah Canal using both QUAL2E and MIKE 11. This comparison presents the question – "Why weren't the observed chlorophyll concentrations in the King Abdullah Canal higher?" There are several possible answers to this question, first perhaps algal concentrations were indeed higher than reflected by the low reported chlorophyll-a values. For example, the Jordanian scientists may have under reported the actual chlorophyll concentration in the King Abdullah Canal due to unspecified methodological difficulties. However, it should be emphasized that this is pure conjecture as we have no data suggesting this actually was the case. It would be worthwhile to conduct split sample comparisons of the chlorophyll concentrations determined by the Jordanian scientists and for another laboratory to rule out this possibility. Another possibility is the King Abdullah Canal was so highly turbid that phytoplankton in the canal were severely light limited. However, the King Abdullah Canal is shallow (i.e. 2-3 m deep) and the turbidity levels and TSS concentrations reported for the King Abdullah Canal were not so high (i.e. □ 100 NTU and 50 mg/l, respectively) that severe light limitation of suspended phytoplankton would be expected. Another possibility is intense herbivory by rotifer or crustacean zooplankton in the King Abdullah Canal suppressed algal blooms. As far was we are aware no estimates of herbivorous zooplankton biomass in the King Abdullah Canal are available. The marked disconnect between the very high nutrient levels and excellent growth conditions (i.e. high water temperatures and light availability) for phytoplankton in the King Abdullah Canal and the relatively low observed chlorophyll-a concentrations warrants further attention in subsequent investigations. It should also be emphasized that the average reported chlorophyll concentrations for the King Abdullah Canal are sufficiently high to lead to periodic taste and odor problems in drinking water.

6. CONCLUSION AND RECOMMENDATIONS

Water quality problems related to the production of chlorophyll-a have occurred in the King Abdullah Canal. This report has described the application of two water quality models in an attempt to identify the most likely causes of eutrophication and management actions that could be taken to reduce algae production. Section 3 of this report identifies twenty-six combinations of actions that can be taken that would likely lower the level of chlorophyll-a to an acceptable level. All of the scenarios were coupled with alternatives designed to meet a 50 µg/L water quality standard for chlorophyll-a. To define the feasibility of these actions, cost associated with each scenario was estimated. It appeared that scenario1, scenario2, and scenario5 are cost effective. Because the water coming into the King Abdullah Canal is already severely degraded (especially regarding its very high nutrient concentrations) and is apparently further degraded by agricultural return flows, it will take a very concerted and probably very expensive effort to reverse eutrophication and reduce the risk on nuisance algal blooms in the canal.

Appropriate next steps include further validation of the models. This would require further collection of appropriate water quality data in the canal at regular intervals during summer periods.

- The Two models arrived at similar estimated chlorophyll-a levels at Abu Sidu but using different assumptions.
- The most sensitive variables in terms of prediction of chlorophyll-a levels were nutrients, light, and retention time
- A combination of actions is required to lowers the chlorophyll-a levels at Abu Sidu to a 50 µg/l standard.
- Of the scenarios investigated, three appeased to be the most promising. These scenarios are 1) building new municipal wastewater treatment plant (WWTP), 2) covering the top of the canal, and 3) dredging and removing sediment.

- The cost effectiveness of actions was evaluated. The cost effectiveness of the three most appropriate actions were 1,000 USD/m^3 of wastewater treatment plant option, 7.7 USD/m^3 of light control, and 7.8 USD/m^3 of removing vegetation option, respectively.
- The cost of meeting the 50 µg/l target could be as great as $864 million based on average daily flow 864,000 cubic meters.
- Addition data and research to improve these results would include:
    - Model calibration and verification with an observed chlorophyll-a data
    - Detailed flow data for the canal system
    - Experimental studies of canal retention time
    - A more formalize QA/QC protocol for data collected for this project
    - Evaluate the model with well-defined nutrient and water balance
    - Observe the model behavior coupled with non-determined model parameter, such as politic involvement and changed boundary condition

7. REPLY TO INTERCONSULT COMMENTS

In earlier communications regarding our modeling results, Kjell Wesstad of Interconsult posed a series of questions. In general, these questions are very appropriate and useful, and addressing them directly will clarify our report. For these reasons we have provided point by point responses to these questions below. In this section we will sequentially list these questions (which have been paraphrased) and follow each question with a response.

1. "Little King Abdullah Canal data has been used for our model development."

This comment is in large part correct. To build a eutrophication model for the King Abdullah Canal we need information for the parameters that regulate net algal growth. The most important of these are nutrients, light, temperature and grazing. To construct our model we especially needed total and dissolved nitrogen and phosphorus data. For nitrogen dissolved equals nitrate (NO_3^-) plus ammonium (NH_4^+). These data were obtained from the King Abdullah Canal project website. We also needed temperature and water clarity data. We used the King Abdullah Canal project temperature data and the total suspended solids (TSS) data was used to estimate water clarity. Several or the parameters mentioned by Kjell are responses to algal blooms (e.g. dissolved oxygen, pH, TOC, BOD_5) and are therefore not used as input parameters in eutrophication models. UV-absorbance (which is determined by the particulate and dissolved carbon content of the water) is also a response to algal blooms. Conductivity is not an important input or response parameter for eutrophication models. Thus we used all of the King Abdullah Canal project data which was needed for input parameters, and we did not use that data which was for response parameters.

However, we never attempted to use the King Abdullah Canal project day to day data for these parameters to run our models. First to have the necessary input parameters for a model of eutrophication in an irrigation canal with a very short retention time (i.e. on the order of days), we would have to have input data recorded several times a day. This was available for temperature, but was not available for total and dissolved nitrogen and phosphorus which were the most important input parameters. This is not however, a criticism of the King Abdullah Canal field sampling program because it is quite unusual for field sampling programs to collect nutrient data at less than weekly increments. The King Abdullah Canal nitrogen and phosphorus data were in fact collected only every 2-4 weeks, which is typical for most field water quality projects.

While there is a clear mismatch between the temporal scale at which we ran our model (i.e. 1 minute increments for MIKE11, 30 minutes increment for QUAL2E) and the scale at which the most important input data were available (i.e. every two weeks for nutrients), this is not nearly the problem it might initially seem. Our objective with the King Abdullah Canal eutrophication model was to determine whether algal blooms were likely to occur in the Canal for “representative conditions”. By representative conditions we mean the nutrient concentrations, temperature and light availability typically seen in the canal. Based on the King Abdullah Canal field data available to us, we believe we have a very clear picture of what typical conditions are in the canal. In general the water has very high nutrient concentrations (TN □ 6.5 mg/l, TP □ 0.300 mg/l), high temperatures, and is turbid (turbidity □ 100 NTU, TSS □ 50 mg/l). However, because the canal is very shallow (□ 2.3 m) and well mixed, low water clarity does not mean low light availability for the phytoplankton suspended in the canal.

2. “Why is the analyzing period for the model runs only 10 days?”

According to our best information the King Abdullah Canal has a retention time of approximately 3 days. This means that in order to accurately model eutrophication in the canal we need not use a longer time frame than this. However, we found that our model was most stable when we ran our simulations for somewhat longer periods. We choose to run the model for a hypothetical 10 day period in August because it is our understanding that this was when taste and odor problems have been most common in the past and because based on the water temperatures and light availability this is when we would expect some of the best conditions for algal growth.

3. “Little was said in the UW report about retaining/storing water in the canal.”

One of the greatest challenges we have faced is getting accurate flow data for the King Abdullah Canal. We would very much like to know how much water is provided from each source, when it is provided, and how it is moved through the canal. We have tried to get this type of data with little success. We have also received sometimes conflicting information about water sources and the operation of the King Abdullah Canal. We have also heard that because this information is considered politically very sensitive (and perhaps of strategic importance) we might not ever obtain the true values. This type of information would be very valuable but given the political complexities of the King Abdullah Canal region, we understand why obtaining this data is difficult.

Despite the fact that we were never able to obtain accurate flow data, we believe we have a very good idea how retaining/storing water in the canal would impact the potential for algal blooms. The key way that retaining/storing water in the canal would affect algal blooms is via canal retention time. Because the canal has a quite short retention time, compared to lakes which phytoplankton are more commonly found in, the amount of time a given mass of water spends in the canal will have a major impact on how large of a bloom actually develops. In fact, our sensitivity analyses have already shown that canal retention time has a very important impact on the magnitude of algal blooms. From this we predict that any management measures that increase the retention time of water in the King Abdullah Canal will increase the likelihood of severe algal blooms. Storing water in the canal for a few extra days will result in ideal conditions for algal growth! Based on this we recommend moving water through the canal as fast a practical at all times.

4. “You did not discuss the importance of sediments in the King Abdullah Canal.”

In Kjell’s email to us he mentioned that data from one sediment sample was available. Unfortunately, it would be very difficult to make predictions about the nutrient dynamics of the canal based on a very small amount of information. Before we could attempt to incorporate sediment interactions in a King Abdullah Canal eutrophication model, we would need substantially more data.

5. “Little has been said in the report UW about . . . nutrient balance, algae sources, and water source characteristics.”

This information has now been incorporated into a preceding section of the report.

6. “What type of information is needed in the future!”

Several types of information would be invaluable for further attempts to study and model eutrophication and nuisance algal blooms in the King Abdullah Canal. These include precise water input and output data. Specifically when and in what quantities is water supplied to the King Abdullah Canal from the Yarmouk River, Lake Tiberias, and the Mukeiba Wells? Deviations from simple steady state for any of these inputs could have major impacts on the algal dynamics in the canal. In addition, very detailed data on agricultural withdrawals and return flows to the King Abdullah Canal would be extremely useful. Our initial nutrient mass balance suggests agricultural return flows along the canal could be a very large source of nutrients. In addition to this detailed flow information, a short term intensive study using tracers to follow the movement of water in the King Abdullah Canal could be very useful to more precisely determine the retention time of water in the canal. This retention time study would have to be repeated several times under a range of appropriate conditions. For QA/QC purposes it would be quite useful for a range of split water quality samples run by the Jordanian scientists to also be run by another water quality laboratory. This is a general recommendation we would make for any large scale water quality project. It would be very useful to have samples from the King Abdullah Canal for the determination of chlorophyll concentrations, as well as phytoplankton and zooplankton taxa identification and quantification sent out for analyses at another laboratory for verification.

References

Ahlgren, I., Frisk, T., Kamp-Nielsen, L. 1988. Empirical and theoretical models of phosphorus loading, retention and concentration vs. lake trophic state. Hydrobiologia 170: 285-303.

Amery, Hussein A. and Wolf, Aaron T., Water in the Middle East: A Geography of Peace, The University of Texas Press, 2000.

Beck, M.B. "Water quality modeling: A review of the analysis of uncertainty," *Water Resources Research*, 23(5), 1393-1441, 1987.

Brown, L. C., Barnwell, T. O. "The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual", Page 82, USEPA, EPA/600/3-87/007, May, 1987

Elhance, Arun P., Hydropolitics in the 3rd World: Conflict and Cooperation in International River Basins, United States Institute of Peace Press, 1999. Chpt. 3.

EPA websites, http://www.epa.gov/docs/QUAL2E_WINDOWS/metadata.txt.html

Hadas, O., Pinkas, R., Delphine, E., Vardi, A., Kaplan, A., Sukenik, A. 1999. Limnological and ecophysiological aspects of *Aphanizomenon ovalisporum* bloom in Lake Kinneret, Israel. Journal Plankton Res. 21: 1439-1453.

Helyar, F. W., "Construction Estimating and Costing", McGRAW-HILL, 1978

Jorgensen, S.E., "Application of Ecological Modelling in Environmental Management, Part A", Elsevier Scientific Publishing Co. 1983

Jorgensen, S.E., Nielsen, S.N., Jorgensen, L.A, "Handbook of Ecological Parameters and Ecotoxicology", Elsevier, 1991

Linsley, R.K., Kohler, M.A., Paulhus, J. L. H., "Hydrology for Engineering", McGraw-Hill Book Company, 1982

Melching, C. S., Bauwens, W., "Uncertainty in Coupled Nonpoint Source and Stream Water-Quality Models", *Journal of Water Resources and Management*, 127(6), 403-413, 2001

MIKE 11 User Guide " A modeling system for rivers and channel", DHI software, 2001.

MIKE 11 Version 3.11. "EU (Eutrophication) reference manual", 1st Edition, DHI shoftware, 1995

RSMeans, "Building Construction Cost Data, 60th Annual Edition", R.S. Means Company, Inc. 2002

WELCH, E.B. 1992. Ecological Effects of Waterwater, 2nd edition.

APPENDIX A

Table A1. The monthly average flow of water at the Yarmouk, Taberia and Mukhebeh

Unit: m^3

Month	Yarmouk	Taberia/Dajania	Mukhebeh
Jan	5,743,576	0,0	1,518,048
Feb	5,040,576	1,751,242	1,340,237
Mar	2,661,811	5,661,360	1,483,834
April	1,391,990	5,230,051	1,312,589
May	1,982,534	6,286,291	1,259,366
June	1,485,821	5,175,792	1,187,136
July	1,429,661	4,909,594	1,140,394
Aug	2,068,502	4,633,891	1,157,587
Sep	1,785,802	4,360,947	1,407,542
Oct	1,833,667	4,123,690	2,672,352
Total	25,423,940	42,132,858	14,479,085

Table A2. Model parameters and coefficients for QUAL2E

	Parameters		Value		Range
Oxygen	Uptake by Ammonia Oxidation (mg O/mg N)		3.5		3~3.5
	Uptake by Nitrite oxidation (mg O/mg N)		1.2		1~1.2
	Reaeration Coefficient		1.5		>=0
Algae	Oxygen production by growth (mg O /mg A)		1.6		1.4~1.8
	Oxygen uptake by respiration (mg O/mg A)		2.0		1.6~2.3
	Nitrogen content (mg N/mg A)		0.085		0.08~0.09
	Phosphorus content (mg P/mgA)		0.012		0.012~0.02
	Maximum specificgrowth rate (1/day)		2.5		1~3
	Respiration rate (1/day)		0.1		0.05~0.5
	Settling rate (/day)		0.15		0~0.914
	Chl~a Algae (ug/mg A)		50		1~100
	P release from sediment (mg/m^2~day)		1		>=0
	N release from sediment (mg/m^2~day)		4		>=0
	Nitrogen Half Saturation coefficient		0.3		0.02~0.04
	Phosphorus Half saturation coefficient		0.04		0.001~0.1
	Linear coeff.		0.0088		0~0.00984
	Nonlinear coeff. (1/m –(ug~Chal/L)^2/3)		0.054		0~0.1968
Light	Saturation Coefficient. (Langley~min)		0.03		0~0.004
	Number of daylight hours		14		4~18
	Daily radiation (Langley)		400		0~400
	Algae preference factor for NH3		0.9		0.01~0.9
	Nitrification inhibition coefficient		0.6		0~10
	Light Extinction Coeff (1/m)		0.2		0~32.8
Temperature	BOD	Decay	1.047		0.001~2

		Settling	1.0		0.001~2
	DO	Reaeration	1.0159		0.001~2
		SOD uptake	1.06		0.001~2
	Nitrogen	Organic N decay	1.047		0.001~2
		Organic N settling	1.0		0.001~2
		Ammonia decay	1.047		0.001~2
		Ammonia source	1.0		0.001~2
		Nitrite decay	1.047		0.001~2
	Phosphorus	Organic P Decay	1.047		0.001~2
		Organic P Settling	1.0		0.001~2
		Dissolved P source	1.0		0.001~2
	Algae	Growth	1.047		0.001~2
		Respiration	1.047		0.001~2
		Settling	1.0		0.001~2

Table A3. Eutrophication module parameters and coefficients for MIKE 11

Benthic Vegetation	Benthic slouching rate at 20 deg. C (0.01~0.2)	0.015 Day^{-1}	
	Production rate of benthic vegetation Range (0.05~0.5)	0.23 Day^{-1}	
	Ecosystem specific parameters	.Minimum conc. Of benthic vegetation	0.1
		Temp.dep. for benthic slouching rate	1.04
		Temp. dep. For production rate of benthic vegetation	1.04
		N/C ration for benthic N slouching rate	0.14
		P/C ration for benthic P slouching rate	0.03
	Physical parameters	Half saturation constant for N in benthic vegetation	0.5
		Half saturation constant for P in benthic vegetation	0.15
		Response rate of benthic vegetation at 20 deg	0
Light Extinction	Light extinction constant for phytoplankton	20	
	Light extinction constant for detritus	0.1	
	Light extinction background constant range	0.2	
	Light extinction constant for benthic vegetation	1	
Oxygen	Reaeration constant for dissolved oxygen	1.5	
	Ecosystem specific parameter	Half saturation constant for dissolved oxygen	2
		Oxygen consumption during detritus mineralis	3.5
Detritus	Detritus C mineralisation rate at 20 deg.	0.03	
	Sedimentation rate, for depth <2m	0.055	
	Sedimentation rate, for depth >2m	0.03	
	Ecosystem/environ. Specific param.	Temp. dep.for carbon mineralisation rate	1.04
		Corr. Factor for release of N from detritus	1

		Corr.factor for rlease of P from detritus	2
Phytoplankton	Maximum growth rate for diatom at 5 deg.	1.3	
	Max. growth rate for Green Algae at 20 deg.	1.8	
	Sedimentation rate, for depth <2m	0.3	
	Sedimentation rate, for depth >2m	0.15	
	Maximum grazing rate at 20 deg. C	1	
	Max. death rate for starving phytoplankton	0.05	
	Ecosystem specific parameters	Temp. dep. Para. For growth rate of Diatoms	1.04
		Temp. dep. Parrm. For Green Algae growth rate	1.04
		Grazing rate on phytoplankton availability	25
		Factor describing dependence of grazing	3
		Temp. dependence of maximum grazing rate	1.04
		Dayno. For shift to Diatom dominans	1
		Dayno. For shift to Green Algae dominans	110
		Minimum chlorophyll-a production	0.07
		Maximum chlorophyll-a production	1.7
	Physiological parameters	Minimum conc. Of nitrogen in phytoplankton	0.07
		Maximum conc. Of nitrogen in phytoplankton	0.17
		Min. conc. Of phosphorus in phytoplankton	0.002
		Max. conc. Of phosphorus in phytoplankton	0.03
		Half saturation conc. For phosphorus	0.005
		Dep. Of N uptake rate on N availability	5
		Dep. Of P uptake rate on P availability	5
		Fraction of nutrients released under decay	0.3
		Correction for dark reaction	1.33
		Light saturation intensity at 20 deg. C	23
		Temp. dep. For light saturation intensity	1.04
Sediment	Prop. Factor for N release from sediment	1.1	
	Prop. Factor for P release from sediment	1.15	
	Prop. Factor for sediment respiration	1.75	

	Ecosystem specific parameters	Temp. dep. For sediment N release rate	1.04
		Temp. dep. For sediment P release rate	1.04
		Sediment N rel. rate under anaerobic cond.	1
		Sediment P rel. rate under anaerobic cond.	1
		Temp. dep. For sediment respiration rate	1.04
Zooplankton	Death rate constant(m3/g/d)	7.5	
	Death rate constant(/d)	0.07	
	Physiological parameters	Zooplankton growth efficiency	0.25
		Nitrogen to carbon ratio in zooplankton	0.07
		Phosphorus to carbon ratio in zooplankton	0.002
		Prop.const.for zooplankton respiration rate	0.3

Table A4. Model parameters and coefficients of QUAL2E for Status Quo

	Parameters		Value		Range
Oxygen	Uptake by Ammonia Oxidation (mg O/mg N)		3.5		3~3.5
	Uptake by Nitrite oxidation (mg O/mg N)		1.2		1~1.2
	Reaeration Coefficient		1.5		>=0
Algae	Oxygen production by growth (mg O /mg A)		1.6		1.4~1.8
	Oxygen uptake by respiration (mg O/mg A)		2.0		1.6~2.3
	Nitrogen content (mg N/mg A)		0.085		0.08~0.09
	Phosphorus content (mg P/mgA)		0.012		0.012~0.02
	Maximum specificgrowth rate (1/day)		2.4		1~3
	Respiration rate (1/day)		0.1		0.05~0.5
	Settling rate (/day)		0.15		0~0.914
	Chl~a Algae (ug/mg A)		20		1~100
	P release from sediment (mg/m^2~day)		1		>=0
	N release from sediment (mg/m^2~day)		4		>=0
	Nitrogen Half Saturation coefficient		0.3		0.02~0.04
	Phosphorus Half saturation coefficient		0.04		0.001~0.1
	Linear coeff.		0.00268		0~0.00984
	Nonlinear coeff. (1/m –(ug~Chal/L)^2/3)		0.0165		0~0.1968
Light	Saturation Coefficient. (Langley~min)		0.03		0~0.004
	Number of daylight hours		15		4~18
	Daily radiation (Langley)		400		0~400
	Algae preference factor for NH3		0.9		0.01~0.9
	Nitrification inhibition coefficient		0.6		0~10
	Light Extinction Coeff (1/m)		0.2		0~32.8
Temperature	BOD	Decay	1.047		0.001~2
		Settling	1.0		0.001~2
	DO	Reaeration	1.0159		0.001~2
		SOD uptake	1.06		0.001~2
	Nitrogen	Organic N decay	1.047		0.001~2
		Organic N settling	1.024		0.001~2
		Ammonia decay	1.083		0.001~2
		Ammonia source	1.074		0.001~2
		Nitrite decay	1.047		0.001~2
	Phosphorus	Organic P Decay	1.047		0.001~2
		Organic P Settling	1.024		0.001~2
		Dissolved P source	1.074		0.001~2
	Algae	Growth	1.047		0.001~2
		Respiration	1.047		0.001~2
		Settling	1.024		0.001~2

APPENDIX B

Table B1. Parameter table of 2^k factorial Design for MIKE 11

	Manning	Zooplankton	Detritus	Light	Phytoplankton						
RUN#	n	VEFO (GE)	KMDM (MR)	PLA (Is)	MYMG (Gmax)	KGRB (Graz)	KDMA (Death)	KC(Kp)	KNI	VM (Fmin)	FAC (CorD)
1	0.05	0.3	0.06	6	2.5	1.8	0.2	0.005	50	0.175	5
2	0.05	0.1	0.06	6	2.5	0.45	0.2	0.02	100	0.7	10
3	0.05	0.3	0.06	6	1	0.45	0.2	0.005	100	0.175	10
4	0.0125	0.1	0.06	24	2.5	0.45	0.2	0.02	50	0.7	10
5	0.05	0.3	0.06	24	1	0.45	0.005	0.005	50	0.175	10
6	0.0125	0.1	0.06	6	1	0.45	0.2	0.005	100	0.7	5
7	0.0125	0.3	0.015	24	2.5	0.45	0.2	0.02	50	0.7	5
8	0.05	0.3	0.015	6	1	0.45	0.2	0.02	50	0.7	10
9	0.05	0.1	0.06	24	2.5	1.8	0.005	0.005	100	0.7	10
10	0.05	0.1	0.06	6	2.5	1.8	0.005	0.005	100	0.7	10
11	0.05	0.1	0.06	24	2.5	0.45	0.005	0.005	100	0.175	5
12	0.05	0.3	0.06	24	2.5	1.8	0.005	0.005	100	0.175	5
13	0.05	0.1	0.06	24	1	1.8	0.2	0.02	100	0.7	5
14	0.05	0.3	0.015	6	1	0.45	0.2	0.02	100	0.175	5
15	0.0125	0.3	0.015	6	2.5	1.8	0.2	0.02	50	0.175	5
16	0.0125	0.1	0.015	6	2.5	1.8	0.005	0.005	100	0.7	10
17	0.05	0.1	0.06	6	2.5	0.45	0.005	0.02	100	0.7	10
18	0.0125	0.1	0.06	24	1	0.45	0.2	0.02	50	0.175	10
19	0.05	0.1	0.06	24	1	1.8	0.005	0.02	50	0.7	5
20	0.0125	0.1	0.015	6	1	1.8	0.005	0.02	100	0.175	5
21	0.05	0.1	0.015	24	1	1.8	0.005	0.005	100	0.7	10
22	0.05	0.3	0.015	24	1	0.45	0.2	0.02	100	0.7	5
23	0.05	0.3	0.015	6	1	1.8	0.005	0.005	50	0.175	10
24	0.0125	0.3	0.06	6	1	0.45	0.2	0.005	100	0.7	5
25	0.0125	0.1	0.06	24	1	0.45	0.2	0.005	50	0.7	5
26	0.0125	0.1	0.06	24	2.5	1.8	0.2	0.02	100	0.175	5
27	0.05	0.3	0.015	6	2.5	1.8	0.005	0.02	50	0.175	5
28	0.0125	0.1	0.06	6	2.5	0.45	0.005	0.005	50	0.7	10
29	0.0125	0.3	0.06	24	2.5	1.8	0.2	0.02	50	0.7	10
30	0.0125	0.1	0.06	6	1	1.8	0.2	0.005	50	0.175	10
31	0.05	0.3	0.015	24	1	0.45	0.2	0.005	50	0.175	10
32	0.0125	0.1	0.06	6	2.5	1.8	0.005	0.02	50	0.175	5
33	0.0125	0.1	0.06	24	1	1.8	0.005	0.005	100	0.7	5
34	0.0125	0.1	0.015	6	1	0.45	0.2	0.005	50	0.7	5
35	0.0125	0.1	0.015	24	2.5	0.45	0.2	0.005	50	0.175	5
36	0.05	0.3	0.015	6	2.5	0.45	0.005	0.02	100	0.175	5
37	0.05	0.3	0.06	24	1	0.45	0.2	0.005	50	0.7	5
38	0.05	0.3	0.06	24	2.5	1.8	0.2	0.02	100	0.175	5
39	0.0125	0.3	0.06	6	2.5	1.8	0.005	0.005	50	0.7	5
40	0.05	0.1	0.015	24	1	0.45	0.005	0.005	100	0.175	10
41	0.05	0.1	0.015	6	2.5	1.8	0.2	0.02	50	0.175	10
42	0.0125	0.1	0.06	6	1	1.8	0.005	0.02	50	0.175	10
43	0.05	0.1	0.015	6	2.5	1.8	0.005	0.005	100	0.175	5
44	0.05	0.1	0.06	24	2.5	1.8	0.005	0.005	50	0.7	10
45	0.05	0.3	0.015	6	1	1.8	0.005	0.02	100	0.7	5
46	0.05	0.3	0.06	6	2.5	1.8	0.005	0.02	50	0.175	10
47	0.05	0.1	0.015	6	1	0.45	0.005	0.005	100	0.175	10
48	0.05	0.3	0.015	24	1	0.45	0.005	0.02	50	0.175	10

49	0.05	0.1	0.015	24	2.5	0.45	0.005	0.02	50	0.7	5
50	0.0125	0.1	0.06	6	1	0.45	0.2	0.005	50	0.7	5
51	0.05	0.1	0.015	24	2.5	1.8	0.005	0.02	100	0.7	5
52	0.0125	0.3	0.06	24	1	1.8	0.2	0.02	50	0.175	10
53	0.0125	0.3	0.015	24	1	1.8	0.2	0.005	100	0.7	5
54	0.0125	0.1	0.06	6	2.5	0.45	0.2	0.02	100	0.7	10
55	0.05	0.1	0.015	24	2.5	0.45	0.2	0.005	50	0.7	10
56	0.0125	0.3	0.015	24	1	1.8	0.005	0.02	100	0.7	5
57	0.0125	0.3	0.06	6	1	0.45	0.005	0.02	100	0.7	5
58	0.05	0.1	0.015	24	2.5	1.8	0.2	0.005	100	0.175	5
59	0.0125	0.1	0.06	24	1	0.45	0.005	0.02	50	0.175	10
60	0.05	0.1	0.015	24	2.5	1.8	0.2	0.005	100	0.7	5
61	0.0125	0.3	0.06	24	1	1.8	0.2	0.005	50	0.7	10
62	0.05	0.1	0.06	24	2.5	0.45	0.005	0.02	50	0.7	10
63	0.05	0.3	0.06	6	2.5	0.45	0.005	0.02	100	0.175	5
64	0.0125	0.1	0.06	6	1	1.8	0.2	0.02	100	0.7	5
65	0.0125	0.1	0.06	24	1	0.45	0.005	0.005	50	0.7	5
66	0.0125	0.3	0.015	24	2.5	0.45	0.2	0.005	50	0.175	5
67	0.05	0.3	0.015	24	1	1.8	0.2	0.02	50	0.7	10
68	0.0125	0.3	0.06	6	1	1.8	0.005	0.02	50	0.175	10
69	0.05	0.3	0.015	6	2.5	1.8	0.2	0.005	50	0.175	5
70	0.05	0.1	0.015	24	2.5	0.45	0.2	0.02	100	0.175	5
71	0.05	0.1	0.015	6	2.5	0.45	0.2	0.02	100	0.7	5
72	0.05	0.1	0.06	24	2.5	0.45	0.005	0.02	100	0.7	10
73	0.05	0.3	0.06	24	2.5	1.8	0.005	0.02	50	0.175	10
74	0.05	0.1	0.015	24	2.5	0.45	0.005	0.02	50	0.7	10
75	0.0125	0.1	0.06	24	1	0.45	0.005	0.02	50	0.175	5
76	0.0125	0.1	0.015	6	1	0.45	0.005	0.005	50	0.7	5
77	0.05	0.1	0.015	6	2.5	0.45	0.2	0.005	50	0.175	10
78	0.05	0.3	0.015	6	1	1.8	0.2	0.02	50	0.7	10
79	0.05	0.3	0.015	6	1	0.45	0.005	0.005	50	0.7	5
80	0.0125	0.3	0.06	6	1	1.8	0.2	0.005	50	0.7	5
81	0.05	0.3	0.06	6	2.5	0.45	0.2	0.005	100	0.175	5
82	0.05	0.3	0.06	24	2.5	0.45	0.005	0.005	50	0.7	5
83	0.05	0.1	0.06	24	1	1.8	0.2	0.02	50	0.175	5
84	0.0125	0.1	0.06	24	2.5	0.45	0.2	0.02	100	0.7	10
85	0.0125	0.1	0.015	24	2.5	1.8	0.2	0.005	100	0.175	5
86	0.0125	0.1	0.06	6	2.5	0.45	0.005	0.005	50	0.175	5
87	0.05	0.1	0.015	24	2.5	1.8	0.005	0.005	50	0.175	10
88	0.05	0.1	0.06	6	2.5	1.8	0.2	0.02	100	0.7	10
89	0.0125	0.1	0.06	6	1	0.45	0.005	0.02	50	0.175	10
90	0.0125	0.1	0.015	24	1	0.45	0.2	0.02	100	0.7	5
91	0.0125	0.1	0.06	6	2.5	1.8	0.005	0.02	50	0.7	10
92	0.05	0.1	0.06	24	2.5	1.8	0.005	0.005	100	0.175	5
93	0.05	0.3	0.06	6	2.5	0.45	0.2	0.02	50	0.7	10
94	0.0125	0.1	0.015	24	1	1.8	0.2	0.005	100	0.7	5
95	0.0125	0.1	0.015	6	1	1.8	0.2	0.02	50	0.7	10
96	0.05	0.1	0.06	6	1	1.8	0.2	0.02	100	0.7	5
97	0.0125	0.1	0.015	24	1	1.8	0.005	0.02	100	0.175	5
98	0.05	0.3	0.015	24	1	1.8	0.2	0.005	100	0.175	10
99	0.0125	0.1	0.06	6	1	0.45	0.005	0.02	100	0.175	10
100	0.0125	0.3	0.015	6	2.5	0.45	0.2	0.005	50	0.175	5
101	0.05	0.3	0.015	24	1	0.45	0.005	0.005	50	0.7	5
102	0.05	0.3	0.015	6	1	0.45	0.005	0.005	100	0.7	5

Table B2. Parameter table of 2^k factorial Design for QUAL2E

RUN#	O2 prod algal growth (α_3)	O2 uptake algal resp (α_4)	Max G phyto (U_{max})	Resp phyto (ρ)	Half sat N (K_N)	Half sat P (K_P)	Linear algal self shading coefficient (λ)	Half sat. light (K_L)	Manning (n)	Sett phyto ($\sigma 1$)	Non-algal light extinction coefficient (λ)
1	1.4	1.6	3	0.05	0.04	0.02	0.009	0.001	0.05	0.5	0.2
2	1.8	2.3	3	0.4	0.2	0.06	0.009	0.001	0.05	0.1	30
3	1.8	1.6	1	0.4	0.04	0.02	0.009	0.001	0.05	0.1	0.2
4	1.8	2.3	3	0.05	0.2	0.06	0.009	0.007	0.0125	0.1	30
5	1.8	1.6	1	0.05	0.04	0.02	0.009	0.007	0.05	0.1	0.2
6	1.4	2.3	1	0.4	0.04	0.02	0.009	0.001	0.0125	0.1	30
7	1.4	1.6	3	0.05	0.2	0.06	0.002	0.007	0.0125	0.1	30
8	1.8	1.6	1	0.05	0.2	0.06	0.002	0.001	0.05	0.1	30
9	1.8	2.3	3	0.4	0.04	0.02	0.009	0.007	0.05	0.5	30
10	1.8	2.3	3	0.4	0.04	0.02	0.009	0.001	0.05	0.5	30
11	1.4	2.3	3	0.4	0.04	0.02	0.009	0.007	0.05	0.1	0.2
12	1.4	1.6	3	0.4	0.04	0.02	0.009	0.007	0.05	0.5	0.2
13	1.4	2.3	1	0.4	0.2	0.06	0.009	0.007	0.05	0.5	30
14	1.4	1.6	1	0.4	0.2	0.06	0.002	0.001	0.05	0.1	0.2
15	1.4	1.6	3	0.05	0.2	0.06	0.002	0.001	0.0125	0.5	0.2
16	1.8	2.3	3	0.4	0.04	0.02	0.002	0.001	0.0125	0.5	30
17	1.8	2.3	3	0.4	0.2	0.06	0.009	0.001	0.05	0.1	30
18	1.8	2.3	1	0.05	0.2	0.06	0.009	0.007	0.0125	0.1	0.2
19	1.4	2.3	1	0.05	0.2	0.06	0.009	0.007	0.05	0.5	30
20	1.4	2.3	1	0.4	0.2	0.06	0.002	0.001	0.0125	0.5	0.2
21	1.8	2.3	1	0.4	0.04	0.02	0.002	0.007	0.05	0.5	30
22	1.4	1.6	1	0.4	0.2	0.06	0.002	0.007	0.05	0.1	30
23	1.8	1.6	1	0.05	0.04	0.02	0.002	0.001	0.05	0.5	0.2
24	1.4	1.6	1	0.4	0.04	0.02	0.009	0.001	0.0125	0.1	30
25	1.4	2.3	1	0.05	0.04	0.02	0.009	0.007	0.0125	0.1	30
26	1.4	2.3	3	0.4	0.2	0.06	0.009	0.007	0.0125	0.5	0.2
27	1.4	1.6	3	0.05	0.2	0.06	0.002	0.001	0.05	0.5	0.2
28	1.8	2.3	3	0.05	0.04	0.02	0.009	0.001	0.0125	0.1	30
29	1.8	1.6	3	0.05	0.2	0.06	0.009	0.007	0.0125	0.5	30
30	1.8	2.3	1	0.05	0.04	0.02	0.009	0.001	0.0125	0.5	0.2
31	1.8	1.6	1	0.05	0.04	0.02	0.002	0.007	0.05	0.1	0.2
32	1.4	2.3	3	0.05	0.2	0.06	0.009	0.001	0.0125	0.5	0.2
33	1.4	2.3	1	0.4	0.04	0.02	0.009	0.007	0.0125	0.5	30
34	1.4	2.3	1	0.05	0.04	0.02	0.002	0.001	0.0125	0.1	30
35	1.4	2.3	3	0.05	0.04	0.02	0.002	0.007	0.0125	0.1	0.2
36	1.4	1.6	3	0.4	0.2	0.06	0.002	0.001	0.05	0.1	0.2
37	1.4	1.6	1	0.05	0.04	0.02	0.009	0.007	0.05	0.1	30
38	1.4	1.6	3	0.4	0.2	0.06	0.009	0.007	0.05	0.5	0.2
39	1.4	1.6	3	0.05	0.04	0.02	0.009	0.001	0.0125	0.5	30
40	1.8	2.3	1	0.4	0.04	0.02	0.002	0.007	0.05	0.1	0.2
41	1.8	2.3	3	0.05	0.2	0.06	0.002	0.001	0.05	0.5	0.2
42	1.8	2.3	1	0.05	0.2	0.06	0.009	0.001	0.0125	0.5	0.2
43	1.4	2.3	3	0.4	0.04	0.02	0.002	0.001	0.05	0.5	0.2
44	1.8	2.3	3	0.05	0.04	0.02	0.009	0.007	0.05	0.5	30
45	1.4	1.6	1	0.4	0.2	0.06	0.002	0.001	0.05	0.5	30
46	1.8	1.6	3	0.05	0.2	0.06	0.009	0.001	0.05	0.5	0.2
47	1.8	2.3	1	0.4	0.04	0.02	0.002	0.001	0.05	0.1	0.2
48	1.8	1.6	1	0.05	0.2	0.06	0.002	0.007	0.05	0.1	0.2

49	1.4	2.3	3	0.05	0.2	0.06	0.002	0.007	0.05	0.1	30
50	1.4	2.3	1	0.05	0.04	0.02	0.009	0.001	0.0125	0.1	30
51	1.4	2.3	3	0.4	0.2	0.06	0.002	0.007	0.05	0.5	30
52	1.8	1.6	1	0.05	0.2	0.06	0.009	0.007	0.0125	0.5	0.2
53	1.4	1.6	1	0.4	0.04	0.02	0.002	0.007	0.0125	0.5	30
54	1.8	2.3	3	0.4	0.2	0.06	0.009	0.001	0.0125	0.1	30
55	1.8	2.3	3	0.05	0.04	0.02	0.002	0.007	0.05	0.1	30
56	1.4	1.6	1	0.4	0.2	0.06	0.002	0.007	0.0125	0.5	30
57	1.4	1.6	1	0.4	0.2	0.06	0.009	0.001	0.0125	0.1	30
58	1.4	2.3	3	0.4	0.04	0.02	0.002	0.007	0.05	0.5	0.2
59	1.8	2.3	1	0.05	0.2	0.06	0.009	0.007	0.0125	0.1	0.2
60	1.4	2.3	3	0.4	0.04	0.02	0.002	0.007	0.05	0.5	30
61	1.8	1.6	1	0.05	0.04	0.02	0.009	0.007	0.0125	0.5	30
62	1.8	2.3	3	0.05	0.2	0.06	0.009	0.007	0.05	0.1	30
63	1.4	1.6	3	0.4	0.2	0.06	0.009	0.001	0.05	0.1	0.2
64	1.4	2.3	1	0.4	0.2	0.06	0.009	0.001	0.0125	0.5	30
65	1.4	2.3	1	0.05	0.04	0.02	0.009	0.007	0.0125	0.1	30
66	1.4	1.6	3	0.05	0.04	0.02	0.002	0.007	0.0125	0.1	0.2
67	1.8	1.6	1	0.05	0.2	0.06	0.002	0.007	0.05	0.5	30
68	1.8	1.6	1	0.05	0.2	0.06	0.009	0.001	0.0125	0.5	0.2
69	1.4	1.6	3	0.05	0.04	0.02	0.002	0.001	0.05	0.5	0.2
70	1.4	2.3	3	0.4	0.2	0.06	0.002	0.007	0.05	0.1	0.2
71	1.4	2.3	3	0.4	0.2	0.06	0.002	0.001	0.05	0.1	30
72	1.8	2.3	3	0.4	0.2	0.06	0.009	0.007	0.05	0.1	30
73	1.8	1.6	3	0.05	0.2	0.06	0.009	0.007	0.05	0.5	0.2
74	1.8	2.3	3	0.05	0.2	0.06	0.002	0.007	0.05	0.1	30
75	1.4	2.3	1	0.05	0.2	0.06	0.009	0.007	0.0125	0.1	0.2
76	1.4	2.3	1	0.05	0.04	0.02	0.002	0.001	0.0125	0.1	30
77	1.8	2.3	3	0.05	0.04	0.02	0.002	0.001	0.05	0.1	0.2
78	1.8	1.6	1	0.05	0.2	0.06	0.002	0.001	0.05	0.5	30
79	1.4	1.6	1	0.05	0.04	0.02	0.002	0.001	0.05	0.1	30
80	1.4	1.6	1	0.05	0.04	0.02	0.009	0.001	0.0125	0.5	30
81	1.4	1.6	3	0.4	0.04	0.02	0.009	0.001	0.05	0.1	0.2
82	1.4	1.6	3	0.05	0.04	0.02	0.009	0.007	0.05	0.1	30
83	1.4	2.3	1	0.05	0.2	0.06	0.009	0.007	0.05	0.5	0.2
84	1.8	2.3	3	0.4	0.2	0.06	0.009	0.007	0.0125	0.1	30
85	1.4	2.3	3	0.4	0.04	0.02	0.002	0.007	0.0125	0.5	0.2
86	1.4	2.3	3	0.05	0.04	0.02	0.009	0.001	0.0125	0.1	0.2
87	1.8	2.3	3	0.05	0.04	0.02	0.002	0.007	0.05	0.5	0.2
88	1.8	2.3	3	0.4	0.2	0.06	0.009	0.001	0.05	0.5	30
89	1.8	2.3	1	0.05	0.2	0.06	0.009	0.001	0.0125	0.1	0.2
90	1.4	2.3	1	0.4	0.2	0.06	0.002	0.007	0.0125	0.1	30
91	1.8	2.3	3	0.05	0.2	0.06	0.009	0.001	0.0125	0.5	30
92	1.4	2.3	3	0.4	0.04	0.02	0.009	0.007	0.05	0.5	0.2
93	1.8	1.6	3	0.05	0.2	0.06	0.009	0.001	0.05	0.1	30
94	1.4	2.3	1	0.4	0.04	0.02	0.002	0.007	0.0125	0.5	30
95	1.8	2.3	1	0.05	0.2	0.06	0.002	0.001	0.0125	0.5	30
96	1.4	2.3	1	0.4	0.2	0.06	0.009	0.001	0.05	0.5	30
97	1.4	2.3	1	0.4	0.2	0.06	0.002	0.007	0.0125	0.5	0.2
98	1.8	1.6	1	0.4	0.04	0.02	0.002	0.007	0.05	0.5	0.2
99	1.8	2.3	1	0.4	0.2	0.06	0.009	0.001	0.0125	0.1	0.2
100	1.4	1.6	3	0.05	0.04	0.02	0.002	0.001	0.0125	0.1	0.2

101	1.4	1.6	1	0.05	0.04	0.02	0.002	0.007	0.05	0.1	30
102	1.4	1.6	1	0.4	0.04	0.02	0.002	0.001	0.05	0.1	30

APPENDIX C

Table C1. Statistic Analysis for MIKE 11 Sensitivity

```
      *** Analysis of Variance Model for MIKE11 ***

Short Output:
Call:
   aov(formula = RUN ~ n + VEFO + KMDM + PLA + MYMG + KGRB + KDMA + KC + KNI + VM + FAC + n
* VEFO * KMDM * PLA * MYMG * KGRB * KDMA * KC * KNI * VM * FAC,data = DS41, na.action =
na.exclude df)
```

Effects (Main + Interaction)	Sum of Square	Effects (Main + Interaction)	Sum of Square
n	**278.246 (3%)**	KDMA:KC	6.373
VEFO	186.758	n:KNI	0.692
KMDM	205.706	VEFO:KNI	13.235
PLA	**6173.09(62%)**	KMDM:KNI	0.25
MYMG	**1500.988 (15%)**	PLA:KNI	39.264
KGRB	29.598	MYMG:KNI	3.176
KDMA	3.931	KGRB:KNI	0.647
KC	2.771	KDMA:KNI	13.434
KNI	95.787	KC:KNI	9.016
VM	41.25	n:VM	13.121
FAC	1091.01	VEFO:VM	3.259
n:VEFO	0.317	KMDM:VM	2.611
n:KMDM	15.37	PLA:VM	0.5
VEFO:KMDM	3.043	MYMG:VM	1.178
n:PLA	55.392	KGRB:VM	0.723
VEFO:PLA	35.19	KDMA:VM	0.854
KMDM:PLA	0.101	KC:VM	0.006
n:MYMG	0.49	KNI:VM	0.533
VEFO:MYMG	9.071	n:FAC	5.885
KMDM:MYMG	0.44	VEFO:FAC	0.361
PLA:MYMG	36.096	KMDM:FAC	0.034
n:KGRB	1.605	PLA:FAC	36.474
VEFO:KGRB	4.915	MYMG:FAC	40.029
KMDM:KGRB	4.538	KGRB:FAC	0.429
PLA:KGRB	0.207	KDMA:FAC	0.072
MYMG:KGRB	0.545	KC:FAC	0.012
n:KDMA	0.05	KNI:FAC	3.15
VEFO:KDMA	12.814	VM:FAC	0
KMDM:KDMA	0.007	n:VEFO:KMDM	2.727
PLA:KDMA	0.006	n:VEFO:PLA	1.259
MYMG:KDMA	0.369	n:KMDM:PLA	0.485
KGRB:KDMA	2.548	VEFO:KMDM:PLA	0.212
n:KC	0.017	n:VEFO:MYMG	1.538
VEFO:KC	1.01	n:KMDM:MYMG	5.479
KMDM:KC	1.282	VEFO:KMDM:MYMG	1.526
PLA:KC	1.416	n:PLA:MYMG	0.062
MYMG:KC	8.298	VEFO:PLA:MYMG	2.621
KGRB:KC	5.105	KMDM:PLA:MYMG	0.448
n:VEFO:KGRB	12.266	VEFO:PLA:KGRB	0.59

n:KMDM:KGRB	0.075	KMDM:PLA:KGRB	10.144
VEFO:KMDM:KGRB	1.095	n:MYMG:KGRB	0.977
n:PLA:KGRB	2.303		0.59

Table C2. Statistic Analysis for QUAL2E Sensitivity

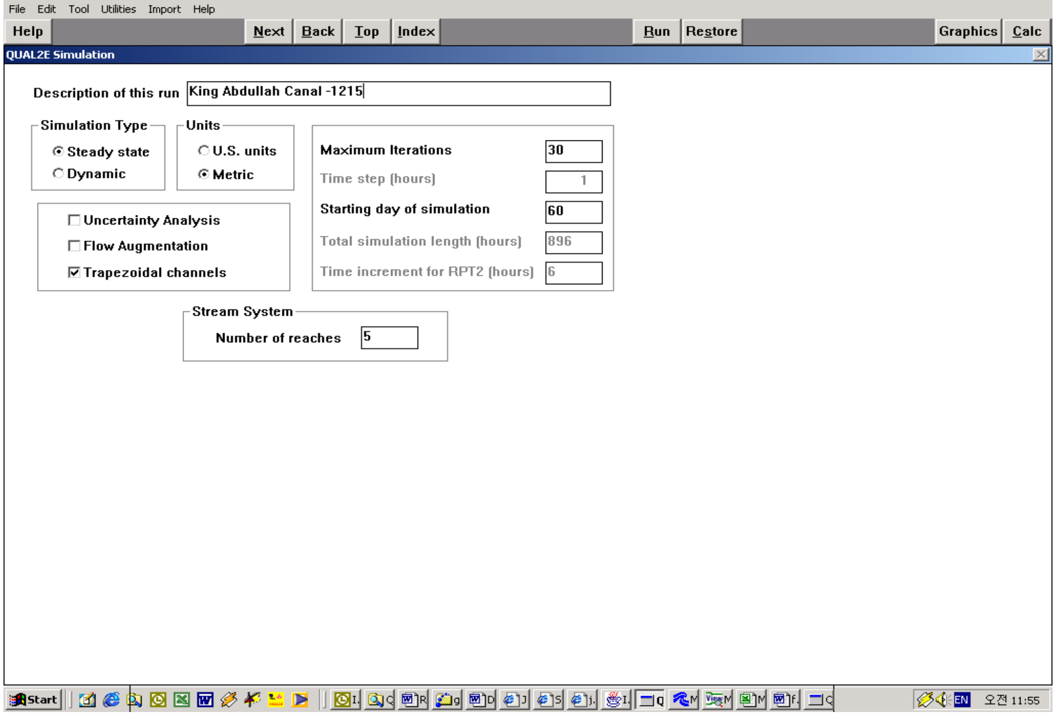
```
*** Analysis of Variance Model for QUAL2E ***
Short Output:
Call: aov(formula = run ~ . + o2pa * o2ua * maxG * resp * halfN * halfP * lineara * halfL *
manningN * sett * ext, data = DS54, na.action = na.exclude)
```

Effects (Main + Interaction)	Sum of Square	Effects (Main + Interaction)	Sum of Square
o2pa	35616.9	resp:sett	50932
o2ua	37604.9	halfN:sett	1793.9
maxG	**731564.9(21%)**	lineara:sett	62494.8
resp	12600.6	halfL:sett	6714.6
halfN	6366.3	manningN:sett	58629.6
halfP	412.6	o2pa:ext	615.4
lineara	60895.1	o2ua:ext	16471.2
halfL	42208.4	maxG:ext	248639.7
manningN	**233278.3 (7%)**	resp:ext	4960.7
sett	110858.7	halfN:ext	5232.3
ext	**705104.5 (20%)**	lineara:ext	3866.4
o2pa:o2ua	22945.7	halfL:ext	1426.7
o2pa:maxG	108693.9	manningN:ext	112753.5
o2ua:maxG	26781.7	sett:ext	931.5
o2pa:resp	87111.4	o2pa:o2ua:maxG	54964.3
o2ua:resp	32	o2pa:o2ua:resp	53.9
maxG:resp	3808.3	o2pa:maxG:resp	124.6
o2pa:halfN	30871.8	o2ua:maxG:resp	2572.1
o2ua:halfN	13275.2	o2pa:o2ua:halfN	14235
maxG:halfN	22970.7	o2pa:maxG:halfN	1523.4
resp:halfN	4604.6	o2ua:maxG:halfN	5943.1
o2pa:lineara	38366.5	o2pa:resp:halfN	114.8
o2ua:lineara	26859.3	o2ua:resp:halfN	4109.4
maxG:lineara	89296.4	maxG:resp:halfN	186.1
resp:lineara	9773.8	o2pa:o2ua:lineara	118.5
halfN:lineara	38833.8	o2pa:maxG:lineara	686.7
o2pa:halfL	12690.5	o2ua:maxG:lineara	6833.7
o2ua:halfL	122.1	o2pa:resp:lineara	824.6
maxG:halfL	85480.3	o2ua:resp:lineara	13747.6
resp:halfL	10586.1	maxG:resp:lineara	266.1
halfN:halfL	184.4	o2pa:halfN:lineara	6328.3
lineara:halfL	296.7	o2ua:halfN:lineara	904.7
o2pa:manningN	61029.5	maxG:halfN:lineara	1534.5
o2ua:manningN	564.4	resp:halfN:lineara	758.3
maxG:manningN	119063	o2pa:o2ua:halfL	1899.5
resp:manningN	7694.2	o2pa:maxG:halfL	27.7
halfN:manningN	12953.3	o2ua:maxG:halfL	139.6
lineara:manningN	11355.4	o2pa:resp:halfL	2081.6
halfL:manningN	67426.5	o2ua:resp:halfL	2522.8
o2pa:sett	14933.2	maxG:resp:halfL	2499.1
o2ua:sett	3.9	o2pa:halfN:halfL	1466.4
maxG:sett	11917.4	o2ua:halfN:halfL	841.5
maxG:halfN:halfL	2159.5	halfN:lineara:halfL	5687.7

resp:halfN:halfL	1128.8	o2pa:o2ua:manningN	1050.2
o2pa:lineara:halfL	1555.7	o2pa:maxG:manningN	25130.9
o2ua:lineara:halfL	15749.2	o2ua:maxG:manningN	3209.2
maxG:lineara:halfL	454	o2pa:resp:manningN	7050.7
resp:lineara:halfL	692.1		

APPENDIX D: QUAL2E Panel for the King Abdullah Canal

Figure D1. QUAL2E Simulation



Description of this run: King Abdullah Canal -1215

Simulation Type
● Steady state
○ Dynamic

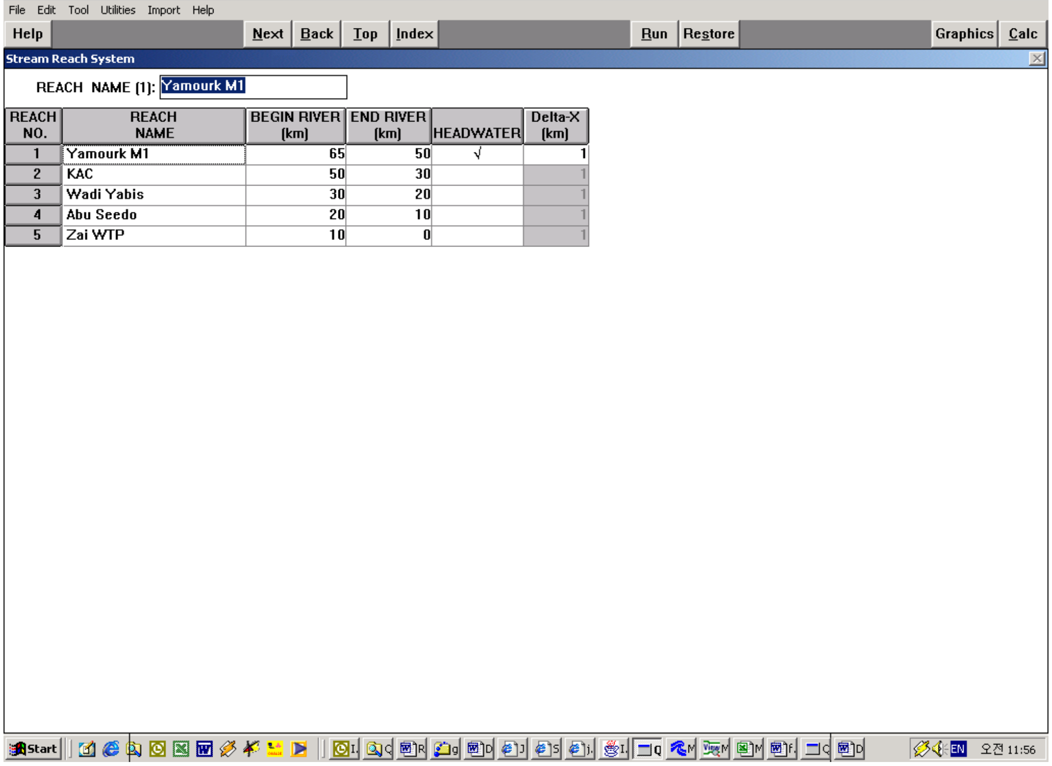
Units
○ U.S. units
● Metric

☐ Uncertainty Analysis
☐ Flow Augmentation
☑ Trapezoidal channels

Maximum Iterations: 30
Time step (hours): 1
Starting day of simulation: 60
Total simulation length (hours): 896
Time increment for RPT2 (hours): 6

Stream System
Number of reaches: 5

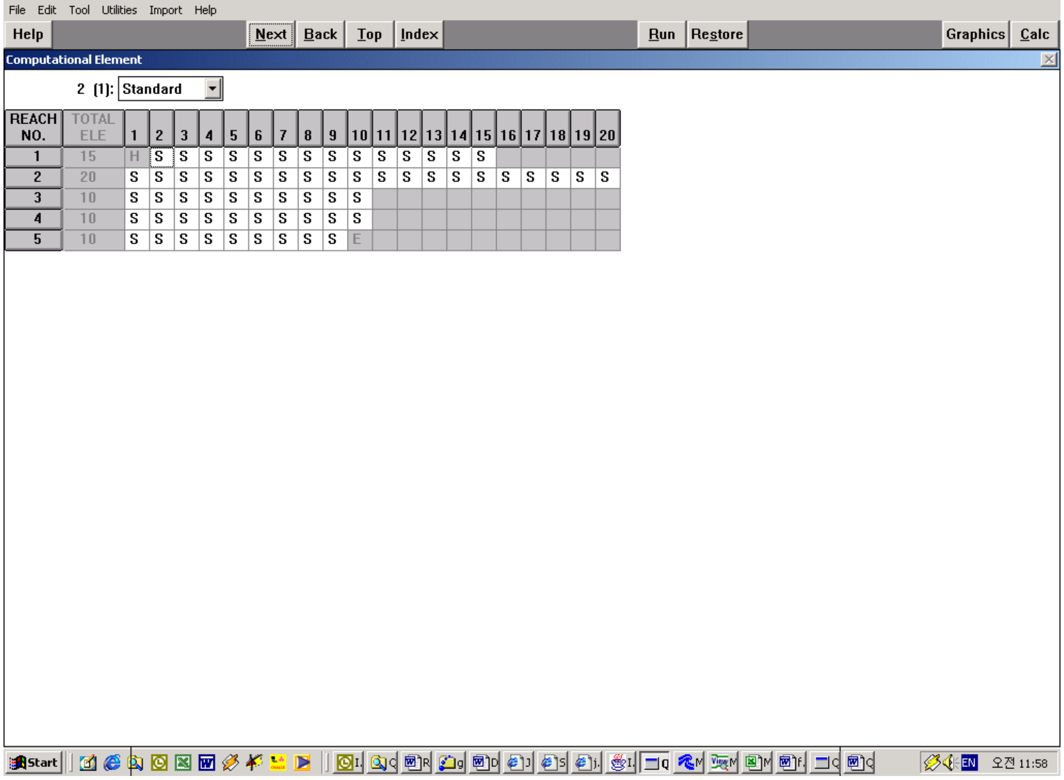
Figure D2. The King Abdullah Canal System



REACH NAME (1): Yamourk M1

REACH NO.	REACH NAME	BEGIN RIVER (km)	END RIVER (km)	HEADWATER	Delta-X (km)
1	Yamourk M1	65	50	√	1
2	KAC	50	30		1
3	Wadi Yabis	30	20		1
4	Abu Seedo	20	10		1
5	Zai WTP	10	0		1

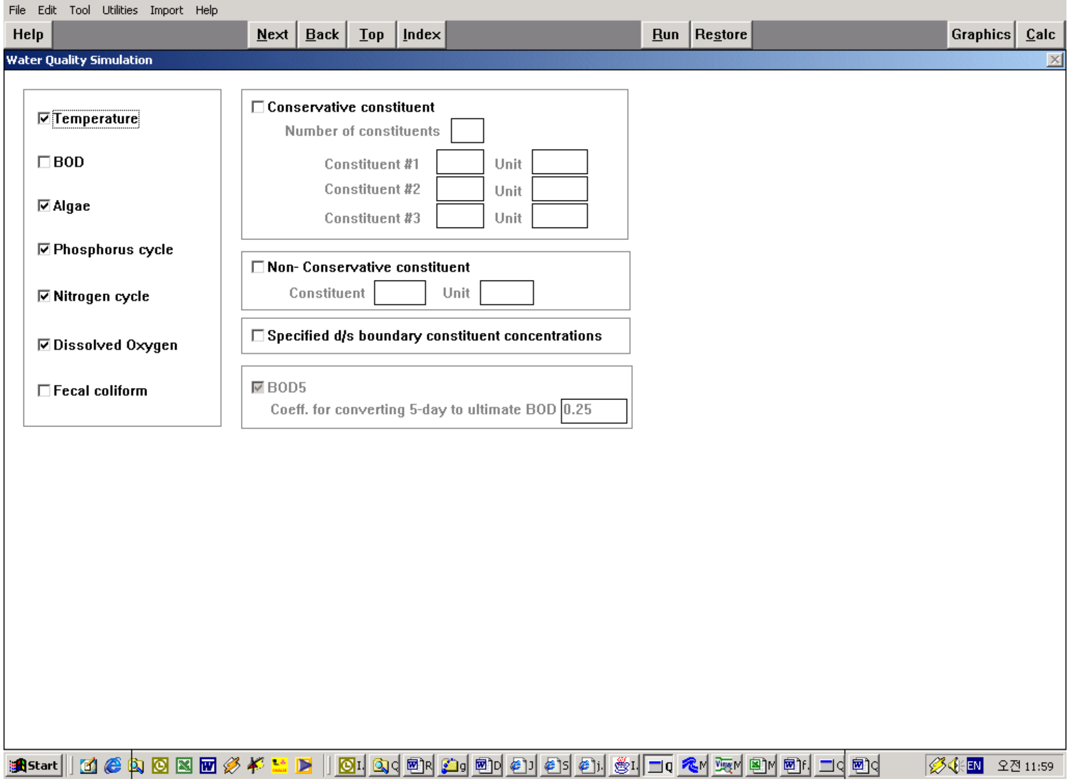
Figure D3. Computational Element



2 [1]: Standard

REACH NO.	TOTAL ELE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	15	H	S	S	S	S	S	S	S	S	S	S	S	S	S	S					
2	20	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
3	10	S	S	S	S	S	S	S	S	S	S										
4	10	S	S	S	S	S	S	S	S	S	S										
5	10	S	S	S	S	S	S	S	S	S	E										

Figure D4. Water Quality Simulation



☑ Temperature

☐ BOD

☑ Algae

☑ Phosphorus cycle

☑ Nitrogen cycle

☑ Dissolved Oxygen

☐ Fecal coliform

☐ Conservative constituent

Number of constituents

Constituent #1 Unit

Constituent #2 Unit

Constituent #3 Unit

☐ Non- Conservative constituent

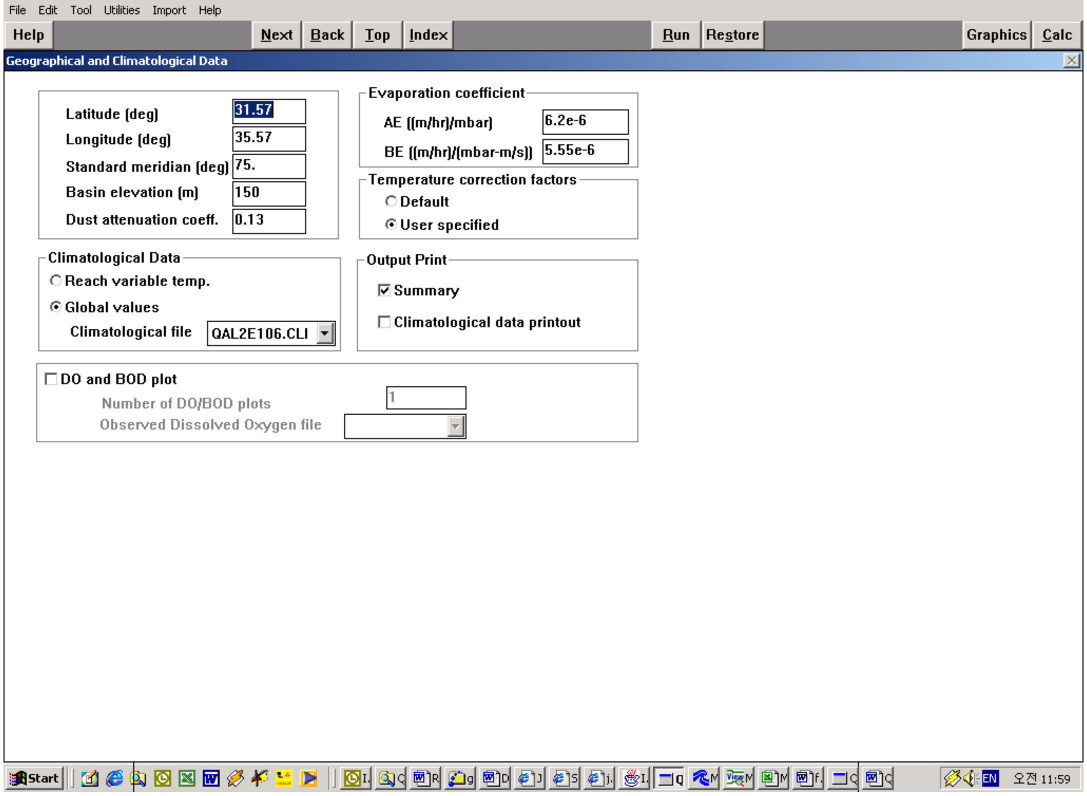
Constituent Unit

☐ Specified d/s boundary constituent concentrations

☑ BOD5

Coeff. for converting 5-day to ultimate BOD 0.25

Figure D5. Geographical and Climatological Data



Latitude (deg) 31.57
Longitude (deg) 35.57
Standard meridian (deg) 75.
Basin elevation (m) 150
Dust attenuation coeff. 0.13

Evaporation coefficient
AE ((m/hr)/mbar) 6.2e-6
BE ((m/hr)/(mbar-m/s)) 5.55e-6

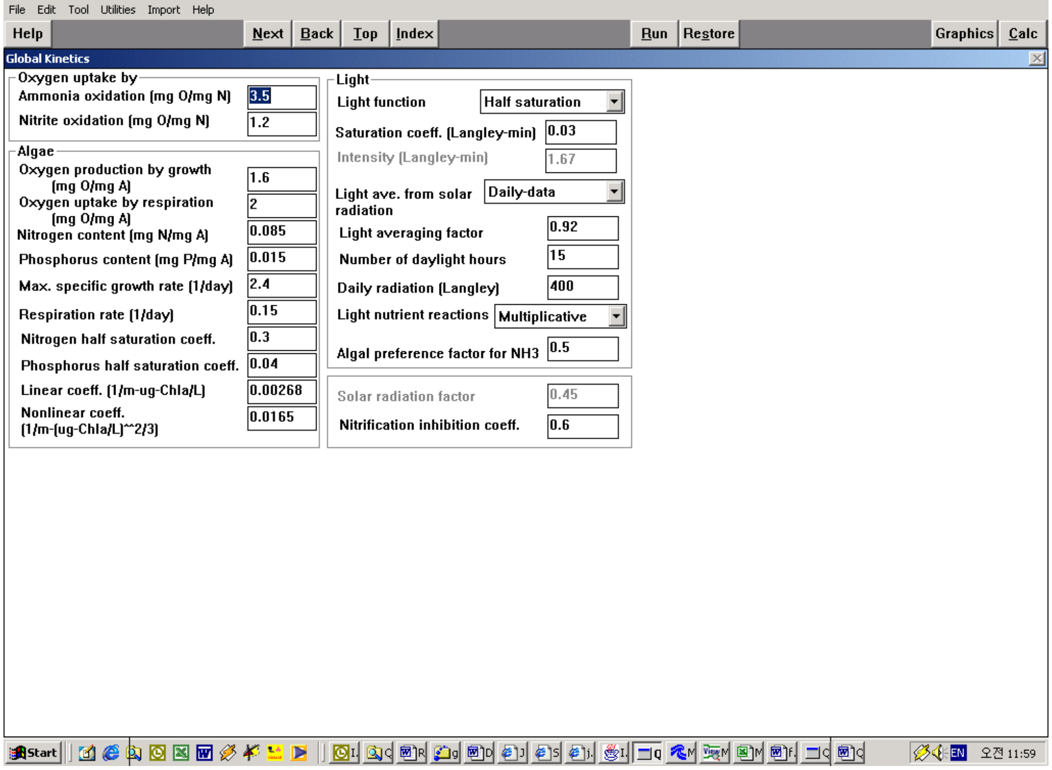
Temperature correction factors
○ Default
● User specified

Climatological Data
○ Reach variable temp.
● Global values
Climatological file QAL2E106.CLI

Output Print
☑ Summary
☐ Climatological data printout

☐ DO and BOD plot
Number of DO/BOD plots 1
Observed Dissolved Oxygen file

Figure D6. Global Kinetics



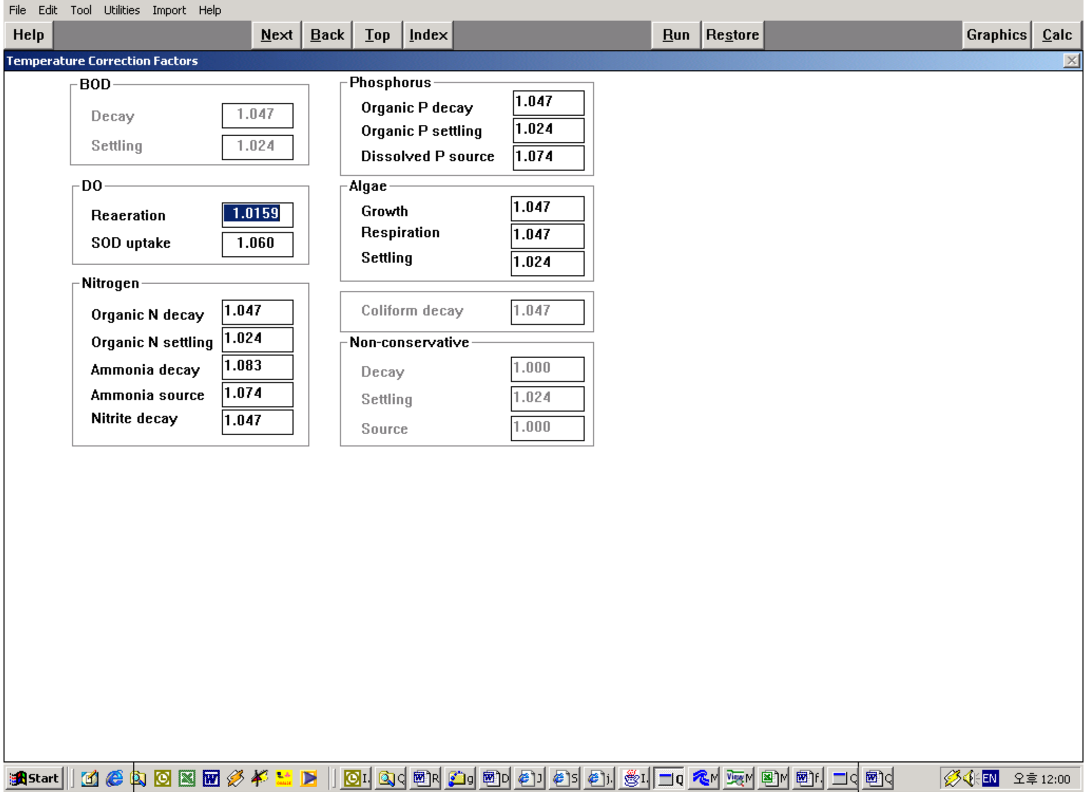
Oxygen uptake by
Ammonia oxidation (mg O/mg N) 3.5
Nitrite oxidation (mg O/mg N) 1.2

Algae
Oxygen production by growth (mg O/mg A) 1.6
Oxygen uptake by respiration (mg O/mg A) 2
Nitrogen content (mg N/mg A) 0.085
Phosphorus content (mg P/mg A) 0.015
Max. specific growth rate (1/day) 2.4
Respiration rate (1/day) 0.15
Nitrogen half saturation coeff. 0.3
Phosphorus half saturation coeff. 0.04
Linear coeff. (1/m-ug-Chla/L) 0.00268
Nonlinear coeff. (1/m-(ug-Chla/L)^2/3) 0.0165

Light
Light function Half saturation
Saturation coeff. (Langley-min) 0.03
Intensity (Langley-min) 1.67
Light ave. from solar radiation Daily-data
Light averaging factor 0.92
Number of daylight hours 15
Daily radiation (Langley) 400
Light nutrient reactions Multiplicative
Algal preference factor for NH3 0.5

Solar radiation factor 0.45
Nitrification inhibition coeff. 0.6

Figure D7. Temperature Correction Factors



BOD

Decay 1.047
Settling 1.024

DO

Reaeration 1.0159
SOD uptake 1.060

Nitrogen

Organic N decay 1.047
Organic N settling 1.024
Ammonia decay 1.083
Ammonia source 1.074
Nitrite decay 1.047

Phosphorus

Organic P decay 1.047
Organic P settling 1.024
Dissolved P source 1.074

Algae

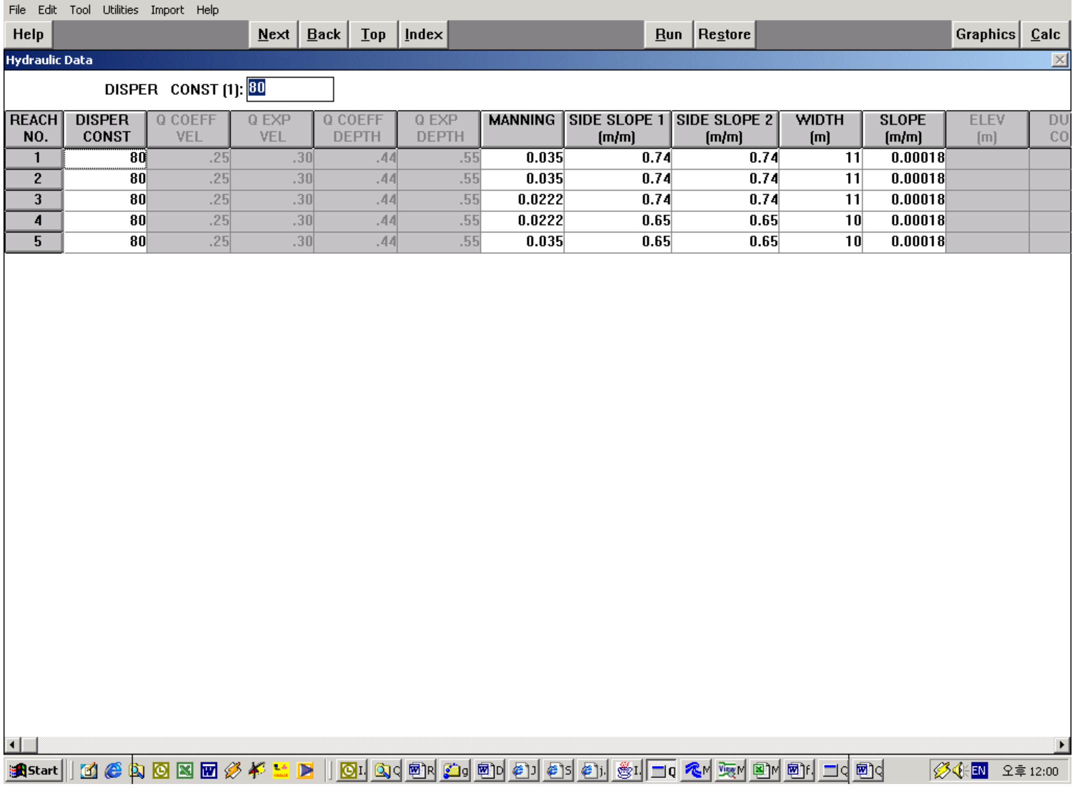
Growth 1.047
Respiration 1.047
Settling 1.024

Coliform decay 1.047

Non-conservative

Decay 1.000
Settling 1.024
Source 1.000

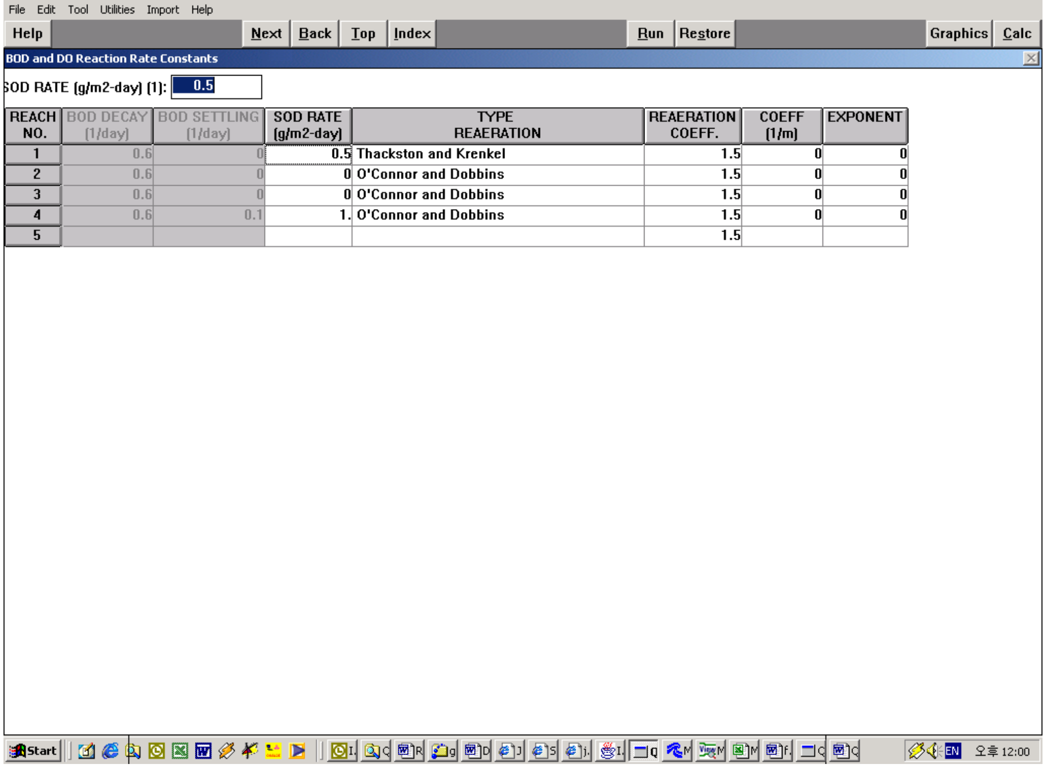
Figure D8. Hydraulic Data



DISPER CONST (1): 80

REACH NO.	DISPER CONST	Q COEFF VEL	Q EXP VEL	Q COEFF DEPTH	Q EXP DEPTH	MANNING	SIDE SLOPE 1 (m/m)	SIDE SLOPE 2 (m/m)	WIDTH (m)	SLOPE (m/m)	ELEV (m)	DU CO
1	80	.25	.30	.44	.55	0.035	0.74	0.74	11	0.00018		
2	80	.25	.30	.44	.55	0.035	0.74	0.74	11	0.00018		
3	80	.25	.30	.44	.55	0.0222	0.74	0.74	11	0.00018		
4	80	.25	.30	.44	.55	0.0222	0.65	0.65	10	0.00018		
5	80	.25	.30	.44	.55	0.035	0.65	0.65	10	0.00018		

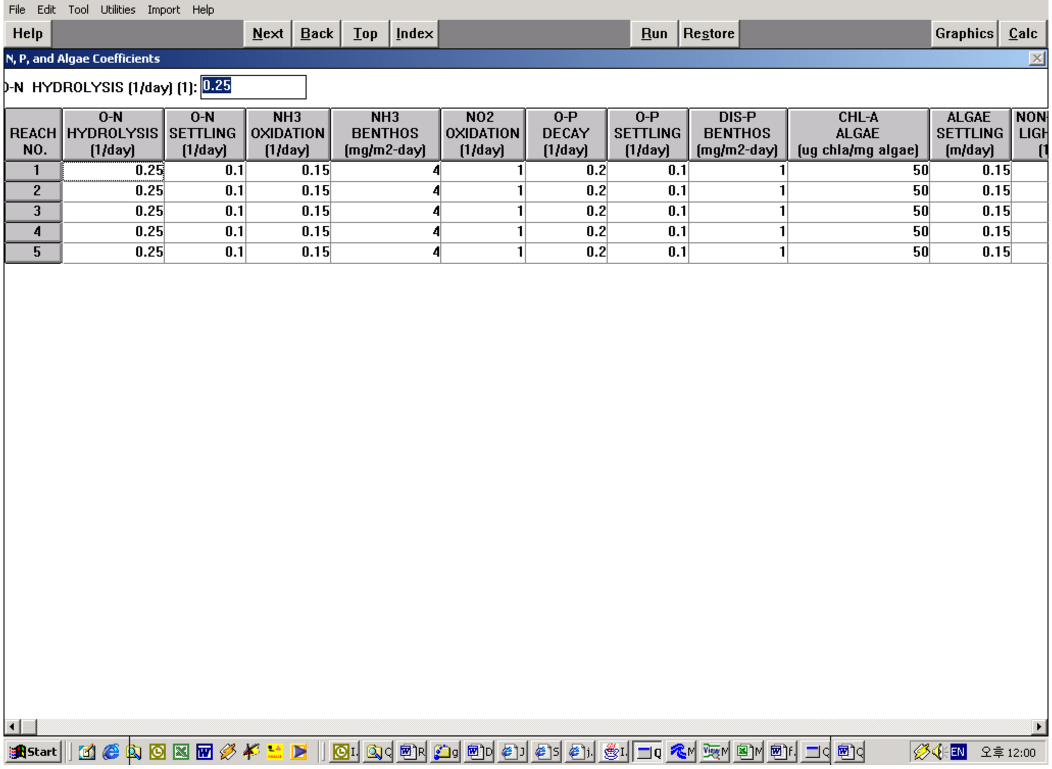
Figure D9. BOD and DO Reaction Rate Constants



SOD RATE (g/m2-day) (1): 0.5

REACH NO.	BOD DECAY (1/day)	BOD SETTLING (1/day)	SOD RATE (g/m2-day)	TYPE REAERATION	REAERATION COEFF.	COEFF (1/m)	EXPONENT
1	0.6	0	0.5	Thackston and Krenkel	1.5	0	0
2	0.6	0	0	O'Connor and Dobbins	1.5	0	0
3	0.6	0	0	O'Connor and Dobbins	1.5	0	0
4	0.6	0.1	1.	O'Connor and Dobbins	1.5	0	0
5					1.5		

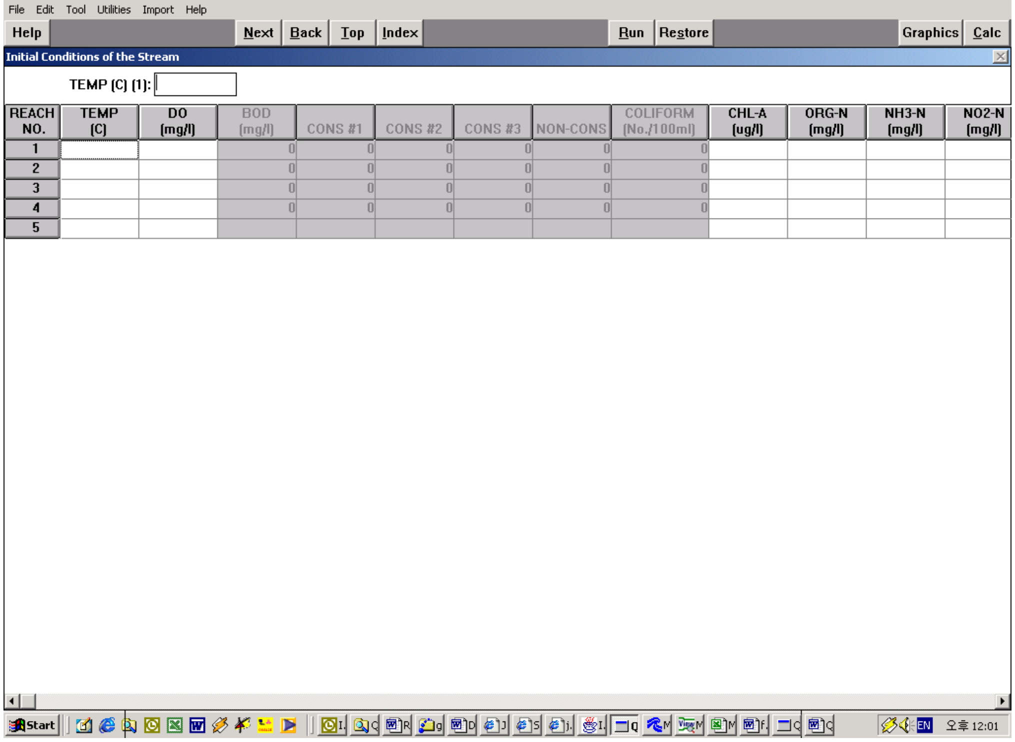
Figure D10. N, P, and Algae Coefficients



O-N HYDROLYSIS (1/day) (1): 0.25

REACH NO.	O-N HYDROLYSIS (1/day)	O-N SETTLING (1/day)	NH3 OXIDATION (1/day)	NH3 BENTHOS (mg/m2-day)	NO2 OXIDATION (1/day)	O-P DECAY (1/day)	O-P SETTLING (1/day)	DIS-P BENTHOS (mg/m2-day)	CHL-A ALGAE (ug chla/mg algae)	ALGAE SETTLING (m/day)	NON LIGH (1
1	0.25	0.1	0.15	4	1	0.2	0.1	1	50	0.15	
2	0.25	0.1	0.15	4	1	0.2	0.1	1	50	0.15	
3	0.25	0.1	0.15	4	1	0.2	0.1	1	50	0.15	
4	0.25	0.1	0.15	4	1	0.2	0.1	1	50	0.15	
5	0.25	0.1	0.15	4	1	0.2	0.1	1	50	0.15	

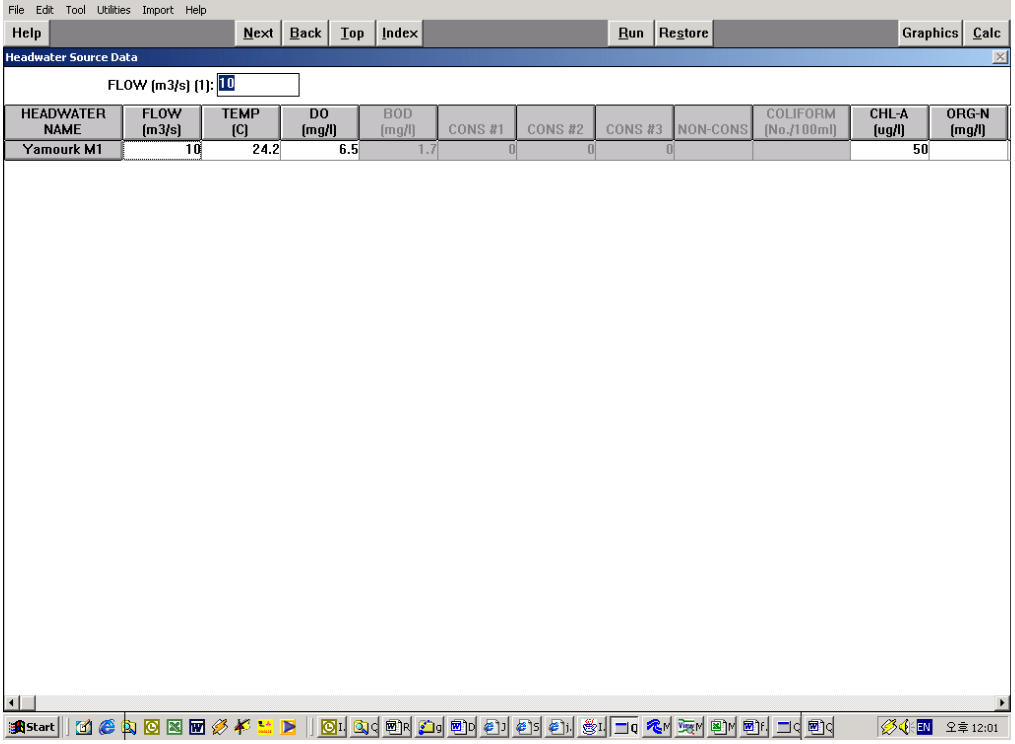
Figure D11. Initial Conditions of the King Abdullah Canal



TEMP (C) (1):

REACH NO.	TEMP (C)	DO (mg/l)	BOD (mg/l)	CONS #1	CONS #2	CONS #3	NON-CONS	COLIFORM (No./100ml)	CHL-A (ug/l)	ORG-N (mg/l)	NH3-N (mg/l)	NO2-N (mg/l)
1			0	0	0	0	0	0				
2			0	0	0	0	0	0				
3			0	0	0	0	0	0				
4			0	0	0	0	0	0				
5												

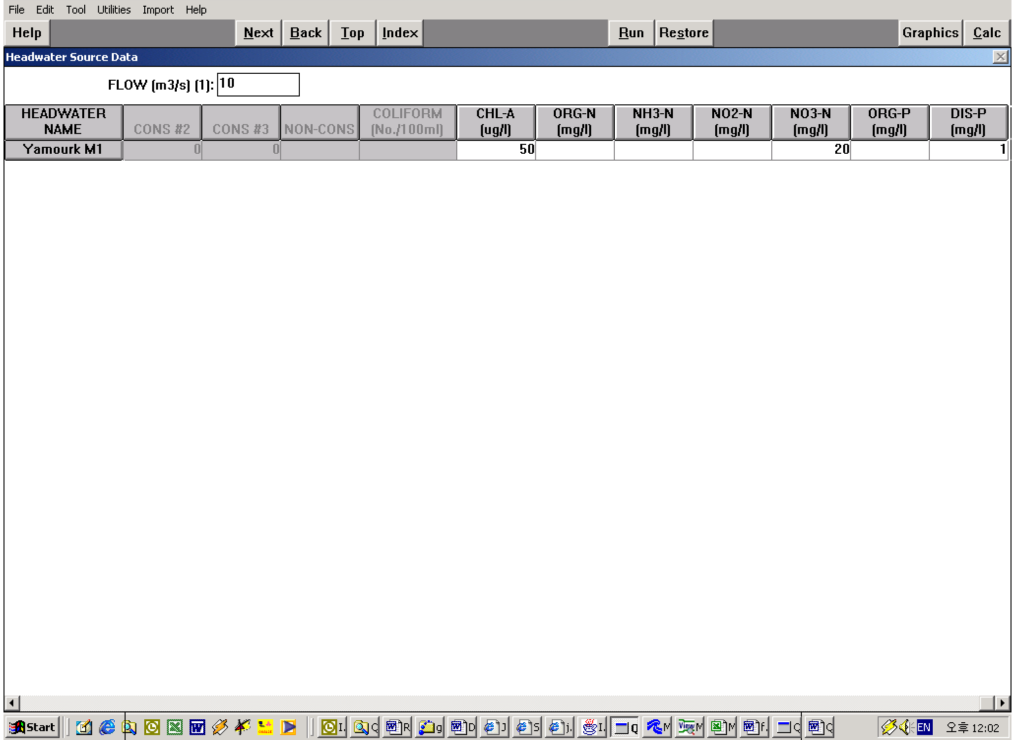
Figure D12. Incremental Flow



FLOW (m3/s) (1): 10

HEADWATER NAME	FLOW (m3/s)	TEMP (C)	DO (mg/l)	BOD (mg/l)	CONS #1	CONS #2	CONS #3	NON-CONS	COLIFORM (No./100ml)	CHL-A (ug/l)	ORG-N (mg/l)
Yamourk M1	10	24.2	6.5	1.7	0	0	0			50	

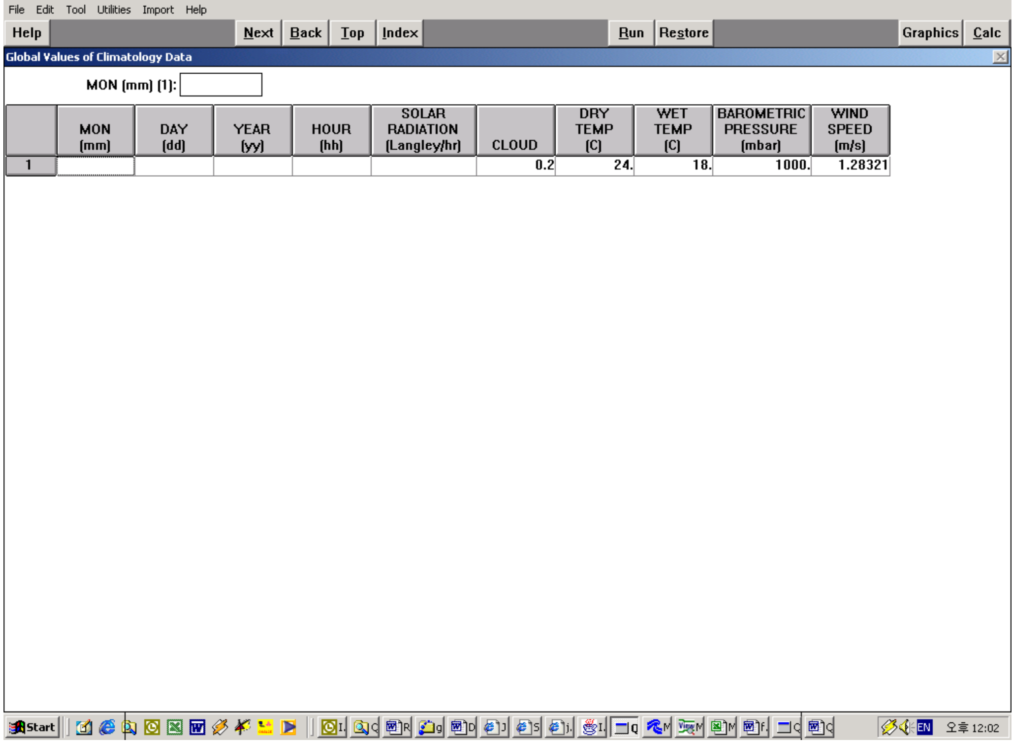
Figure D13. Headwater Source Data



FLOW (m3/s) (1): 10

HEADWATER NAME	CONS #2	CONS #3	NON-CONS	COLIFORM (No./100ml)	CHL-A (ug/l)	ORG-N (mg/l)	NH3-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	ORG-P (mg/l)	DIS-P (mg/l)
Yamourk M1	0	0			50				20		1

Figure D14. Global value of the Climatologic Data



MON (mm) (1):

	MON (mm)	DAY (dd)	YEAR (yy)	HOUR (hh)	SOLAR RADIATION (Langley/hr)	CLOUD	DRY TEMP (C)	WET TEMP (C)	BAROMETRIC PRESSURE (mbar)	WIND SPEED (m/s)
1						0.2	24.	18.	1000.	1.28321