Paper No. 668

NUMERICAL SIMULATION OF CANALS IRRIGATION SYSTEMS IN PAKISTEN

Mazhar Hussain

NUMERICAL SIMULATION OF CANALS IRRIGATION SYSTEMS IN PAKISTEN

Mazhar Hussain[1]

1.1 ABSTRACT

Hydraulic numerical models of irrigation canals are valuable tools to simulate actual canal behaviour and check its design and operational practices under different scenarios. In Pakistan, hydrodynamic simulations models are applied only on two canals to check the design and planned operation of Chashma Right Bank Canal (CRBC) and Pehur High Level Canal (PHLC) in North West Frontier Province (NWFP) of Pakistan. Application of numerical models to Irrigation Canals Systems in Pakistan is discussed. Researchers and Engineers have spent many years of work on various numerical models, which can simulate an actual canal. The Task Committee on Irrigation Canal Systems Hydraulic Modeling established by American Society of Civil Engineers (ASCE) examined a number of the computer programs available for simulating open-channel flow (MODIS, DUFLOW, CANAL, CARIMA, USM). Irrigation canals modeling is based on the same unsteady flow conditions as used in river modeling. However, the canal and irrigation environment present several unique simulation problems generally not uncounted in river modeling. This paper identifies current application and limitations of these models and the needs for improvements. Numerous other mathematical models to compute the water flow in open canals are available (among others SIC, PROFILE, FLOP, MIKE, SOBEK). Among them, Mike II (Danish Hydraulic Institute, 1995), DORC (HR Wallingford, 1992), SOBEK (Delft Hydraulic, 1994), ODIRMO (Delft University of Technology, DUT, 1985) can also be used for simulation of Sediment Transport.

1 Principal Hydraulic Engineer, National Development Consultants (NDC).

1.2 INTRODUCTION

Numerical Simulation Models are used for concept development, extension of physical model results, design analysis/evaluation and field evaluation. (USBR, 2005). Mathematical models can provide answer to the main problems being faced by the Canal Managers (a) to simulate actual hydraulic and operational conditions, (b) for calibration & validation of design parameters, (c) simulation of distribution network to evaluate Hydraulic Response of the Canal System.

In late 1980s, American Society Civil Engineers (ASCE) Task Committee on Irrigation Canal System Hydraulic Modelling was formed to evaluate the various unsteady flow simulation models. The committee was primarily interested in the model's ability to simulate water level and flow variations in canal systems with gates and weirs. The committee's findings were presented in 1990 in a special issue of the Journal of Irrigation and Drainage Engineering including descriptions of unsteady flow programs. The Task Committee on Irrigation Canal System Hydraulic Modelling (ASCE, 1998) examined a number of the computer programs available for simulating open-channel flow. Among them are MODIS, DUFLOW, CANAL, CARIMA, USM. The to-date available simulation models are SIC (Cemagref, France), PROFILE, FLOP, Mike II (Danish Hydraulic Institute), DORC (HR Wallingford), SOBEK (Delft Hydraulic), ODIRMO (Delft University of Technology). The SIC model (Cemagref, 2006) has been extensively used in more than 33 countries on different canal irrigation systems.

In late 1990s, as a follow up to the committee, a new committee was formed to evaluate canal control algorithms. The results of this task committee were published in a special issue of Journal of Irrigation and Drainage Engineering in 1998. Clemmens et al, 2005 has studied that all of the available models adequately simulate water level response. Examples of studies and the simulations models used to analyze control algorithms include Malterre (1998), who used "SIC", Merkley and Walker (1991) who used "CANAL", Liu et al. (1998) who used CASIM, Deltour and Sanfilippo (1998) who used SIC.

1.3 MODELING PROBLEMS OF IRRIGATION CANALS

Major Modeling problems are Zero-depth condition /or dry-bed flow, Mixed-regime flow, gate submergence. The details are discussed below. Unsteady-flow modeling in an existing canal system requires detailed field data for calibration in addition to numerical algorithms that treat these unique problems.

1.3.1 Zero-depth condition

Filling and emptying of the canals occurs regularly in many irrigation systems. During the filling of a dry canal, water flows downstream over the canal bed. Near the advancing front, the assumption of one-dimensional flow in the Saint Venant equations is violated, and a special boundary condition must be formulated to approximate the flow conditions A number of different approaches have been taken to characterize the hydraulics in the advancing front, which is differentiated in part by the numerical solution technique employed in the model (Walker and Skogerboe 1987; Clemmens and Strelkoff 1979; Singh and Chauhan1972). An alternative approach that obviates the need for dynamic grid management is to suppress the inertial terms in the Saint Venant equations when dry-bed conditions appear imminent. Such techniques, borrowed from two-dimensional flow modeling on tidal flats, rely on a non-inertial film of water to maintain hydraulic connectivity (Mishra and Holly 1992). However, this problem is not fully overcome and still needs more research.

1.3.2 Mixed-regime flow

Within a canal reach, the transition between supercritical and sub-critical flow is manifested by a discontinuity in the water surface, and also in the solution to the governing hydraulic equations. This discontinuity is called a hydraulic jump, and is characterized by large-scale localized turbulence and a consequent loss of energy. A hydraulic jump in itself is simply another kind of boundary condition, similar to an inline gate or pump. Thus, when the jump location is known, to be stationary due to the existence of a stabilizing structure, an unsteady model could easily include the necessary program steps to successfully handle the governing hydraulics. Research suggests that numerical methods for treatment of shocks in aerodynamics may find successful application to mixed-regime and discontinuous canal hydraulics (Savic 1991).

1.3.3 Gate submergence The problems associated with the modeling of the complete operational range of a gated structure are (a) changes in flow regime, and the form of the governing equations, can introduce numerical instability during simulation and (2) the data required to calibrate a given structure for specific conditions are not usually available, nor are they easy to obtain from field measurements. For these reasons, many unsteady-flow models incorporate simplifying assumption about transitions between flow regimes across a gated structure, and often limit the range of operational possibilities. These limitations are significant in some modeling applications and irrelevant in others. The full range of operation of gated structure still need more research.

1.4 POTENTIAL PITFALLS (ERRORS) OF CANAL MODELS

Three model parameters that influence errors in the model output are (a) the distance step, the time step, & a weighting factor. By varying above computational parameters, one can regulate the accuracy and stability of the numerical solution. Contractor & Schuurmans, (1992) has concluded that all the models (DUFLOW, MODIS, CARIMA, CANAL, USM) that were tested indicated negligible errors in long-term mass conservation.

1.5 LIMITATIONS AND REMDEY OF SIMULATIONS MODELS1.5.1 USM (1993)

USM is a fairly rigorous hydraulic-simulation model that incorporates accurate numerical solutions of the governing equations for a limited range of flow conditions.USM can accommodate various cross-sectional channel shapes, several automatic-gate-control algorithms, and either metric or English units. The model has been used extensively for several years in the design and analysis of Reclamation canals. USM is most useful for analyzing relatively rapid flow changes during a short time interval.

1.5.2 CARIMA (1994)

CARIMA code simulates unsteady free-surface flow in simple or multiply connected systems of rivers or canals. The simulation uses the Preissmann implicit finite difference method for solution of the complete Saint Venant equations and appropriate equations for hydraulic structures. The strengths of CARIMA are its maturity, robust and accurate numerical procedures, and capability to treat networks of any complexity, automatic topology recognition, regulation interface, and user support.

1.5.3 CANAL (1994)

CANAL is an excellent tool for modeling daily canal operations to help calculate structure settings, determine control strategies, and provide operator training. It is easy to understand and use, runs quickly, can accurately simulate most canals, and has minimal hardware requirements. CANAL is not as well suited to studying canal-system design, which involves worst-case flow scenarios with rapid flow change. Quantitative evaluations involving hypothetical (Contractor and Schuurmans 1992) and real flow conditions have verified the ability of the model to correctly simulate many gradually varied, unsteady-hydraulic-flow conditions in canals.

1.5.4 CANALCAD (1994)

CANALCAD is unsteady simulation software to test automatic canal-control algorithms. (Holly and Parrish 1992). CANALCAD uses the implicit Preissman scheme where all nodes are assigned values for both depth and discharge. CANALCAD can not handle branching canals.

1.5.5 DUFLOW 1994)

Duflow is public domain software, designed for simple networks of channels with simple structures. Water levels and flow rates are determined by solving the Saint Venant equations of continuity and momentum with Preissmann scheme. This Program can not handle some of the more-sophisticated modeling needs (i.e., dry bed condition, automatic gates).

1.5.6 CANALMAN (1998)

CANALMAN performs hydraulic simulations of unsteady flow in Branch canals networks only. It implicitly solves an integrated form of the Saint Venant equations of continuity and motion for one-dimensional unsteady open-channel flow only.

1.5.7 SIC (2005)

Simulation of Irrigation Canal (SIC) developed by Cemagref, France) is a mathematical model, which can simulate the hydraulic behaviour of irrigation canals under steady and unsteady flow conditions. Steady flow and unsteady flow computations can be performed on any type of hydraulic networks (linear, looped or branched). The Saint Venant Equations have no known analytical solutions in real geometry. They are solved numerically by discretizing the equations. The SIC has been extensively used in more than 33 countries on different irrigation projects (Cemagref, 2005)

1.6 DATA ANALYSIS

Simulation models for unsteady open channel flows are commercially available for more than 2 decades. All the available simulation models have adequate ability to simulate water level and flow variations in canal systems. (Clemmens et al, 2005). There are a number of tradeoffs between simplicity and functionality. Basically all the simulation models present difficulties and limitations. (Clemmens et al, 2005). The to date available simulation models such as Sobek, CanalCAD, SIC use finite-difference methods, where the canal is broken into a series of cells, lengthwise. Nodes represent the boundaries between cells.

1.7 APPLICATION OF CANAL SIMULATION MODELS IN PAKISTAN

In Pakistan, SIC has been used at the main canal level for the operational and delivery performance studies of Chashma Right Bank (CRBC) and Pehur High Level Canal (PHLC) in North West Frontier Province (NWFP). CANALMAN & SIC are used by International Water Management Institute (IWMI) for Machai Branch and Maira Branch of USC-PHLC System in NWFP. In Punjab, for Fordwah Eastern Saddiqia irrigation system at secondary canal level, SIC has been used to study water delivery, canal capacities and maintenance for different distributaries in its different study areas. In 1992, the preliminary hydraulic studies of two distributaries (#3 and #4) of CRBC were conducted by IWMI, Pakistan. In the Chishtian subdivision of Punjab, SIC has been used at the main canal and distributary levels in a number of studies. In this paper, only CRBC and PHLC modeling is described.

1.7.1 Upper Swat Canal (USC) and Pehur High Level Canal (PHLC) system

Two canal simulations models (SIC and CanalMan) are used by International Water Management Institute (IWMI) to evaluate the steady and unsteady state behavior of Upper Swat Canal and Pehur High Level Canal system. The location of both canals command is shown in Figure 1 while general characteristics are given in Table 1 and 2. The hydraulic and operational behavior of all three branch canals of the system; namely, Machai, PHLC and Maira are checked. Performance of the major hydraulic parameters for the branch canals like water levels, velocities and Froude Numbers is studied using hydrodynamic models.

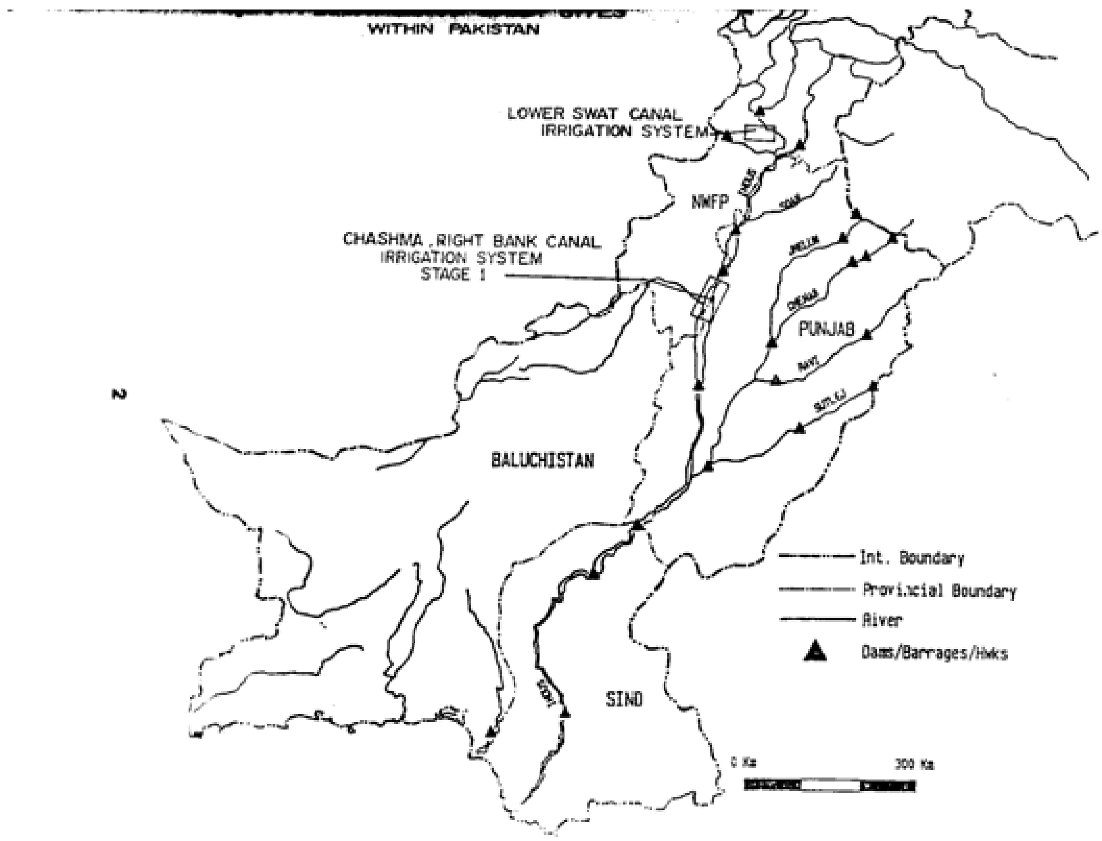

Fig. 1: Location of canals command of CRBC & PHLC

The delivery patterns of distributaries and direct outlets are computed to check the delivery efficiency. The responsiveness of different manual up-steam control and automatic downstream control regulators has been evaluated under different sets of operations. Unsteady flow model, SIC (Cemagraf, France) is used to simulate and check the remodeling of Machai Branch (Skogerboe et al, 1996). The objectives of simulations and results achieved are described in the following paragraphs. USC system irrigates 3 districts, Charsada, Mardan & Swabi. The existing system was designed in 1915 with headworks on the Swat River at Amandara to divert 51 cumecs. In 1971, Pehur Branch Canal through pump station from Terbela was constructed. In 1991, Pehur High Level canal through tunnel from Terbela was constructed. Figures 2 & 3 show the PHLC project area and flow line sketch respectively.

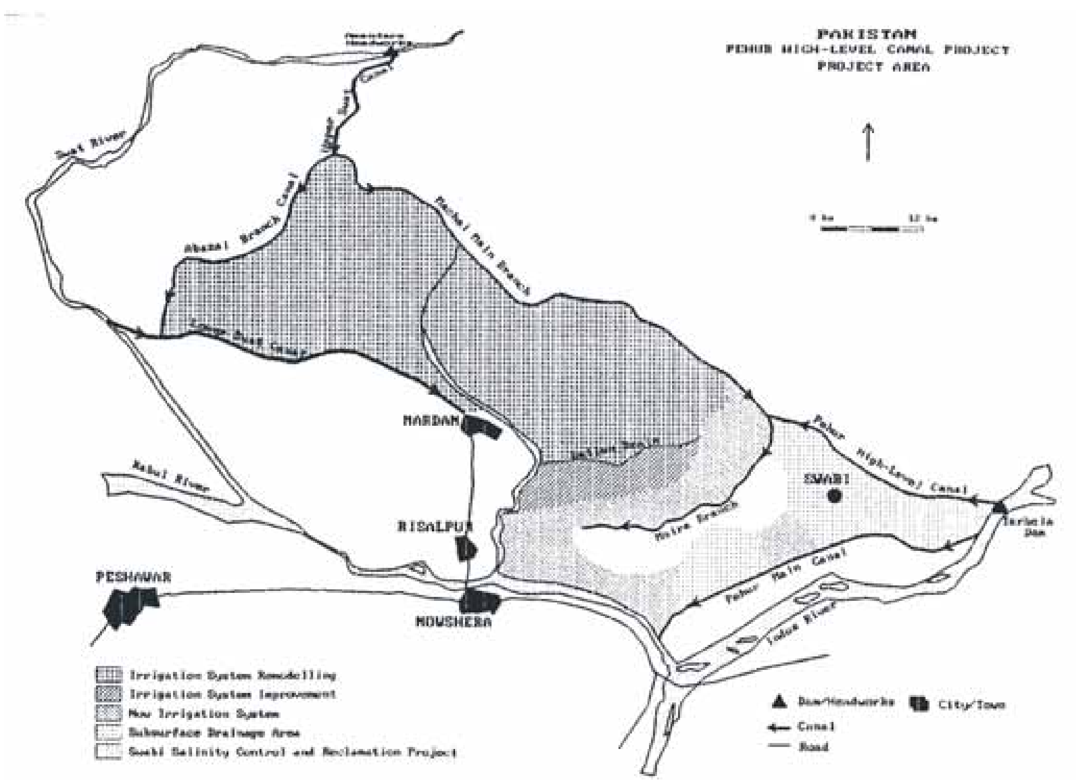

Fig. 2: Project area of PHLC

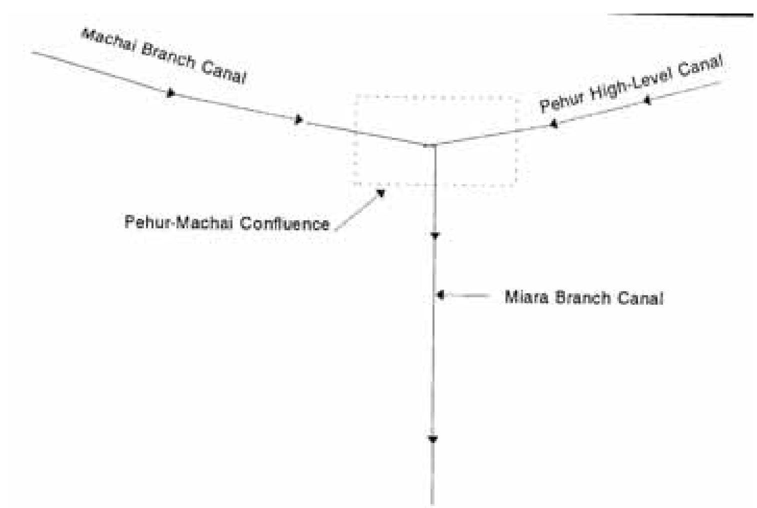

Fig. 3: Flow line sketch of USC & PHLC

1.7.2 Simulation of USC-PHLC System

USC-PHLC system is divided into 4 sub-systems. International Water Management Institute (IWMI) studied the hydraulic and operational behaviour of three branch canals i.e., Machai, PHLC, and Maira for (a) Physical parameters like water levels, (for canal capacities), velocities and Froude Number, (b) the delivery efficiency & (c) the response of different manual upstream control and automatic downstream control regulators. The results of study are summarized in the report

"Unsteady flow simulation of the designed PHLC and proposed remodeling of Machai & Maira Br. Canals (NWFP)", 1996, IWMI. The report neither describes the details about model setup nor it highlights the assumptions considered. So no comments are given on model description. For Maira Br. PHLC & Machai Branch, The SIC model is used. For Confluence structure, CanalMan is used. SIC is calibrated for Scenarios tested under four flow regimes in Machai Branch Canal. The canal deals with natural drains and obstacles through numerous structures: Siphons 5, Aqueducts 5, Tunnels 6, Falls 20, Distys 14, Minors 3, Direct outlets 61, Radial gates cross regulators 12, Q = 67 m^3/sec at head and at tail 31 m^3/sec The results indicates that the canal capacities are sufficient to take 120% of the Q_d. Distys can take Q_d in Kharif & recommended Q in Rabi rotation by regulating gate. Direct outlets have some problems and draw -10% & +15% discharge. The Figure 4 depicts Machai Branch Canal, km 33-35, and Designed and Computed water Levels while Figure 5 shows Machai Branch Canal, km 20-33, Designed and Computed water Levels. The comparison of simulation results are given in Table-3.

PHLC offtakes from Gandaf Tunnel to serve as link canal carrying water to feed the Machai Branch Canal from Terbela Reservoir. The details of Pehur High Level Canal are as: Length 26 km, Siphon 2, Tunnel 1, discharge at head = 27 m^3/sec. The results indicates that no problems are expected regarding canal capacities and operations of the gates when Manning'n is increased from 0.016 to 0.019. Gate shows stable behavior for 30% variation in discharge. Structure is calibrated using CanalMan. AVIS gate at the end of PHLC and the replacement of Machai tail x-regulators, by another AVIS gate shows stable operational conditions.

In case of PHLC, CanalMan Model has limitations. The general evaluation is made and simulation is based on approximation. For example, Siphons and tunnels are modeled with drops (Invert "rise") and Radial control gates, which result in slower canal response to upstream flow changes than the designed PHLC has multiple cross sections and longitudinal slopes. Therefore, this model has complexity to be used as unsteady flow mathematical models.

1.7.3 Simulation of Chashma Right Bank Canal

The Chashma Right Bank Canal (CRBC) offtakes form right bank of Chashma Barrage with a discharge capacity of 138 cubic meters per second having an intensive distribution system on its left bank to serve the command area between the canal and the river Indus. The canal design has been planned and constructed in three stages. The details are given in Table-1. The simulation results are presented in the report" Hydraulic Simulation to evaluate and Predict design and operation of the CRBC" dated March 1999, IWMI. The report does not show the details about model set up and assumptions adopted. The report only presents the steady and unsteady hydraulic behavior, sediment deposition trends of main canal. The simulation results are shown in Table-3.The study identifies sensitive reaches, cross regulators, and distys head, sediment calibration, sensitivity, and limitations.

In case of CRBC, SIC Model is sensitive to: (a) Slope and roughness, (b) Flow conditions and calibration of outlets, (c) Downstream boundary conditions, (d) Volume conservation, (e) Supercritical flow and negative slope, (f) some structures like siphon cannot be defined directly, (g) Calibration and flow conditions of offtakes structures, (h) transport capacity. The Figures 6 & 7 show designed and computed water levels of CRBC stage I, II & III.

1.8 CONCLUSIONS

The mathematical simulation models are basically decision support tools for canal managers to provide wide range of operational scenarios. The worldwide available mathematical simulation models are discussed and their use and limitations are described. Problems in modeling of canals irrigation systems are highlighted. In Pakistan, PHLC and CRBC are simulated using hydrodynamic computer models i.e., SIC and CanalMan. The simulation results show stable patterns both for steady and unsteady conditions. While using the computer models, setting up of models needed some adjustments to match the requirements of local conditions. Both SIC and CanalMan have certain difficulties in modeling CRBC and PHLC. In fact, all the available simulation models have limitations and do not address the full spectrum of modeling of Canal Irrigation System.

1.9 REFERENCES

1. Clemmens, et al., “Simualtion of Automatic CanalControls Systems”, J. Irrig. Drain. Engg., August 1, 2005.
2. “Unsteady flow simulation of the designed PHLC and proposed remodeling of Machai & Maira Br. Canals (NWFP)”, 1996, IWMI.
3. Hydraulic Simulation to evaluate and Predict design and operation of the CRBC” dated March 1999, IWMI.

Table-1: Stage wise characteristics of CRBC

Design Parameters	Stage -1	Stage -2	Stage-3	NWFP	Punjab
CCA (ha)	60728	38041	131930	141643	89032
Canal Length (km)	78	36	144	156	102
Max. Allocation (cms)	138	101	79	87	52
Mini. Allocation (cms)	42	31	24	27	16
Max. Delivery to CCA	32	22	77	81	50
Total Seepage (cms)	5.1	0.54	1.9	6.1	1.42
Assumed roughness	0.016	0.016	0.018	-	-
Max. Velocity (m/sec)	1.22	1.10	0.94-0.70	-	-
No. of x-regulators	2	3	16	8	13
No. Distributaries	12	16	54	45	37
Head regulator dgn. criteria	100%FSL	100%FSL	67%FSL	-	-

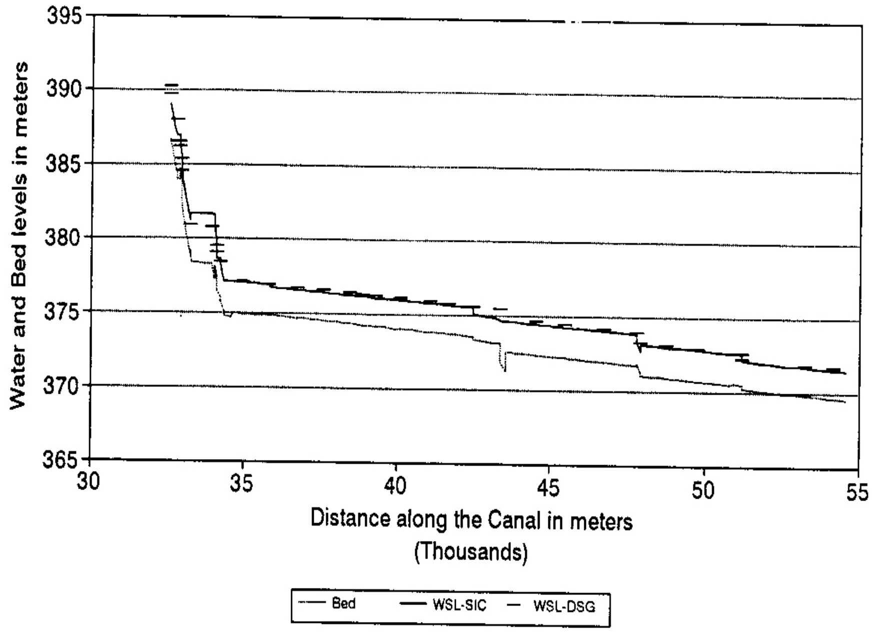

Fig. 4: Machai Branch Canal, km 33-35, and Designed and Computed water Levels

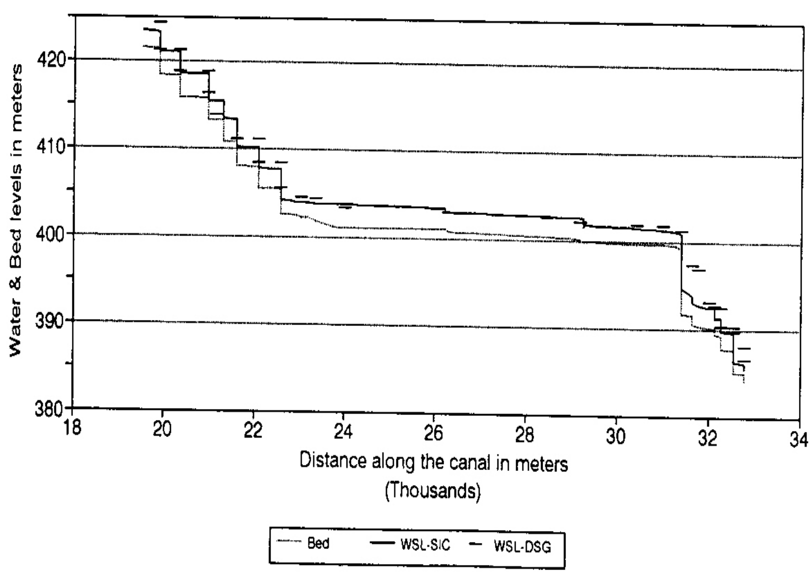

Fig.5: Machai Branch Canal, km 20-33, Designed and Computed water Levels

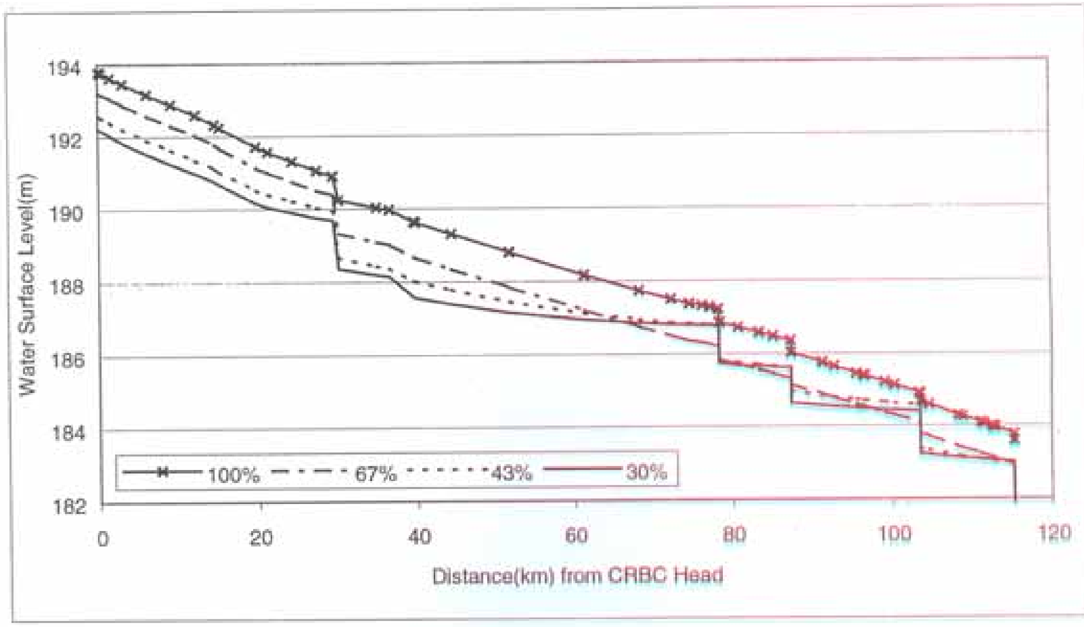

Fig-6: Water surface levels for proportionate distribution in Stage I & II

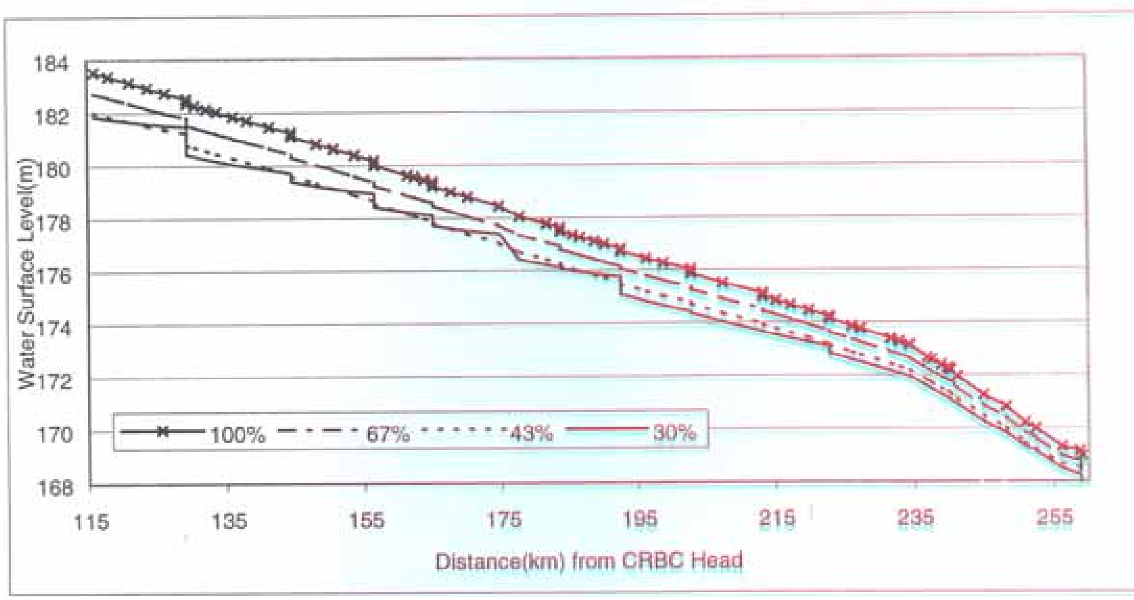

Figure 7: Water surface levels for proportionate distribution in Stage - III

Table-2: Comparison of main Characteristics of CRBC and PHLC

Description	CRBC	PHLC
Discharge	138 m^3 /sec	Machai Br.= 67 m^3/sec
		PHLC = 27 m3/sec
		Maira Br. = 24 m3/sec
Length of Main Canal	260 km	PHLC 26 KM
Section	Lined & unlined	Parabolic concrete lined
Bed width	6 m-1.5 m	5 m
Side slope	Lined 1.5H :1V , Unlined 0.5H :1V	1.34
Manning ' n	Lined 0.018 & 0.016, Unlined 0.023	0.016 to 0.019
Lacey's silt factor, f	0.97	-
flow depth	3.5 m -0.75m	3.75
Longitudinal slope	I in 8000 to 14000	.0002 to 0.0003
No. of Inline strcutres (X-Reg.)	22	12
No. of Escapes Reg.	5	1
No. of offtakes	64	14

Table-3: Comparison of simulation modeling between CRBC and PHLC

Description	CRBC	PHLC
Simulation model used	SIC	SIC, CanalMan
Agency	IWMI	IWMI
Client	WAPDA in collaboration with PIDs	WAPDA in collaboration with PID
Year	1999	1993-1996
Application	Primary system and offtaking strucutres	Machai br. , PHLC, & Maira branch
Objective	Simulation of main canal	Hydraulic & operational behaviour
	Design Checking of main canal	of all three branches canals
	Delivery patterns of distys & direct	Delivery patterns of distys & direct
	outlets to check the delivery efficieny	outlets to check the delivery efficieny
		Responsiveness of differnet manual
		u/s control and automatic d/s control
		regulators
Analysis	Steady state and Unsteady analysis	Hydraulic simulation of unsteady flow in
		branch canal networks
Lined section (n= 0.018 to 0.016)	Manning's equation	Manning's equation
Unlined section (n = 0.023)	Equivalent Coefficient of roughness	