

**UNSTEADY FLOW SIMULATION
OF PEHUR HIGH-LEVEL CANAL
INCLUDING AUTOMATIC
DOWNSTREAM WATER LEVEL CONTROL GATES**

CONSULTANCY REPORT

by

Dr. Kobkiat Pongput

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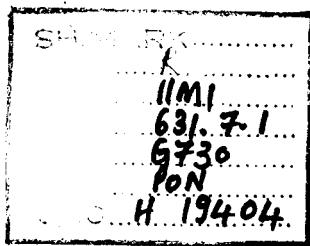
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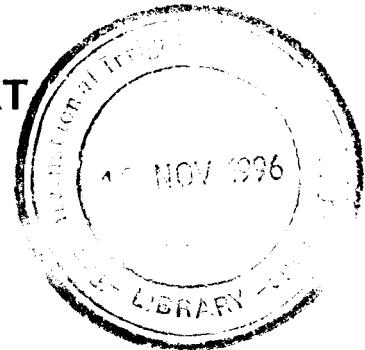
**PAKISTAN NATIONAL PROGRAM
INTERNATIONAL IRRIGATION MANAGEMENT INSTITUTE
LAHORE**

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FOREWORD

The Pehur High-Level Canal (PHLC) Project was approved for loan funding by the Asian Development Bank (ADB) in late 1993. This U.S. \$ 153 million project got underway in 1994. The executing agency is the federal Water and Power Development Authority (WAPDA) who work in collaboration with the Irrigation Department (ID) of the North West Frontier Province (NWFP). A consortium of European and Pakistani consulting firms, called Pehur High Level Canal Consultants, have been retained by WAPDA for the design and construction supervision of this project. The International Irrigation Management Institute (IIMI) has a contract with ID to provide support for operating this project.

The water supply for the existing Upper Swat Canal (USC) comes from the Swat River, while the new Pehur High-Level Canal (PHLC) will divert water from the reservoir created by the construction of Tarbela Dam in the 1970s on the Indus River. The Swat River is a tributary to the Indus River, with their confluence being downstream of Tarbela Dam.

In September 1993, based on experiences at Chashma Right Bank Canal, the ADB Appraisal Mission decided that it would be advantageous to place the USC-PHLC system on the computer using the model, "Simulation of Irrigation Canals (SIC)", during the design stage rather than wait until PHLC was commissioned. Since this task had to be done anyway, there was an advantage in using an unsteady flow model to check the hydraulic design of PHLC and the remodelling of USC. Such a model is used to verify water surface elevations at design discharge rates for each reach to ensure adequate freeboard and for designing offtakes. Usually, a sensitivity analysis is done regarding hydraulic roughness, sediment deposition (however, SIC does not model sediment transport) and the stability of fairly rapid changes in discharge rates.

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At a PHLC Design Workshop held in Peshawar during May 1995, the decision was made to incorporate automatic water level control gates. This necessitated that IIMI obtain appropriate computer software and a consultant experienced in using such a computer model. Arrangements were made in April 1996 and Dr. Kobkiat Pongput (Kasetsart University in Thailand) spent a few weeks in Pakistan during May 1996. He used the software, "CanalMan (CM)", developed at Utah State University that has an algorithm for unsteady flow simulation of automatic gates. In early June, he submitted a draft report, "Unsteady Flow Simulation of Pehur High-Level Canal Including Automatic Downstream Water Level Control Gates", which was shared with the design consultants. He was again brought to Pakistan for one week in early July and again the third week of October in 1996, partially to complete this report.

Dr. Kobkiat Pongput was specially trained in canal automation at Utah State University (USU) for the Royal Irrigation Department (RID) of Thailand. He was one of two RID staff provided Ph.D. training (there were also a number of RID staff who received an M.S. degree). He is presently on the faculty of Kasetsart University, which has a strong affiliation with RID. Dr. Kobkiat did his Ph.D. dissertation on unsteady flow simulation of canals having automatic gates, under the supervision of Dr. Gary Merkley, who is a specialist in this subject area. With this background, we felt very fortunate in having his services.

Gaylord V. Skogerboe, Director
Pakistan National Program
International Irrigation Management Institute

1. Introduction

The proposed Pehur High Level Canal (PHLC) is intended to function as a supplementary source of irrigation water, initially serving the tail end of the Upper Swat Canal system, including the Lower Machai Branch, Maira Branch and their distributaries as shown in Fig. 1. A fully automated operation of the PHLC is proposed by employing float operated constant downstream level control gates. The type of automation depends on such things as canal properties (including slope, structures, and storage volumes), the rules for delivery service, the types of water delivery, the availability of communication between the control center and local automatic structures, expectations of water users and operations staff, and economic considerations. Most of the things have been considered before the AVIO and AVIS gates are introduced to the PHLC canal system; however, many details still need to be considered. Control of an irrigation canal is typically a complex task, even when employing automatic control structures, due to the need for defining the hydraulic conditions. Flow within a canal is often unsteady, flow changes are damped as they move downstream, lag times for changes to reach the downstream end can be long, flow conditions change over the season with moss and algae growth, along with sediment deposition, and water demands change over the season. In this study, an unsteady flow model, *CanalMan*, will be used to simulate the PHLC system for considering the hydraulic performance of the canal system.

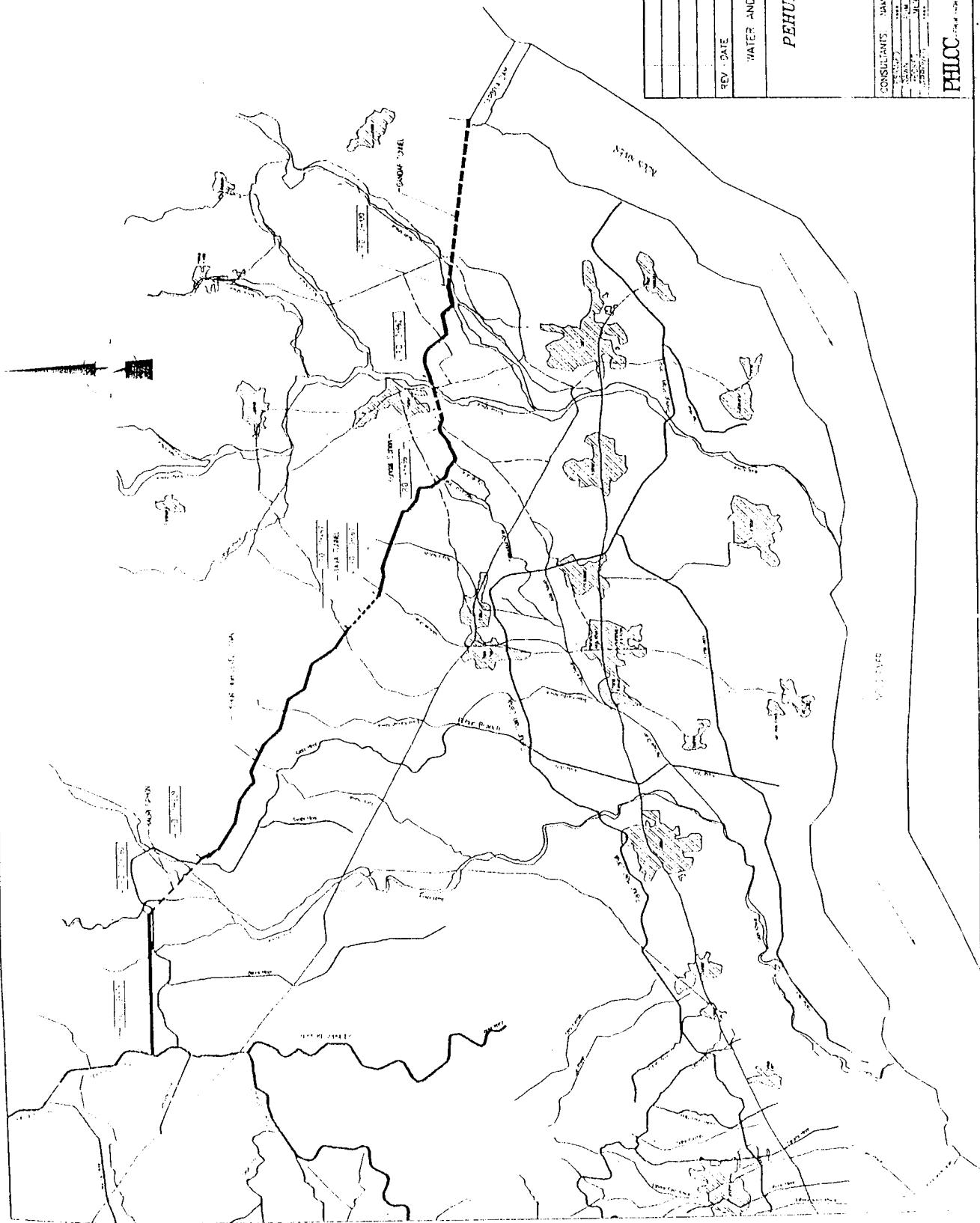


Figure 1. Location Plan of the PHLC.

2. The Pehur High Level Canal

The PHLC offtakes from Gandaf tunnel to serve mainly as a link canal carrying water to feed the Machai Branch Canal from the Tarbela Reservoir. The designed flow rate at the Gandaf tunnel outlet is $27.11 \text{ m}^3/\text{s}$, while the maximum lateral and/or turnout discharges along the canal total about $2.9 \text{ m}^3/\text{s}$. The designed cross-sections of the PHLC are typically parabolic concrete lined shape of 15.04 m and 3.75 m maximum depth. When routed through a rock cutting, the canal is changed to a rectangular or trapezoidal cross section and its longitudinal slope increased from 0.0002 to 0.0005 in order to reduce the volume of cut. Transition sections are introduced at canal structures such as cross-regulators and siphons.

Total length of the PHLC is about 26.2 km including two siphons and a tunnel according to the schematic shown in Fig. 2. The first siphon, called Kundal siphon, connects with canal reaches at RD 2+961 and RD 4+487. The Badri siphon, the second one, connects canal reaches at RD 19+300 and RD 21+338. The Baja tunnel exist between the siphons to connect canal reaches at RD 10+096 and RD 11+485. Properly sized twin AVIO gates are proposed to be installed at the downstream end of the siphons and the tunnel. Twin AVIS gates are also proposed to be installed at RD 15+032 and RD 25+280.

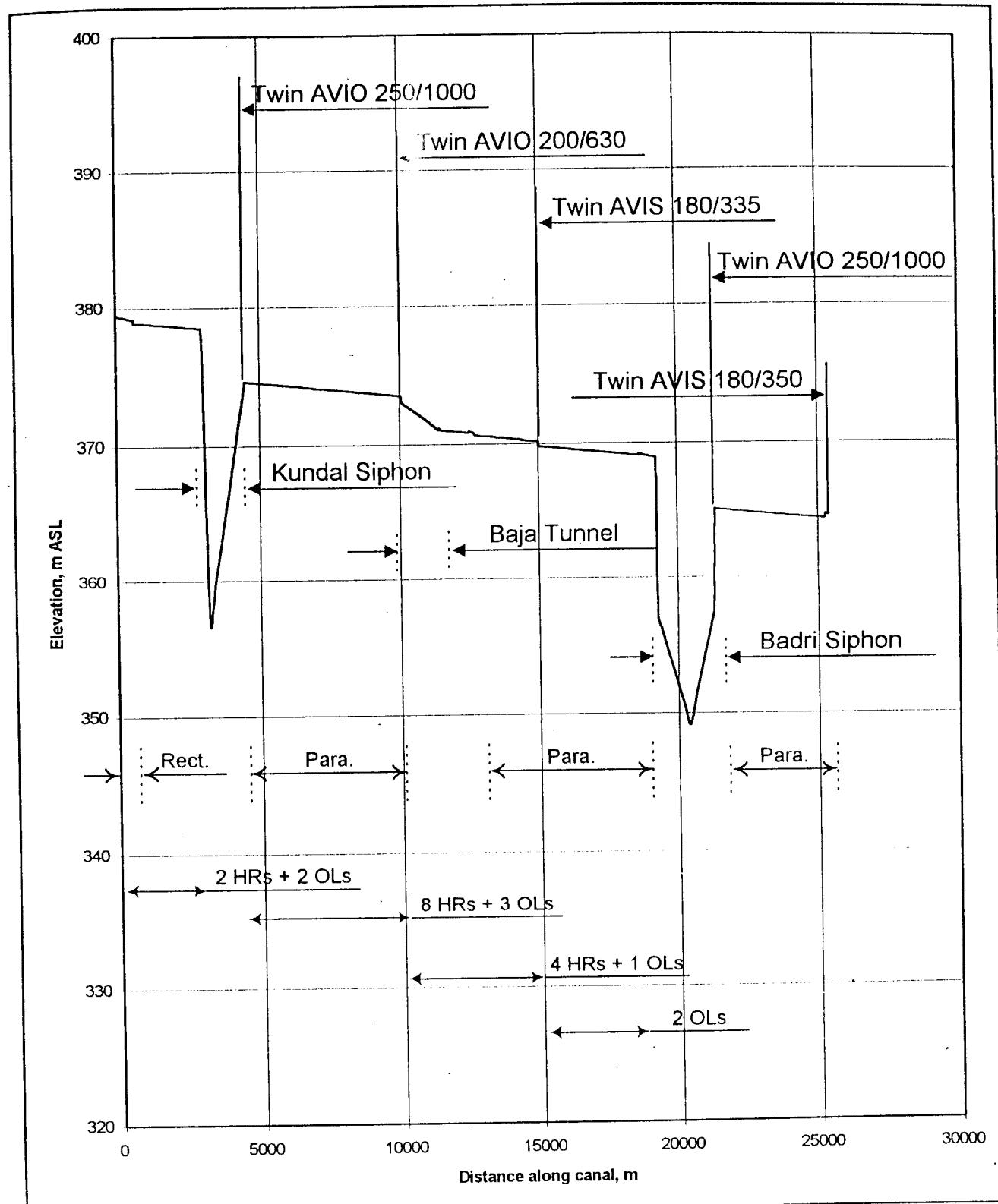


Figure 2. Schematic of PHLC.

3. The *CanalMan* Model

The *CanalMan* model was developed by the Department of Biological and Irrigation Engineering, Utah State University. This software application performs hydraulic simulations of unsteady flow in branching canal networks. The model is intended primarily for use in operational and training activities, and it can also be applied to design and analysis studies of canal systems. The model can be used to simulate canal operations in manual mode, and it can generate proposed operating schedules through a centralized automatic mode. Several common types of local gate automation schemes are also included in the model, and these can be easily selected and calibrated through the model interface.

CanalMan implicitly solves an integrated form of the Saint-Venant equations of continuity and motion for one-dimensional unsteady open-channel flow. Computation nodes are used internally by the model, and they automatically inserted along the length of canal reach, between the system layout nodes that the user creates. Simulations can be started by filling an empty canal system, continuing a previous simulation, or from a specified steady or unsteady flow condition.

The model will directly simulate the layout of most canal systems, including branching canals. Canal reaches are separated by in-line control structures such as gates, weirs, and pumps. Several in-line structures can be independently simulated in parallel at the downstream end of a canal reach. Turnouts can be used to remove water from the simulated canal system, or divert water into laterals (distributaries) or sub-laterals (minors) within the system. Turnout operation can be simulated by specifying a setting (the model calculates the flow rate), specifying a "demand" flow rate (the model then calculates the setting), or given an "actual" flow rate in which the model simply assumes the flow is correct. Time graphs of flow rate and setting can also be created for individual turnouts and applied to these three operational modes.

A variety of in-line and turnout structures can be selected from the editor for inclusion in a system layout, including weirs, underflow gates, pumps, "non-structure" section changes, and uniform flow boundaries. The inflow rate at the system source can be "manually" specified, calculated according to local conditions, or calculated according to system-wide delivery requirements.

Results from **CanalMan** include flow depths in the canal reaches, volumetric flow rates, and control structure (gate) settings -- all as a function of time. Simulation results can be viewed in numerical and graphical formats on-screen, and tabular results can be written to text files. Direct printouts of the tabular results can also be obtained from the model. Changes in selected reach depth profiles, downstream target levels, and gate settings can be monitored during a simulation through graphical flow profile windows. Reach inflow and outflow rates, modes and status can also be viewed during a simulation.

4. AVIS and AVIO in *CanalMan*

The AVIS and AVIO gates are radial gates operated by one or several floats rigidly fitted to an arm opposite to the gate leaf. The radial gates are in equilibrium whenever the downstream water levels are at the gate hinge elevation. The hydraulic thrust on the leaf passes through the gate hinge axis and has no effect on the equilibrium. Therefore, only the torque due to the weight of the gate and the buoyancy of the float affect the gate opening. A decrease in the downstream water surface causes the buoyancy torque to become smaller than the weight-acting torque, causing the gate to open, and approximately restoring the downstream water level to the reference water level. The reverse process is applied for raising the upstream water surface.

An equilibrium condition of the AVIO and AVIS gates can be expressed as follows:

$$Q = KR^2 \frac{\Delta z}{\Delta z_{\max}} \sqrt{H_u - H_d} \quad (1)$$

where Q is the flow rate (m^3/s); K is a constant depending on the gate type; R is the float radius (m); ΔZ and ΔZ_{\max} are the decrement and maximum decrement, respectively (m); and H_u and H_d are upstream and downstream flow depths, respectively. The values of K are 4.1, 1.0 and 2.0 for the AVIS, high-head AVIO, and low-head AVIO, respectively. The value of ΔZ_{\max} is equal to five percent of the float radius.

Since both AVIS and AVIO gates are orifice gates and typically operate under submerged conditions, the flow rate can also be expressed as

$$Q = C_d H_d \sqrt{2g (H_u - H_d)} \quad (2)$$

and,

$$C_d = \xi_{s_1} \left(\frac{A_o}{H_d} \right)^{\xi_{s_2}} \quad (3)$$

where Q is the flow rate (m^3/s); C_d is a coefficient of discharge for submerged orifice flow. A_o is the area of gate opening (m^2); and ξ_{s_1} and ξ_{s_2} are coefficients. All other parameters are as defined above.

As a rule, ΔZ_{\max} in the AVIS and AVIO gates corresponds to the maximum gate setting, and a decrement of zero corresponds to a closed gate. Assuming the gate setting and decrement are linearly related, the following can be stated:

$$\frac{Go}{Go_{\max}} = \frac{\Delta z}{\Delta Z_{\max}} \quad (4)$$

Substituting A_o , which is the product of the gate opening, G_o , and gate width, b , into Eq. 2 and rearranging:

$$C_d = \xi_{s_1} \left[\frac{b Go_{\max}}{0.05 R} \right]^{\xi_{s_2}} \left[\frac{\Delta z}{H_d} \right]^{\xi_{s_2}} \quad (5)$$

where b is the gate width (m); and Go_{\max} is the maximum gate setting (m). Since Eqs. 1 and 2 are equivalent; therefore, the equation for C_d can also be written as Eq. 2 and rearranging:

$$C_d = \left[\frac{20 K R}{\sqrt{2g}} \right] \frac{\Delta z}{H_d} \quad (6)$$

Rearranging Eqs 5 and 6, the following relationships are obtained:

$$\xi_{s_2} = 1.0, \quad \xi_{s_1} = \frac{K R^2}{\sqrt{2g} b Go_{\max}} \quad (7)$$

For the AVIS gate, an alternative for calculating the coefficients in Eq. 7 is to start from the AVIS equation:

$$Q = 0.43 \cdot \frac{\beta}{100} \cdot b^2 \sqrt{2g \cdot (H_u - H_d)} \quad (8)$$

where

$$\beta = 100 \frac{\Delta Z}{\Delta Z_{\max}} \quad (9)$$

Substitute Eqs. 4 and 9 into Eq. 8, and since Eqs. 2 and 8 are equivalent, therefore,

$$\xi_{s1} \left(\frac{b \cdot Go}{H_d} \right)^{\xi_{s1}} \cdot H_d = 0.43 \left(\frac{Go}{Go_{\max}} \right) \cdot b^2 \quad (10)$$

rearranging

$$\xi_{s1} \left(\frac{b \cdot Go}{H_d} \right)^{\xi_{s1}} = \left(\frac{0.43 \cdot b}{Go_{\max}} \right) \left(\frac{b \cdot Go}{H_d} \right) \quad (11)$$

since

$$Go_{\max} = 0.43 \cdot b^2 \quad (12)$$

the following relationships are obtained:

$$\xi^{s2} = 1.0, \quad \xi = \frac{1}{b} \quad (13)$$

Eqs. 7 and 13 would give the same results.

CanalMan requires the maximum gate setting, allowable maximum of gate changing in one step, and gate float radius for simulation of AVIO and AVIS gates. The maximum gate setting and gate float radius can be obtained from the manufacturer. The allowable maximum gate change is specified as a percentage of the maximum gate setting. This restriction is for simulation purposes, and is believed to be automatically taken care of in actual installations. Without a limit on the amount of change in the gate setting from one time step to the next, the model will often manifest fluctuations of the gate, possibly leading to failure of the simulation.

5. Simulation of the PHLC

To model the PHLC canal with *CanalMan*, some assumptions are made regarding design conditions so that an inexact, although useful, solution could be attained. For example, siphons and tunnels are modeled with drops (invert "rise") and radial control gates. One would expect these approximations to result in slower canal response to upstream flow changes than the designed PHLC canal. The PHLC canal reaches with their multiple cross sections and longitudinal slopes cannot be precisely modeled with existing unsteady flow mathematical models. This level of detail and complexity may be important, but is not necessary for a general evaluation.

The schematic of the PHLC as shown in Fig. 3 is simplified from Fig. 2. The PHLC is simply divided into six reaches; namely, Kundal, Baja, AVIS15, Badri, AVIS25, and Machai reaches. Providing only trapezoidal and circular cross-section shapes in the *CanalMan*, therefore, all reaches in the PHLC are assumed to be a trapezoidal cross-section with configuration data shown on Table 1. The values of longitudinal slope represent average values of each reach slope. They are 0.0002 for most reaches except for the first one, the Kundal reach which is 0.0003.

To have cross-sections placed in the model quite close to the designed PHLC cross-section, the base width and each side slope of the trapezoidal cross-sections were determined to be 5 m and 1.34 side slope, respectively. The maximum cross-section depth of 3.75 m is provided for observing the maximum required depth for the designed discharge with various situations such as different values of roughness coefficient, or several operational conditions. A comparison between characteristics of trapezoidal and parabolic cross-sections is presented on Table 2 and Fig. 4. Water depths in the simulation model will vary approximately from 2 to 3 m, therefore, the simulated trapezoidal cross-section should be a good representation of the designed parabolic cross-section for the PHLC.

Table 1. Configuration of Canal Reaches.

	Reach Name	Length (m)	Slope	Inv.Rise (m)	Seepage (mm/day)	n
1.	KUNDAL	2961	0.0003	-4.10	5	0.016
2.	BAJA	5609	0.0002	-2.55	5	0.016
3.	AVIS15	3547	0.0002	-0.24	5	0.016
4.	BADRI	4268	0.0002	-4.10	5	0.016
5.	AVIS25	3942	0.0002	-0.24	5	0.016
6.	MACHAI	720	0.0002	0.00	5	0.016

	Reach Name	X-section	Max. Depth (m)	BaseWidth (m)	SS. L	SS. R
1.	KUNDAL	Trapez.	3.75	5	1.34	1.34
2.	BAJA	Trapez.	3.75	5	1.34	1.34
3.	AVIS15	Trapez.	3.75	5	1.34	1.34
4.	BADRI	Trapez.	3.75	5	1.34	1.34
5.	AVIS25	Trapez.	3.75	5	1.34	1.34
6.	MACHAI	Trapez.	3.75	5	1.34	1.34

Table 2. Trapezoidal and Parabolic Cross-sections.

Depth m	Trapezoidal Section			Parabolic Section			
	Side Slope	=	1.34	Full Depth, m	=	3.75	
	Base Width, m	=	5.00	Top Width, m	=	15.04	
P m	A m^2	R m	X m	P m	A m^2	R m	
0.00	5.000	0.000	0.000			0.000	
1.20	9.013	7.930	0.880	0.564	8.940	6.806	0.761
1.30	9.347	8.765	0.938	0.587	9.341	7.675	0.822
1.40	9.682	9.626	0.994	0.609	9.730	8.577	0.881
1.50	10.016	10.515	1.050	0.631	10.110	9.512	0.941
1.60	10.350	11.430	1.104	0.651	10.480	10.479	1.000
1.70	10.685	12.373	1.158	0.672	10.843	11.477	1.058
1.80	11.019	13.342	1.211	0.691	11.198	12.504	1.117
1.90	11.354	14.337	1.263	0.710	11.547	13.560	1.174
2.00	11.688	15.360	1.314	0.728	11.889	14.645	1.232
2.10	12.022	16.409	1.365	0.746	12.226	15.757	1.289
2.20	12.357	17.486	1.415	0.764	12.558	16.896	1.345
2.30	12.691	18.589	1.465	0.781	12.885	18.061	1.402
2.40	13.026	19.718	1.514	0.798	13.208	19.251	1.458
2.50	13.360	20.875	1.562	0.814	13.527	20.467	1.513
2.60	13.694	22.058	1.611	0.830	13.842	21.707	1.568
2.70	14.029	23.269	1.659	0.846	14.153	22.971	1.623
2.80	14.363	24.506	1.706	0.862	14.461	24.259	1.678
2.90	14.698	25.769	1.753	0.877	14.766	25.570	1.732
3.00	15.032	27.060	1.800	0.892	15.068	26.904	1.786
3.10	15.366	28.377	1.847	0.907	15.367	28.261	1.839
3.20	15.701	29.722	1.893	0.921	15.663	29.639	1.892
3.30	16.035	31.093	1.939	0.936	15.957	31.039	1.945
3.40	16.370	32.490	1.985	0.950	16.249	32.461	1.998
3.50	16.704	33.915	2.030	0.964	16.538	33.903	2.050
3.60	17.038	35.366	2.076	0.977	16.825	35.367	2.102
3.70	17.373	36.845	2.121	0.991	17.110	36.851	2.154
3.80	17.707	38.350	2.166	1.004	17.394	38.355	2.205

P = Wetted Perimeter

A = Cross-section Area

R = Hydraulic Radius

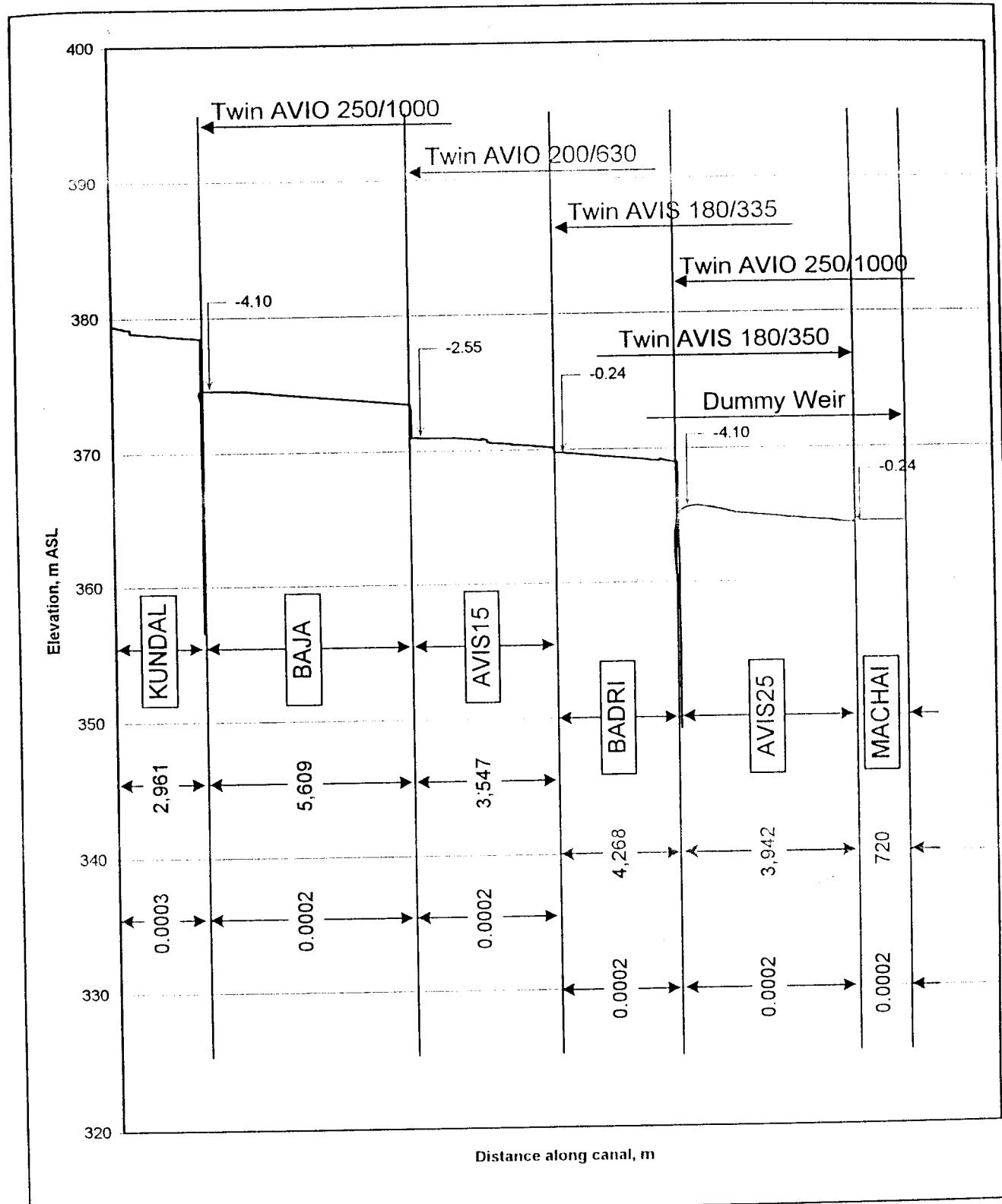


Figure 3. The Schematic of the Simplified PHLC.

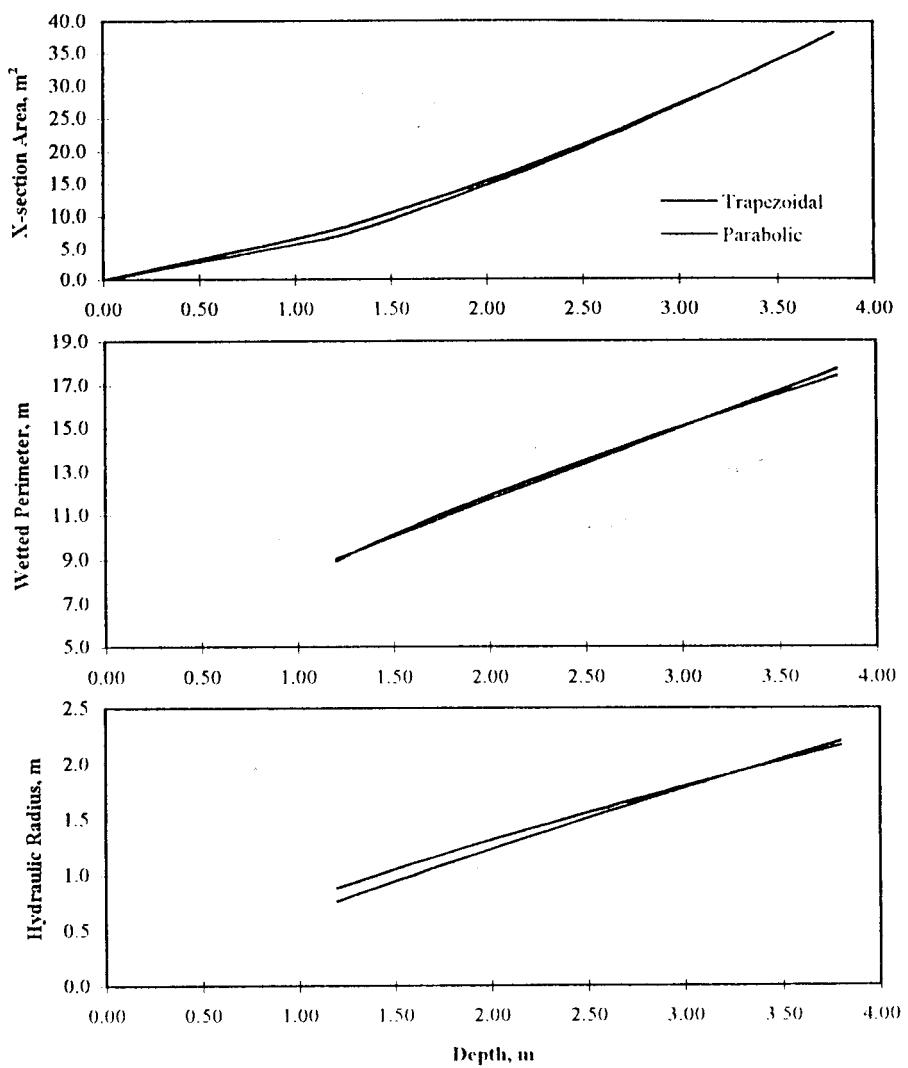


Figure 4. Hydraulic Comparison of Trapezoidal and Parabolic Cross-sections

In-line control structures are installed at the end of each reach, as shown in the schematic of Fig. 3 and the configuration data listed in Table 3. Either twin AVIO or twin AVIS gates are placed at the end of the first until the forth reach, but not for the last reach. The last reach of PHLC is linked to the Machai Branch Canal , but the Machai Branch Canal is not included in this simulation system, consequently, a dummy weir is therefore provided at the end of the last reach of PHLC in order to maintain a certain depth in the reach.

The *CanalMan* considers twin AVIO and AVIS structures as radial gates that are simulated using a Local Automation algorithm as explained in the previous section. On Table 2, dimensions are taken from the manufacturer document for the specific sizes of AVIO and AVIS. Coefficients ξ_{S1} and ξ_{S2} are calculated using Eq. 7. The values of invert "rise" indicate that the sill elevation of the control structures are located down below the previous reach end.

Head regulators and outlets exist along Kundal, Baja, AVIS15, and Badri reaches as shown in Table 4. There are neither head regulators nor outlets along the AVIS25 and Machai reaches. However, for the PHLC hydraulic simulation study, turnout structures are included at the most downstream end of AVIS25 and Machai reaches. Location and designed discharge are the only available data for these head regulators and outlets; therefore, *CanalMan* handles all of these structures as turnout structures and makes use of the Specified Flow Rate mode provided in the model. Using the Specified Flow Rate, the model will just release the specified flow rate through the turnouts. This is also considered as an approximation, since a constant rate of flow to the turnouts for a particular gate setting will occur only when a constant water level at the turnouts is provided.

Table 3. Configuration of In-line Structures.

	Reach Name	Structure Name (at the d/s end of Reach)	Twin	Width (m)	Height (m)	Inv.Rise (m)	
1.	KUNDAL	AVIO 250/1000L	2 x	4.50	2.20	-4.10	
2.	BAJA	AVIO 200/630L	2 x	1.80	3.55	-2.55	
3.	AVIS15	AVIS 180/335	2 x	3.90	3.05	-0.24	
4.	BADRI	AVIO 250/1000L	2 x	4.50	2.20	-4.10	
5.	AVIS25	AVIS 180/335	2 x	3.90	3.05	-0.24	
6.	MACHAI	DUMMY Weir		9.00	2.00	0.00	

	Reach Name	Structure Name (at the d/s end of Reach)	MaxSel (m)	r (m)	K	Es1	Es2
1.	KUNDAL	AVIO 250/1000L	2.20	2.50	2.00	0.285	1.00
2.	BAJA	AVIO 200/630L	3.55	2.00	2.00	0.283	1.00
3.	AVIS15	AVIS 180/335	3.00	1.80	4.10	0.256	1.00
4.	BADRI	AVIO 250/1000L	2.20	2.50	2.00	0.285	1.00
5.	AVIS25	AVIS 180/335	3.00	1.80	4.10	0.256	1.00
6.	MACHAI	DUMMY Weir	2.00	n/a	n/a		

Table 4. Offtaking Turnout Data for PHLC.

Reach Name Turnout Name	Location from u/s reach end (m)	Discharge (m ³ /s)	Accum. Discharg. (m ³ /s)	RD (m)
1. KUNDAL				
1.1 HR Shakray mr	1440	0.223	0.223	1440
1.2 Outlet1	1575	0.004	0.227	1575
1.3 Outlet2	1875	0.002	0.229	1875
1.4 HR Shakray wc	2550	0.036	0.265	2550
2. BAJA				
2.1 HR Miani dist	13	1.063	1.063	4500
2.2 HR Miami wc	63	0.018	1.081	4550
2.3 Outlet3	103	0.005	1.086	4590
2.4 Outlet4	413	0.006	1.092	4900
2.5 HR KC01	1473	0.053	1.145	5960
2.6 HR KOTHA mr	1773	0.232	1.377	6260
2.7 HR KCor	2753	0.060	1.437	7240
2.8 Outlet5	3133	0.001	1.438	7620
2.9 HR Baja mr	4163	0.203	1.641	8650
2.10 HR BS01	5263	0.080	1.721	9750
2.11 HR Bamkhel	5553	0.317	2.038	10040
3. AVIS15				
3.1 HR BN01	235	0.032	0.032	11720
3.2 Outlet6	465	0.011	0.043	11950
3.3 HR Bamkhel	555	0.090	0.133	12040
3.4 HR Tauheed	1835	0.188	0.321	13320
3.5 HR Saleem	3215	0.100	0.421	14700
4. BADRI				
4.1 TOPI15	1018	0.105	0.105	16050
4.2 TOPI16	2193	0.070	0.175	17225
5. AVIS25				
5.1 AVIS25 DUMMY	3900	10.000	n/a	n/a
6. MACHAI				
6.1 MACHAI DUMMY	700	10.000	n/a	n/a

6. PHLC Case Studies

6.1 Overview of Case Studies

In any case study, an unsteady flow condition is initiated throughout the entire simulation of the PHLC system. After hydraulic stability occurs in the system for awhile, then a disturbance will be introduced into the system; then, the automatic gates respond and the hydraulic conditions will be observed and recorded. Several simulation studies have been done and eight case studies are summarized and presented in Tables 5 and 6.

Table 5 shows conditions of five case studies including initial and final hydraulic status, outflow hydrography at a turnout in the most downstream end of the Machai reach, required recovery time, and the figure number to indicate the corresponding graphical results. The initial hydraulic status indicates the values of upstream and downstream flow depth at the end of each reach and also the average flow rate in the reach. The final status shows again values of depths and flow rate after simulation of a one-day period. The outflow hydrography at the Machai reach represents downstream demand from the Machai Branch Canal. In Case I, as an example, Machai water demand increased from 2.0 to 10.0 m³/s within 3 hours and then remained constant at this final flow demand. The required recovery time, listed just before the last column in Table 5, shows the time required for the automatic gates in each reach to adjust gate openings and attain a proper flow rate. Graphical results are shown in the figures indicated in the last column of Table 5.

Table 6 summarizes the roughness and low flow case studies. Case IV and VI show the effects of roughness coefficient using values of 0.016 and 0.022. Initial hydraulic conditions and disturbance (outflow hydrography) in Case IV and VI are exactly the same, except that the value of the roughness coefficient "n" in Case VI is 0.022 instead of 0.016. The graphical results in Fig. 10 (Case VI) show a delay in

Table 5. Flow Conditions for the Operations Case Studies.

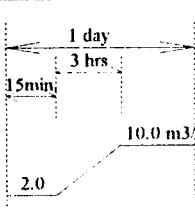
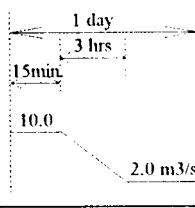
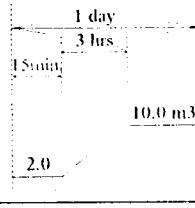
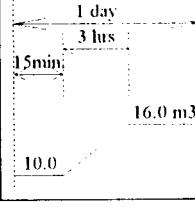
Reach Name	Initial Status (elapsed time = 0)			Final Status (elapsed time = 1 day)			Outflow Hydrograph at Machai Reach	Required Time for Recovering (hrs)	Graphical Results			
	Depth at Reach End		Flow Rate (m³/s)	Depth at Reach End		Flow Rate (m³/s)						
	U/S (m)	D/S (m)		U/S (m)	D/S (m)							
CASE I			14.672			22.262						
1. KUNDAL	2.873	3.697	14.596	2.866	3.586	22.257		approximately vary from 9 to 10 hrs	Fig. 5			
2. BAJA	2.666	3.622	14.676	2.651	3.294	22.227						
3. AVIS15	2.561	3.231	14.707	2.623	2.965	22.197						
4. BADRI	2.645	3.351	14.662	2.505	2.815	22.220						
5. AVIS25	2.666	3.318	14.696	2.647	3.056	22.176						
6. MACHAI	2.648	2.767	12.681	2.598	2.719	12.171						
CASE II			22.192			14.775						
1. KUNDAL	2.862	3.585	22.125	2.866	3.688	14.754		approximately vary from 1 to 2 hrs	Fig. 6			
2. BAJA	2.649	3.297	22.204	2.668	3.623	14.640						
3. AVIS15	2.623	2.966	22.182	2.651	3.232	14.651						
4. BADRI	2.507	2.821	22.206	2.645	3.352	14.690						
5. AVIS25	2.647	3.057	22.177	2.666	3.319	14.701						
6. MACHAI	2.598	2.719	12.174	2.648	2.767	12.683						
CASE III			22.192			9.933						
1. KUNDAL	2.862	3.585	22.125	2.859	3.713	10.211		approximately vary from 1 to 2 hrs	Fig. 7			
2. BAJA	2.649	3.297	22.204	2.678	3.729	9.793						
3. AVIS15	2.623	2.966	22.182	2.666	3.322	10.016						
4. BADRI	2.507	2.821	22.206	2.664	3.450	10.155						
5. AVIS25	2.647	3.057	22.177	2.678	3.405	10.022						
6. MACHAI	2.598	2.719	12.174	2.666	2.799	7.996						
CASE IV			9.933			17.545						
1. KUNDAL	2.859	3.713	10.211	2.866	3.663	17.693		approximately vary from 11 to 12 hrs	Fig. 8			
2. BAJA	2.678	3.729	9.793	2.659	3.521	17.777						
3. AVIS15	2.666	3.322	10.016	2.640	3.147	17.769						
4. BADRI	2.664	3.450	10.155	2.631	3.250	17.813						
5. AVIS25	2.678	3.405	10.022	2.660	3.236	17.757						
6. MACHAI	2.666	2.799	7.996	2.635	2.773	7.754						
CASE V			17.545			22.611						
1. KUNDAL	2.866	3.663	17.693	2.860	3.576	22.809		approximately vary from 8 to 9 hrs	Fig. 9			
2. BAJA	2.659	3.521	17.777	2.649	3.255	22.765						
3. AVIS15	2.640	3.147	17.769	2.620	2.934	22.771						
4. BADRI	2.631	3.250	17.813	2.437	2.572	22.773						
5. AVIS25	2.660	3.236	17.757	2.643	3.022	22.764						
6. MACHAI	2.635	2.773	7.754	2.526	2.662	6.767						

Table 6. Flow Conditions for the Hydraulic Roughness and Low-flow Operations Case Studies.

Reach Name	Initial Status (elapsed time = 0)			Final Status (elapsed time = 1 day)			Disturbance	Required Time for Recovering (hrs)	Graphical Results			
	Depth at Reach End		Flow Rate (m³/s)	Depth at Reach End		Flow Rate (m³/s)						
	U/S (m)	D/S (m)		U/S (m)	D/S (m)							
CASE VI												
1. KUNDAL	2.859	3.713	9.933	10.211	2.870	3.552	17.316	17.362	1 All conditions as in CASE IV, except... 2 change value of n from 0.016 to 0.022 for every reach			
2. BAJA	2.678	3.729	9.793	2.659	3.185	17.264			approximately vary from 17 to 18 hrs			
3. AVIS15	2.666	3.322	10.016	2.639	2.911	17.239						
4. BADRI	2.664	3.450	10.155	2.620	2.949	17.150						
5. AVIS25	2.678	3.405	10.022	2.570	2.991	17.234						
6. MACHAI	2.666	2.799	7.996	2.625	2.714	7.227						
CASE VII												
1. KUNDAL	2.775	3.623	4.376	4.638	2.781	3.644	7.559	5.895	After 1 hr. simulation, all turnouts along each reach supply water at full Qdesign.			
2. BAJA	2.690	3.786	5.118	2.676	3.774	3.347	4.823		fluctuate flow and depths			
3. AVIS15	2.683	3.385	3.565	2.663	3.347	4.040						
4. BADRI	2.685	3.522	4.366	2.684	3.512	4.222						
5. AVIS25	2.692	3.464	4.016	2.682	3.461	4.047						
6. MACHAI	2.686	2.828	4.065	2.684	2.826	4.051						
CASE VIII												
1. KUNDAL	2.658	3.512	4.452	3.512	2.514	3.390	8.468	4.237	After 1 hr. simulation, all turnouts along each reach shut down.			
2. BAJA	2.637	3.725	3.725	2.691	3.840	3.930			fluctuate flow and depths			
3. AVIS15	2.663	3.381	3.381	2.658	3.363	3.935						
4. BADRI	2.681	3.524	3.524	2.678	3.513	4.362						
5. AVIS25	2.687	3.461	3.461	2.689	3.465	3.988						
6. MACHAI	2.687	2.828	2.828	2.684	2.824	4.042						

stabilizing the simulated canal system compared to those results in Fig. 8 (Case IV). Required recovery time in Cases IV and VI are approximately 12 and 18 hours, respectively.

Cases VII and VIII simulate low flow operation in the PHLC with increasing and decreasing in water demand from turnouts along the reaches. The flow rate in Case VII is initiated at approximately $4.0 \text{ m}^3/\text{s}$ variation from reach to reach, as presented in Table 6, without supplying water to any turnout. After one hour of the simulation period, all turnouts supplying water at their full designed discharge. Case VIII starts the simulation at an average flow rate of $3.5 \text{ m}^3/\text{s}$ with full water supply for every turnouts, then, all turnouts are instantly shut down after one hour of the simulation period. Figures 11 and 12 show the graphical results from Cases VII and VIII. As the total design flow rate for the turnouts are 0.265, 2.038, 0.421, and 0.175 in Kundal, Baja, AVIS15, and Badri reaches, respectively, the fluctuation of flows and depths are noticeable in these reaches. The fluctuations vary from less to more at downstream to upstream reaches, and can be observed for the entire one-day simulation period.

The details for each case study are listed below:

6.2 Details of Case Studies

Case I

Initial flow rate in the canal reaches are approximately $14.6 - 14.7 \text{ m}^3/\text{s}$, which is about 50% of canal capacity of $28.2 \text{ m}^3/\text{s}$. At this stage, the system is almost stable with the downstream depth for every automatic gate close to the targets. Note that the downstream depth of a control structure is the upstream depth of the next downstream reach. The outflow hydrograph at the downstream of Machai reach represents the water requirement from Machai Branch. The required flow rate was increased from 2 to $10 \text{ m}^3/\text{s}$ within 3 hours. Graphical results in Fig. 5 show that the

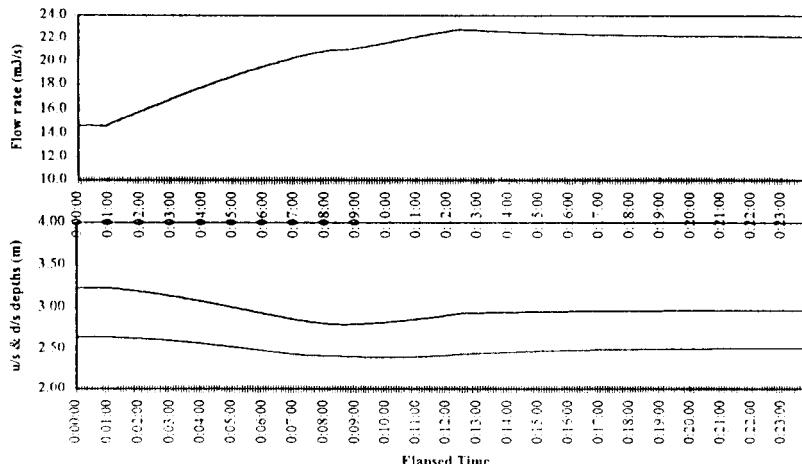
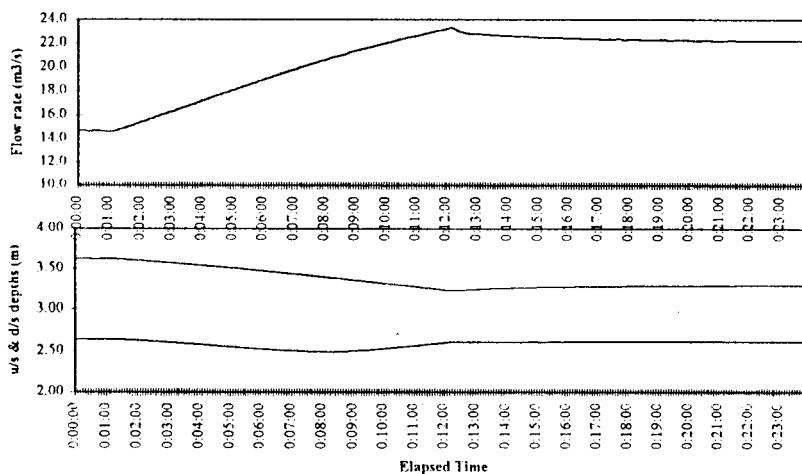
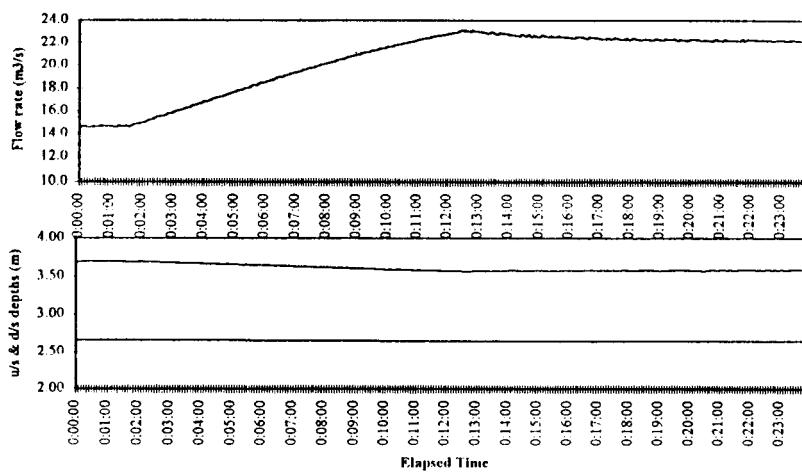
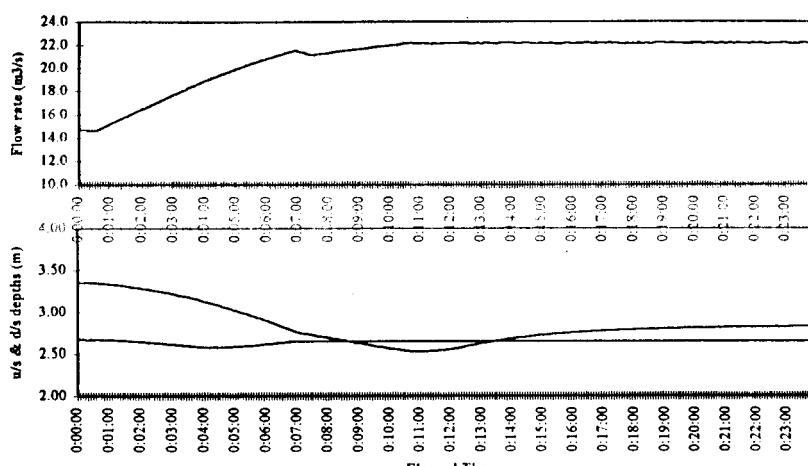
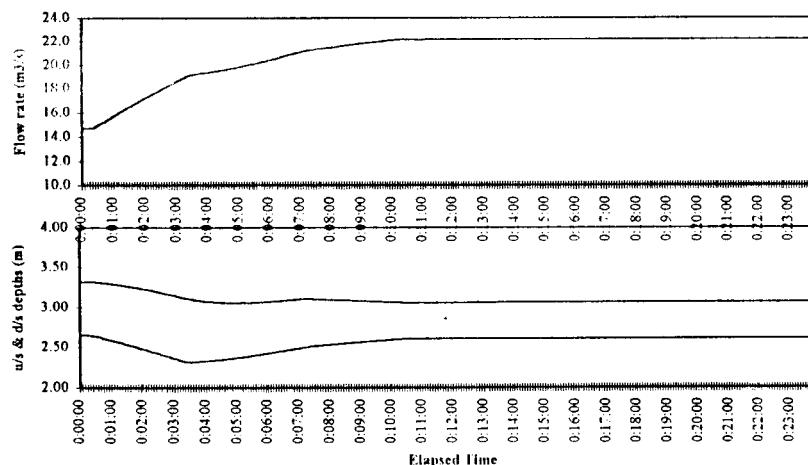


Figure 5. Hydraulic Response of PHLC for Case Study I.

BADRI
Twin AVIO 250/1000



AVIS25
Twin AVIS 180/335



MACHAI
Dummy Weir

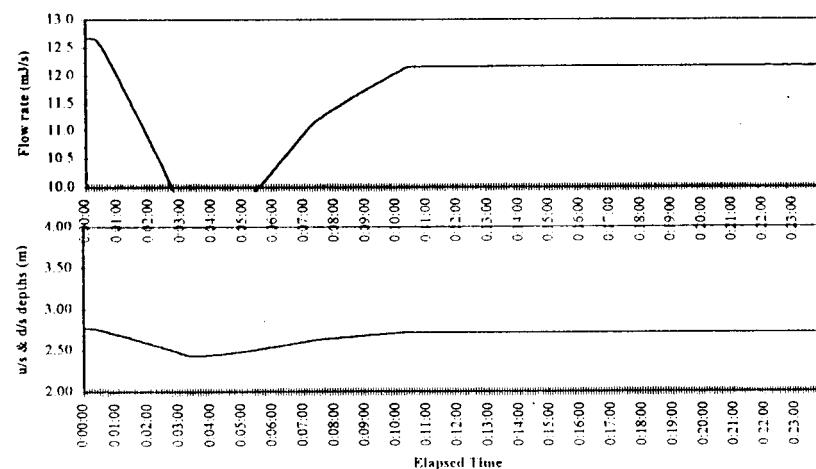


Figure 5. (Contd.)

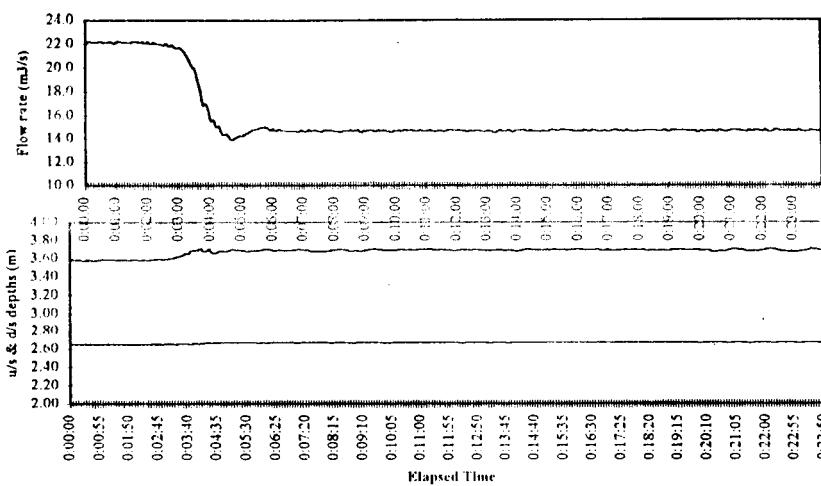
AVIS25 gates respond in 5 min. after increasing the flow. Consequently, BADRI and AVIS15 gates start to increase their gate opening. The last one, KUNDAL gates start increasing the opening one hour after increasing the flow in the Machai reach. All gates are adjusted smoothly without much fluctuation. Control depths vary from 0.1 to 0.2 m over a period of 9 - 10 hours. However, more time is needed when increasing the flow rate to 22 m³/s.

Case II

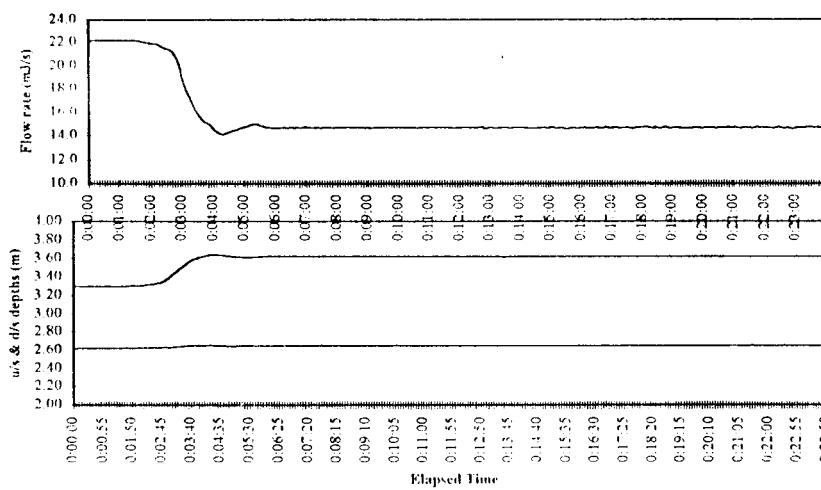
Case II is a reverse procedure of Case I. The initial flow rate in the canal system is about 22.2 m³/s. The Machai Branch required flow rate was decreased from 10 to 2 m³/s within 3 hours. The graphical results show rapid response of the system. The control depths are almost constant without significant variation. The flow rate dropped very fast within 1-3 hours to a new equilibrium. This is a typical phenomena of a downstream control system. (Fig. 6).

Case III

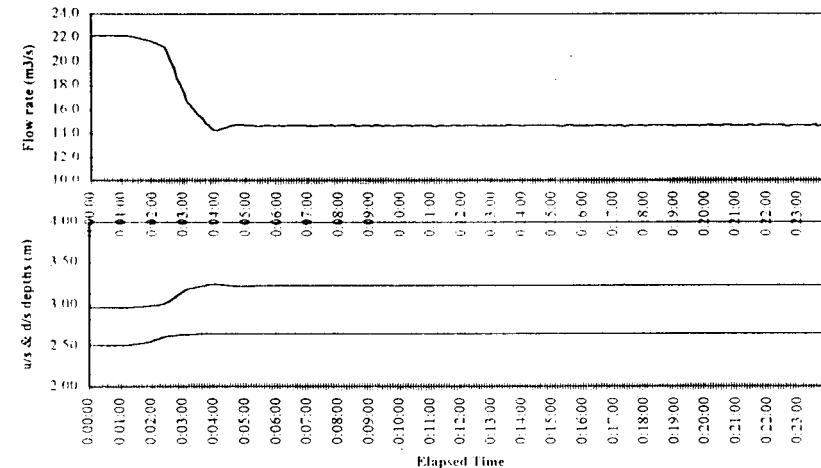
Since performance of the simulated canal is very good in Case II, conditions in Case III were made more severe. The initial status is almost the same as those in Case II, except that the crest elevation of the dummy weir at Machai reach is increased. Noticed that there are two disturbances in this case. First, the required flow rate in the Machai Branch was decreased from 10 to 2 m³/s within 3 hours. Second, the flow rate through the dummy weir is suddenly decreased from 12.5 to 8.0 m³/s. Fortunately, the performance of the simulated system is still very good as in Case I. (Fig. 7).



KUNDAL
Twin AVIO 250/1000



BAJA
Twin AVIO 200 630



AVIS15
Twin AVIS 180 335

Figure 6. Hydraulic Response of PHLC for Case Study II.

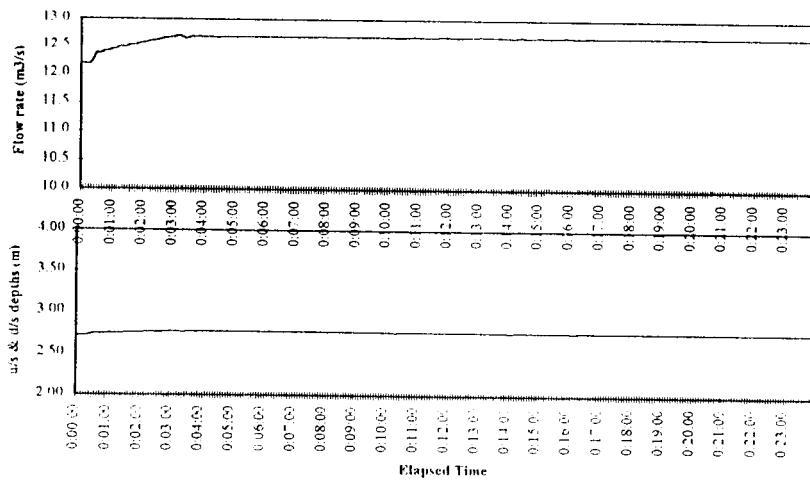
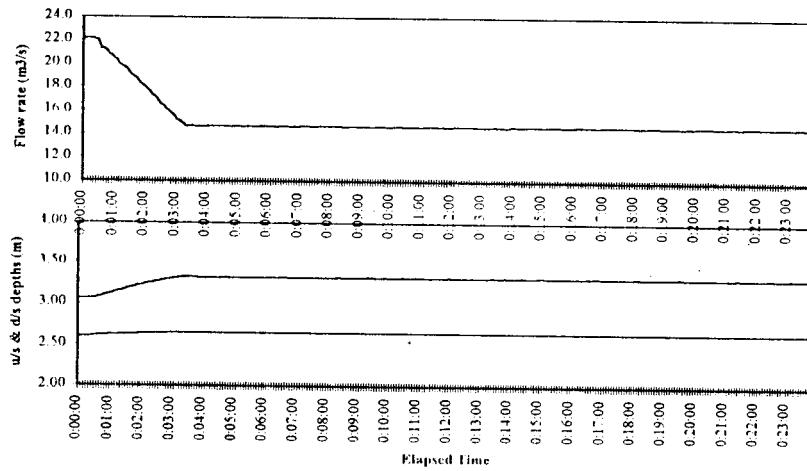
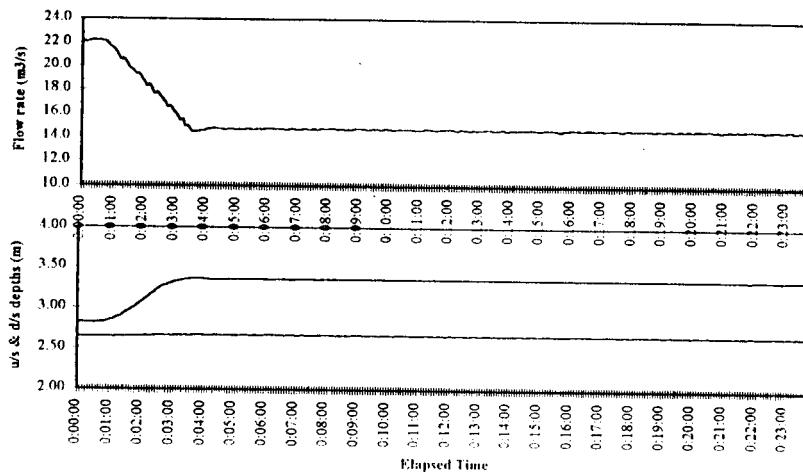
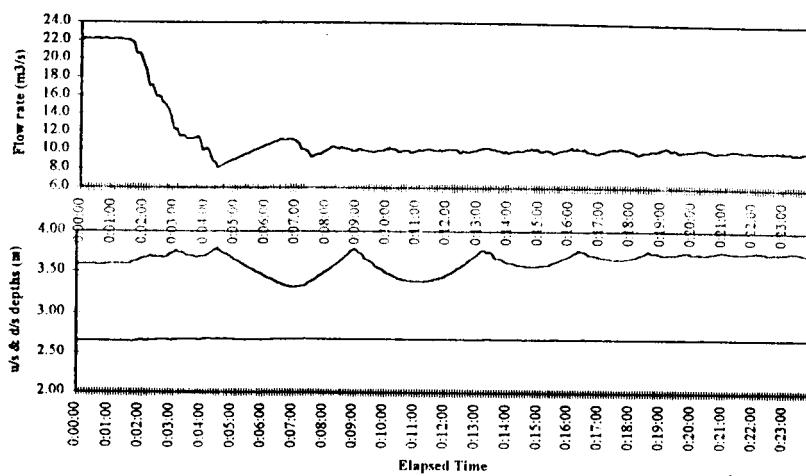
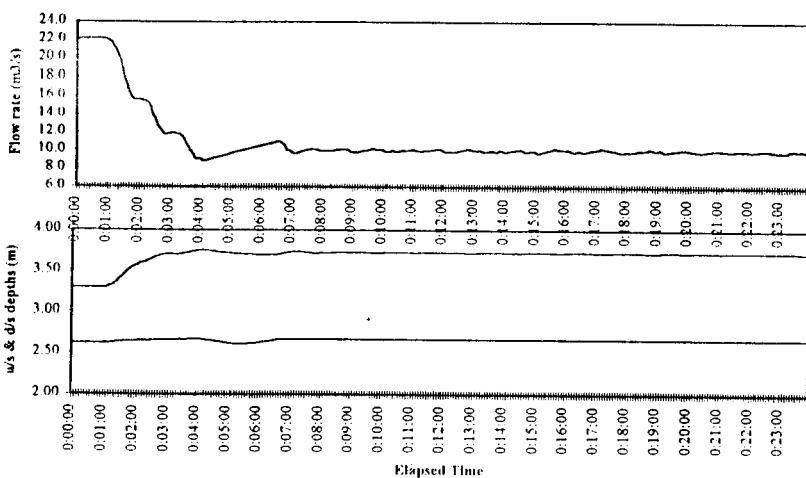


Figure 6. (Contd.)

KUNDAL
Twin AVIO 250/1000



BAJA
Twin AVIO 200/630



AVIS15
Twin AVIS 180/335

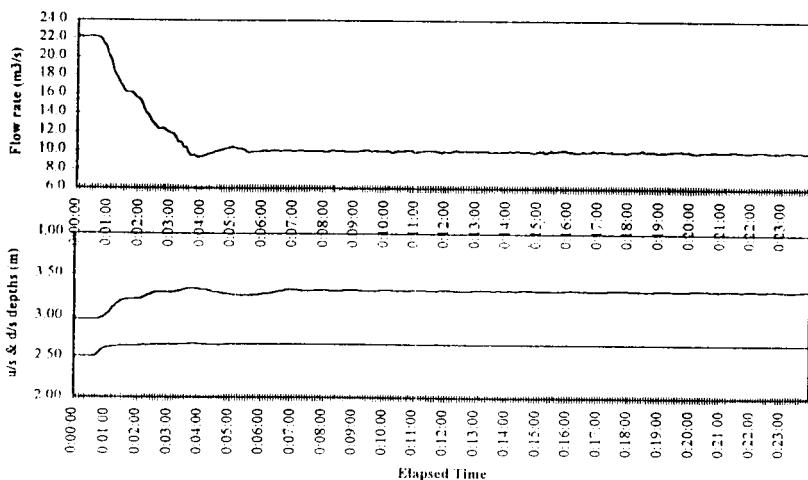
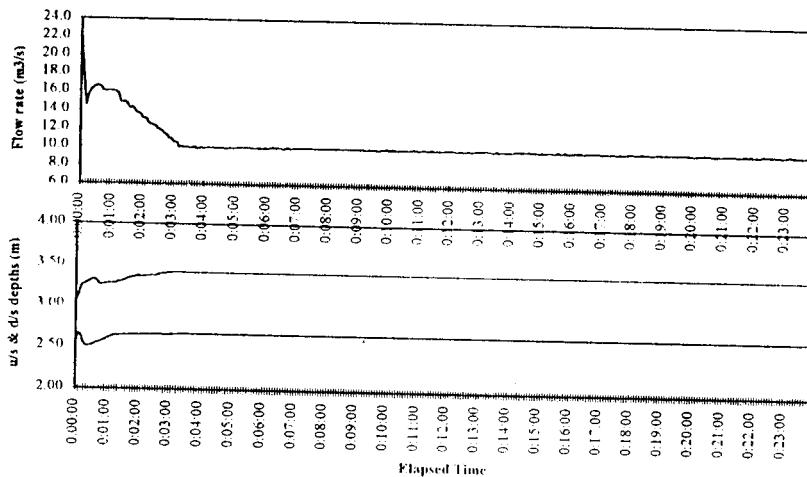
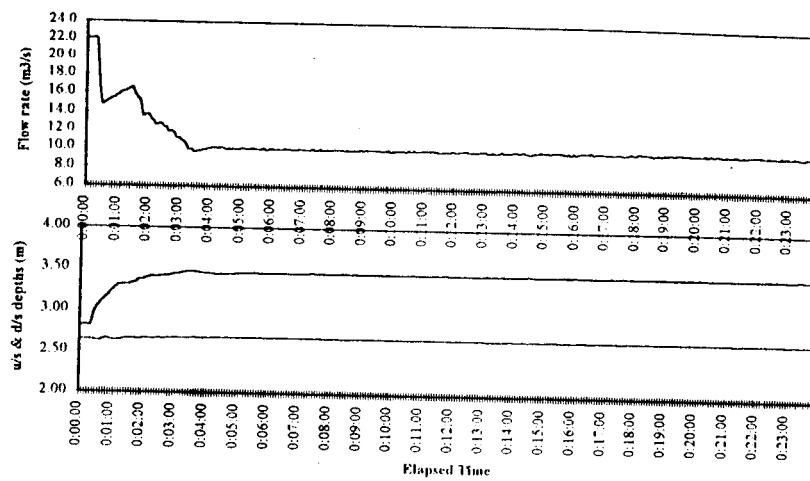
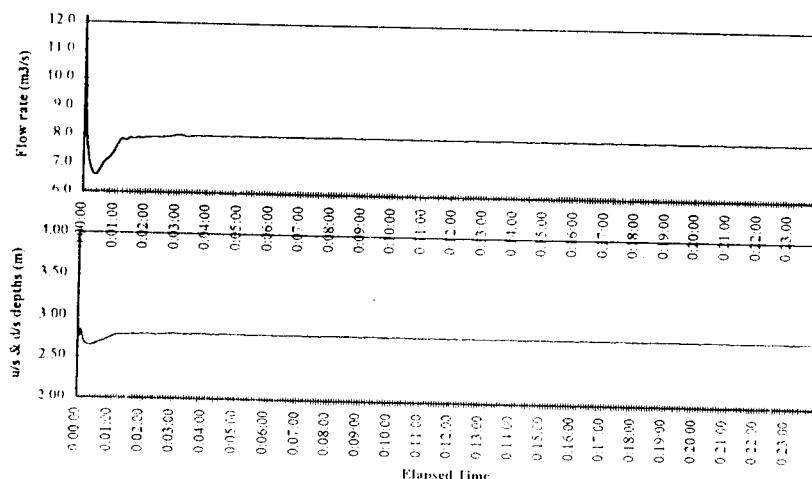


Figure 7. Hydraulic Response of PHLC for Case Study III.

BADRI
Twin AVIO 250/1000



AVIS25
Twin AVIS 180 335



MACHAI
Dummy Weir

Figure 7. (Contd.)

Cases IV and V

From the several runs in Cases II and III, It is clear that decreasing the downstream flow demand will not cause any major problem to the canal system. In Cases IV and V, therefore, the required flow was increased.

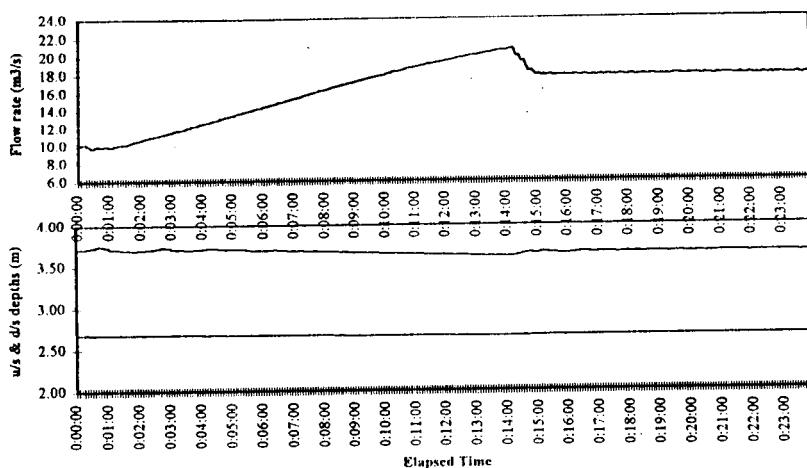
Case IV starts with an initial flow rate of about 10 m³/s with about 8 m³/s passing through the dummy weir at the tail of Machai reach. The required flow rate was increased from 2 to 10 m³/s. However, the percent of increase of flow in this case is considered higher than in Case I. There is about an 80% flow change in this case, while only about a 55% flow change in Case I. More variation of flow depths can be seen in this case as compared with Case I. In addition, overshooting of the flow rates occurs, which are significant in this case. (Fig. 8).

Case V starts from the final status of Case IV; however, the required flow hydrograph is modified. The flow rate was increased from 10 to 16 m³/s. The important objective of this case is to observe a very high flow rate in the canal system (almost full capacity). However, the simulation model in this situation could not increase the flow rate to more than 22.8 m³/s. The twin AVIS gates at two locations are the constraint. (Fig. 9)

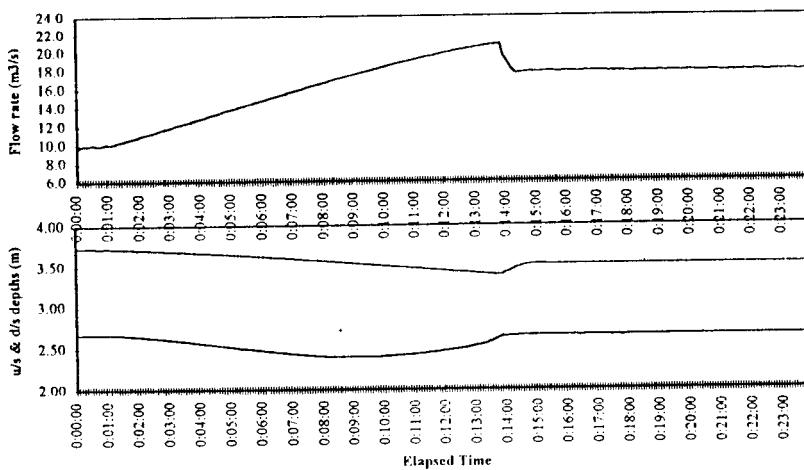
Case VI

Case VI simulates the same condition as Case IV, but the roughness value is changed from 0.016 to 0.022. The performance of the system is almost the same, except that Case VI need more recovery time. (Fig. 10).

KUNDAL
Twin AVIO 250/1000



BAJA
Twin AVIO 200/630



AVIS15
Twin AVIS 180/335

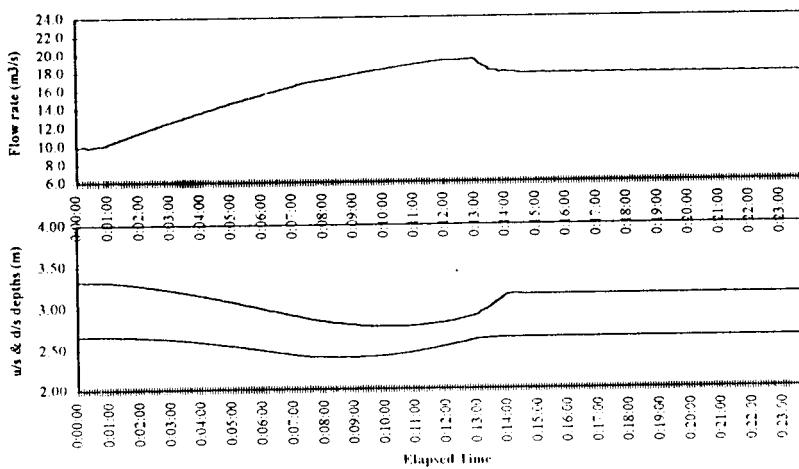
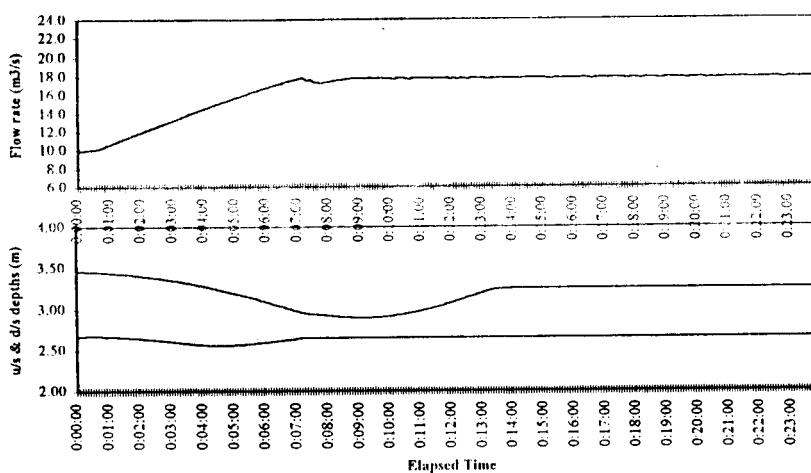
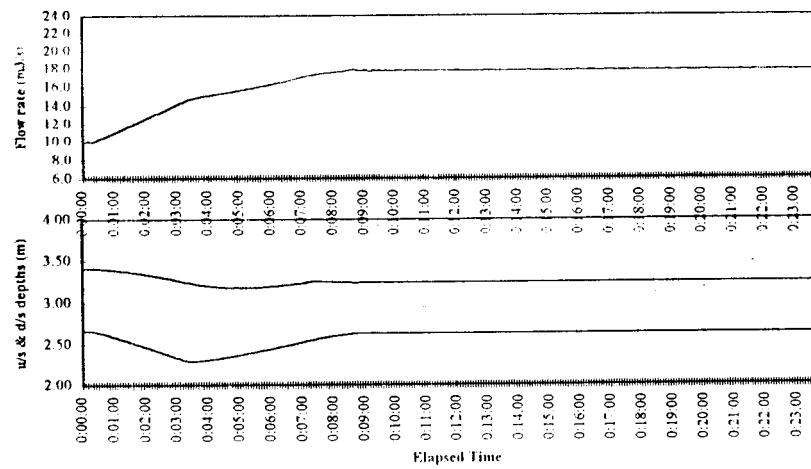


Figure 8. Hydraulic Response of PHLC for Case Study IV.

BADRI
Twin AVIO 250 1000



AVIS25
Twin AVIS 180 335



MACHAI
Dummy Weir

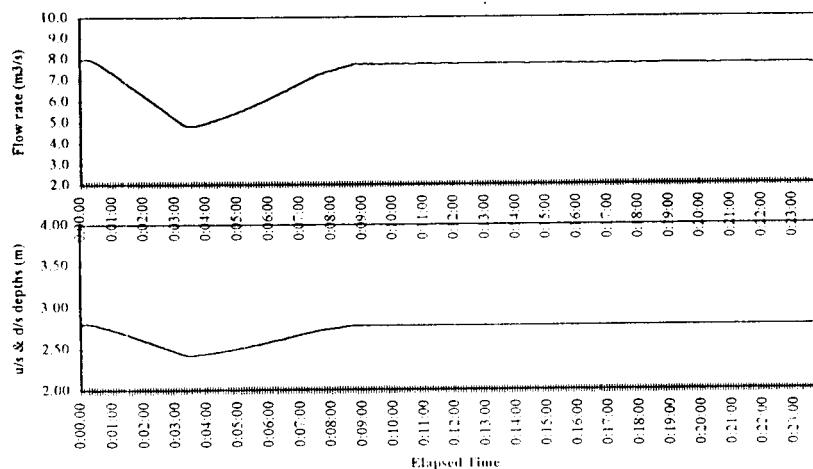
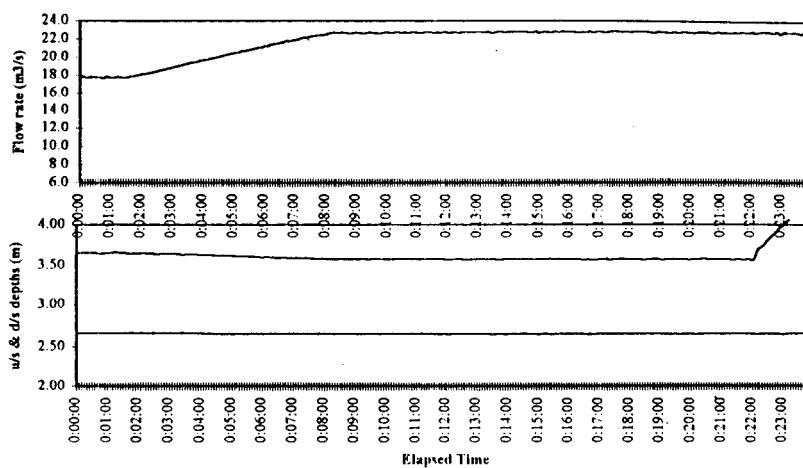
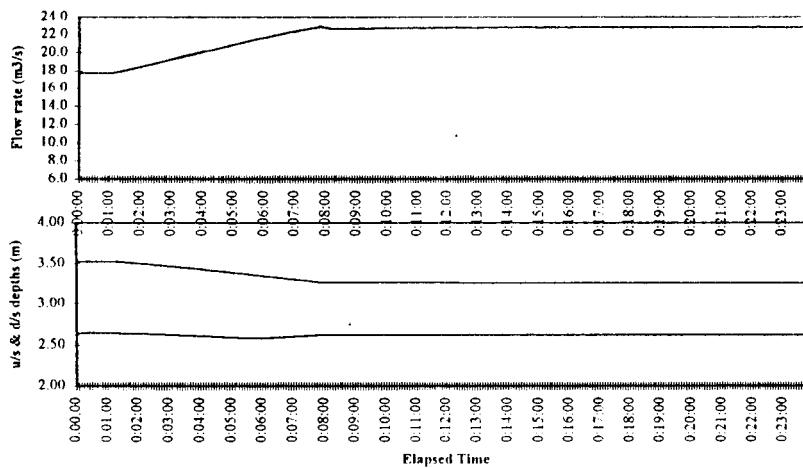


Figure 8. (Contd.)

KUNDALI
Twin AVIO 250/1000



BAJA
Twin AVIO 200/630



AVIS15
Twin AVIS 180/335

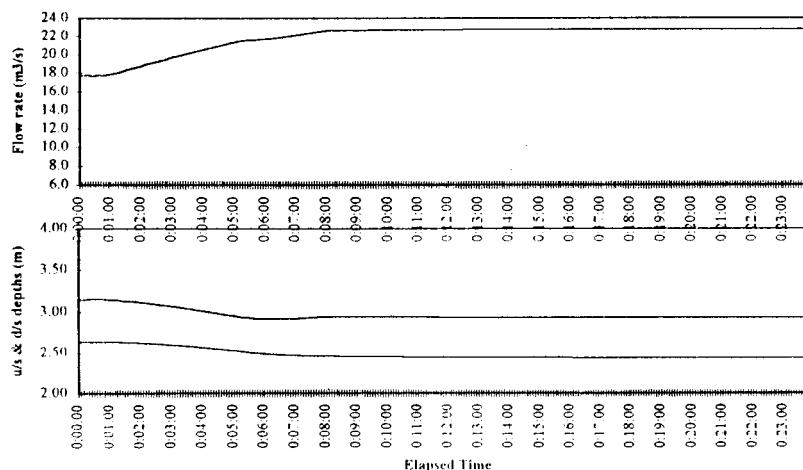
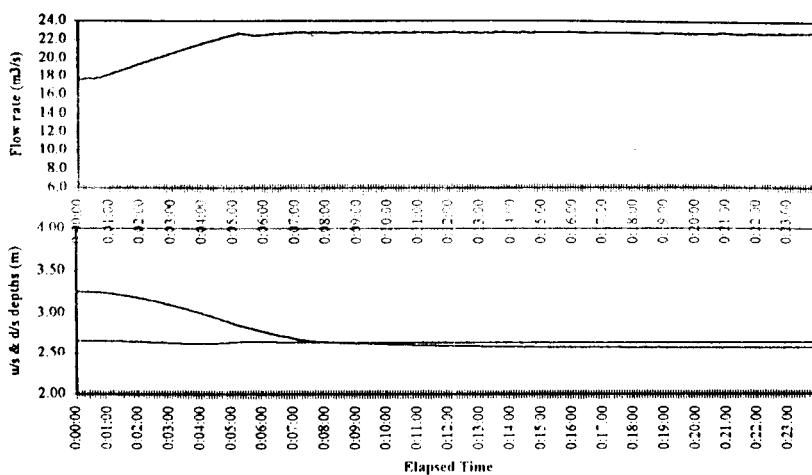
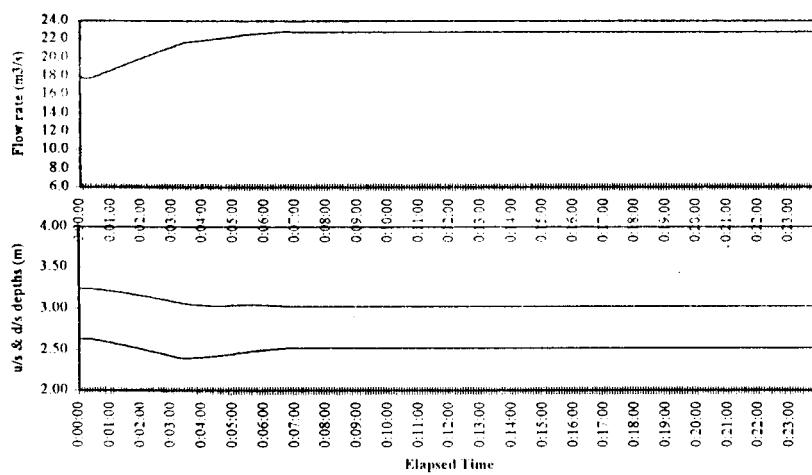


Figure 9. Hydraulic Response of PHLC for Case Study V.

BADRI
Twin AVIO 250/1000



AVIS25
Twin AVIS 180/335



MACHAI
Dumung Weir

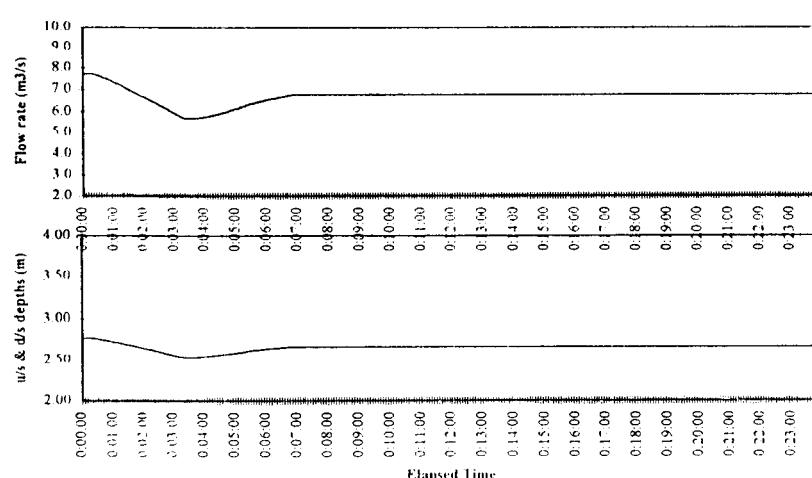
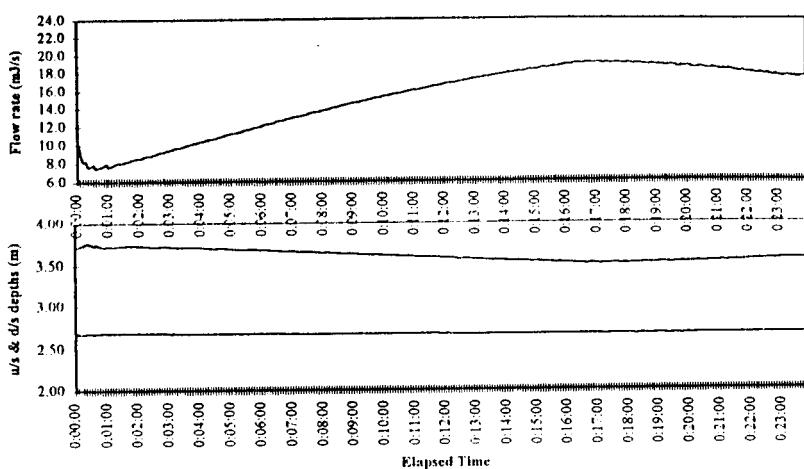
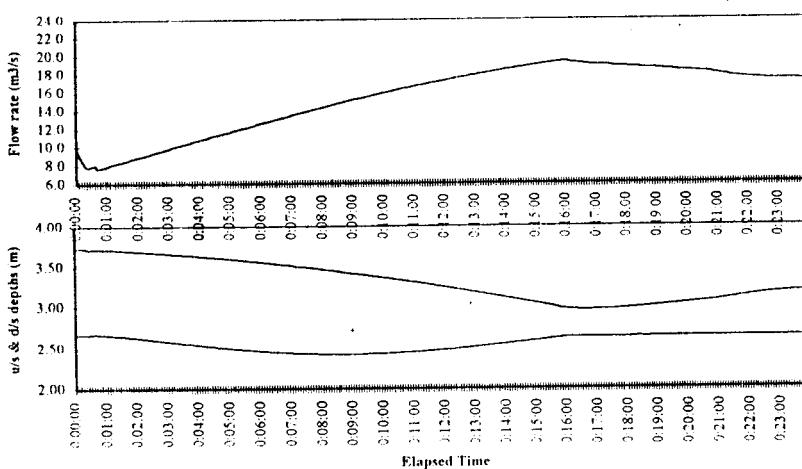


Figure 9. (Contd.)

KUNDAL
Twin AVIO 250/1000



RAJA
Twin AVIO 200/630



AVIST5
Twin AVIS 180/335

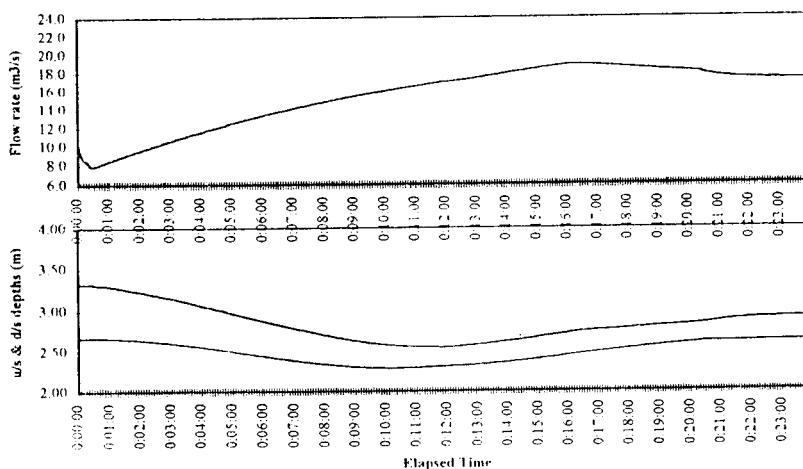


Figure 10. Hydraulic Response of PHLC for Case Study VI.

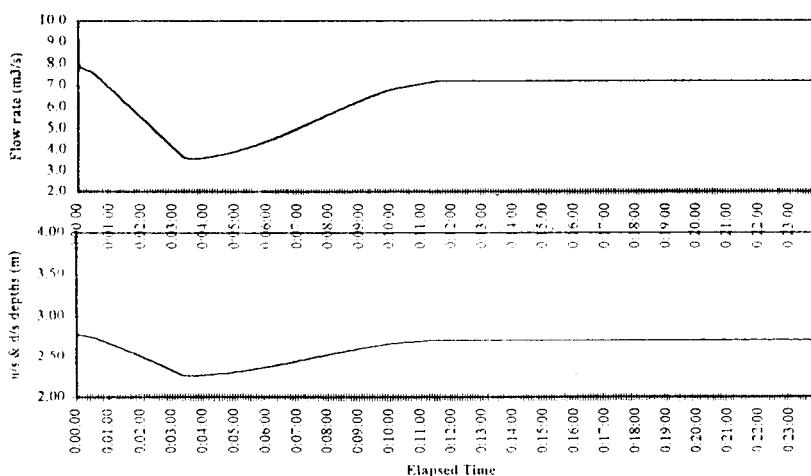
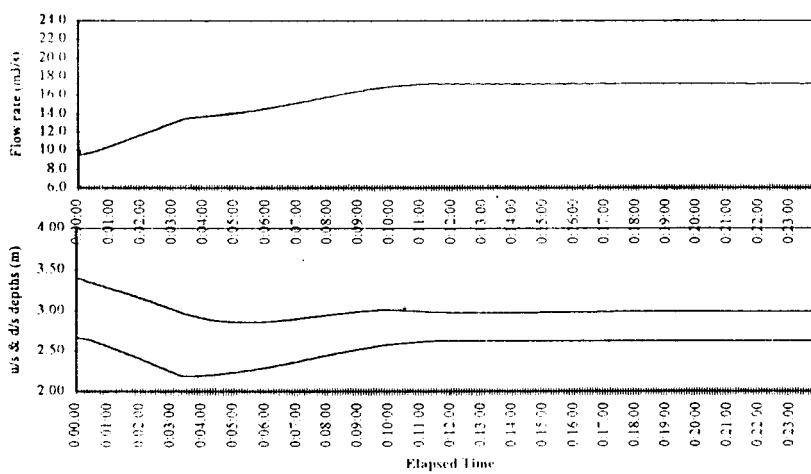
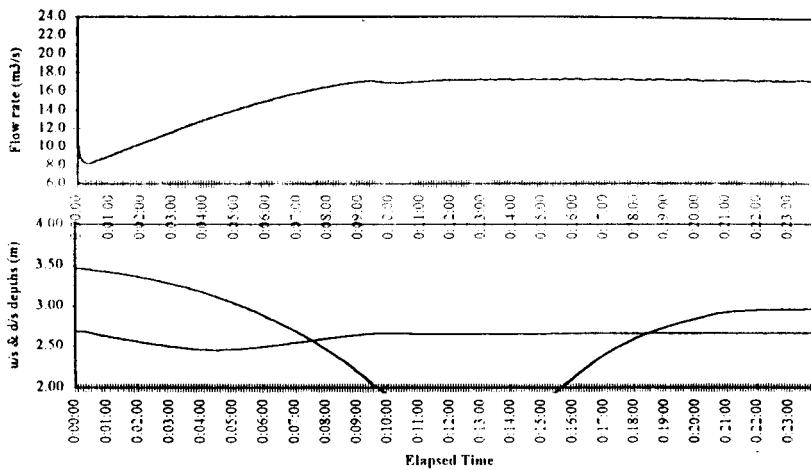


Figure 10. (Contd.)

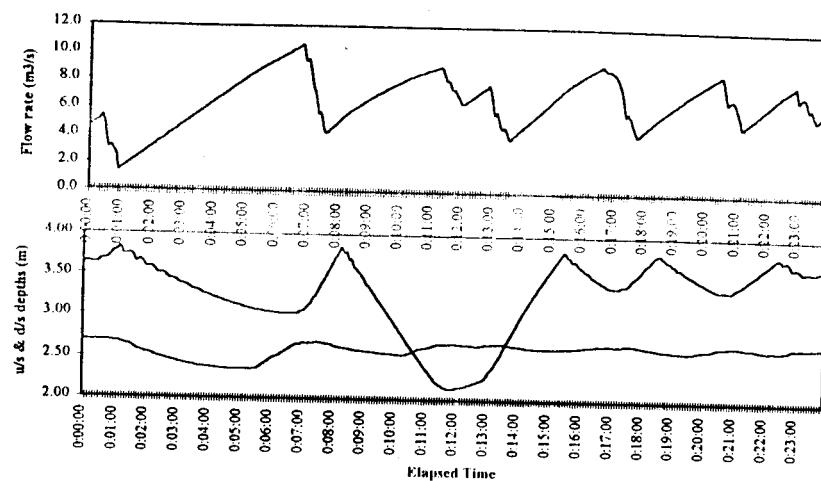
Cases VII and VIII

These two cases represent low flow in the canal. The initial flow rate is about 3.4 to 3.6 m³/s, which is only 13% of full canal capacity. The downstream water requirement from Machai branch is assumed to be zero. The water demand of 2.899 m³/s from all turnouts along the canal are a disturbance in these cases. This amount of water represents a 80% flow change in the low flow condition. Graphical results in Figures 11 and 12 show the fluctuation of flow rate. A comparison between these two cases and Case IV shows that an 80% flow change under low flow conditions may not be suitable for canal operation.

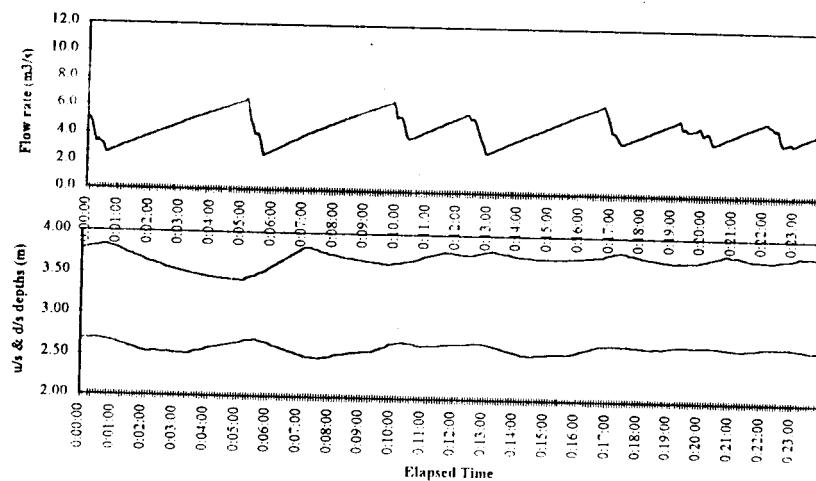
Water Levels

Finally, the simulation model was operated using the designed discharges. For each reach, the discharge rate, flow depth and velocity are listed for each nodal point in Table 7.

KUNDAL
Twin AVIO 250/1000



BAJA
Twin AVIO 200/630



AVIS15
Twin AVIS 180/335

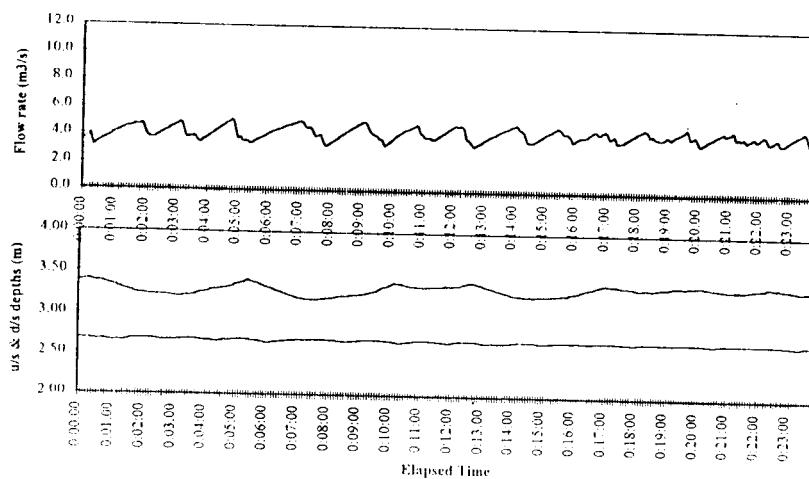
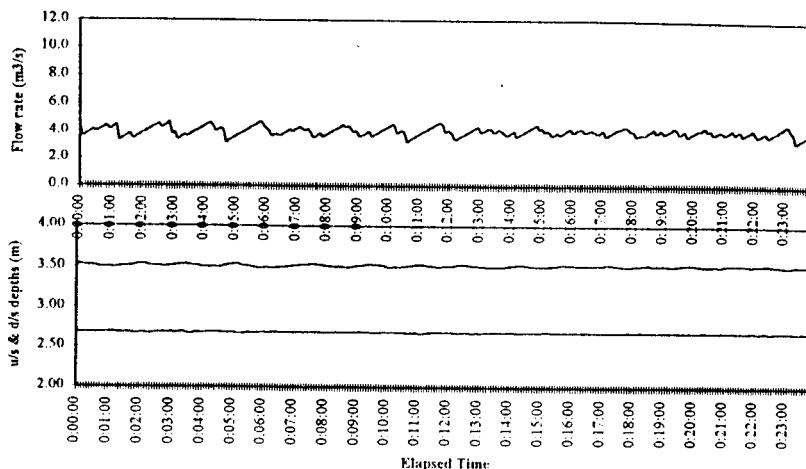
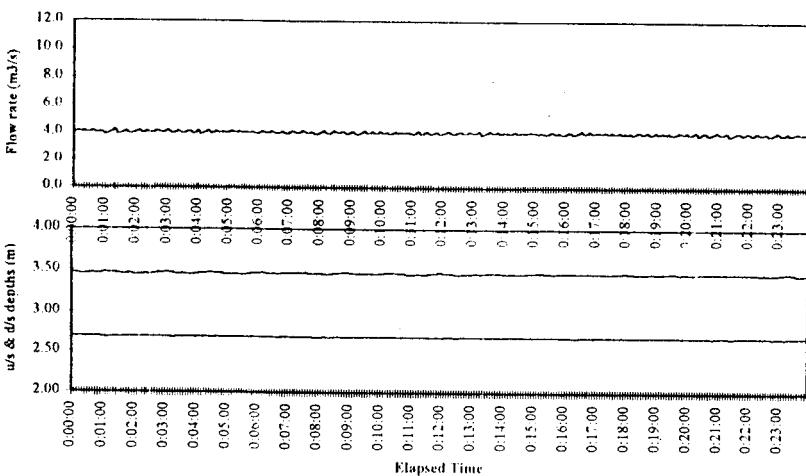


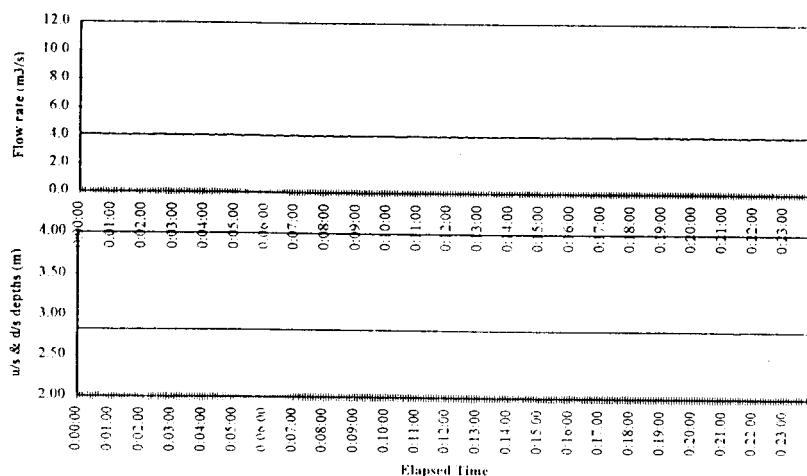
Figure 11. Hydraulic Response of PHLC for Case Study VII.



BADRI
Twin AVIO 250/1000



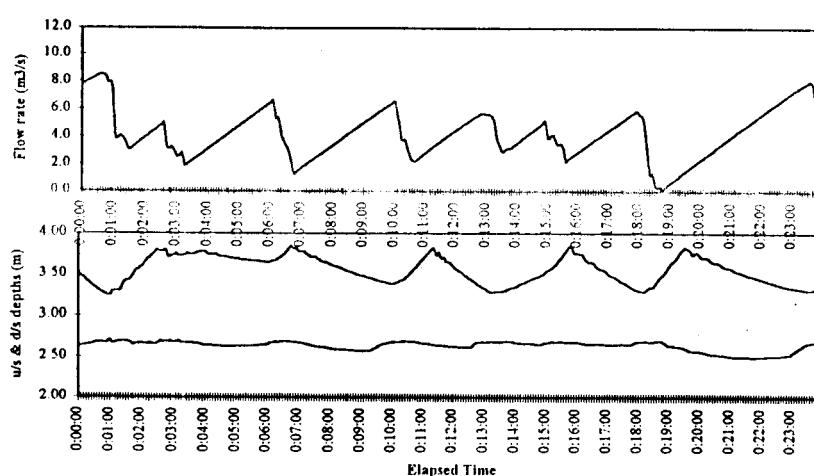
AVIS25
Twin AVIS 180 335



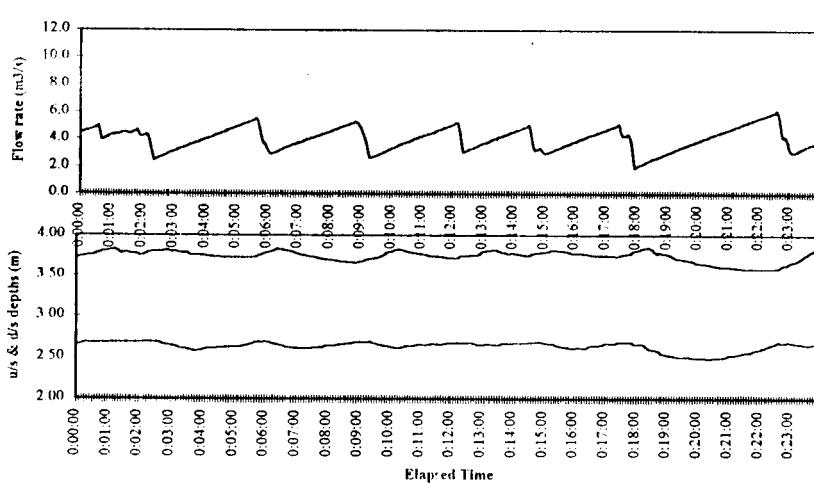
MACHAI
Dummy Weir

Figure 11. (Contd.)

KUNDAL
Twin AVIO 250/1000



BAJA
Twin AVIO 200/630



AVIS15
Twin AVIS 180/335

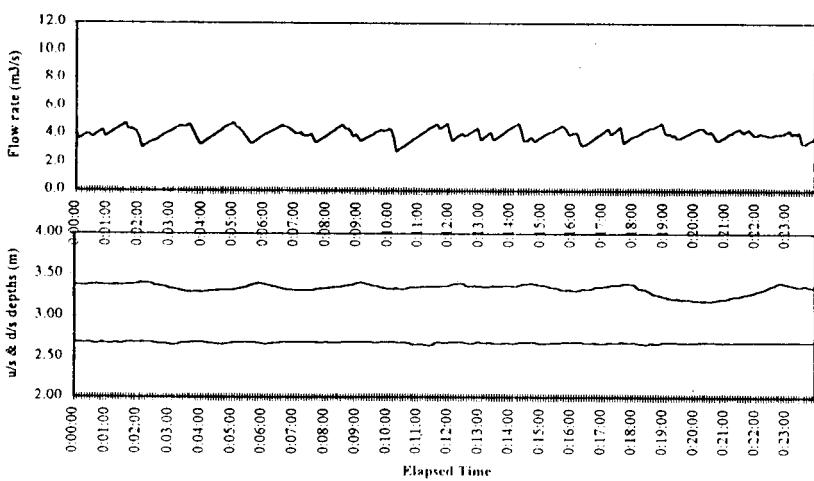
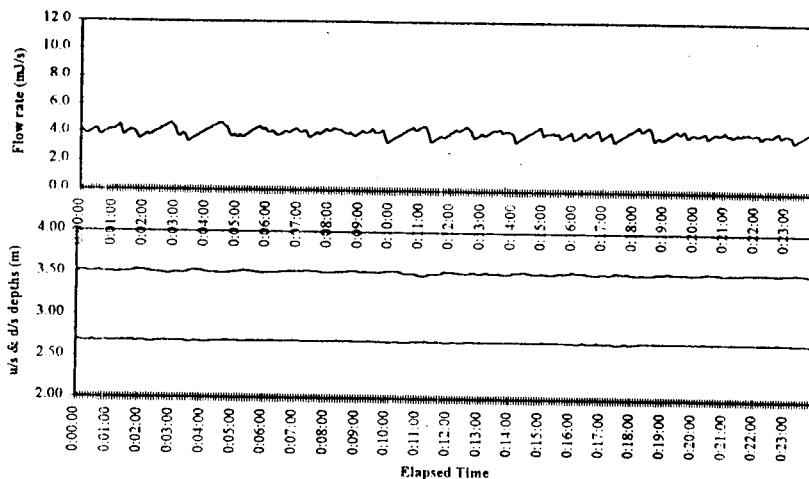
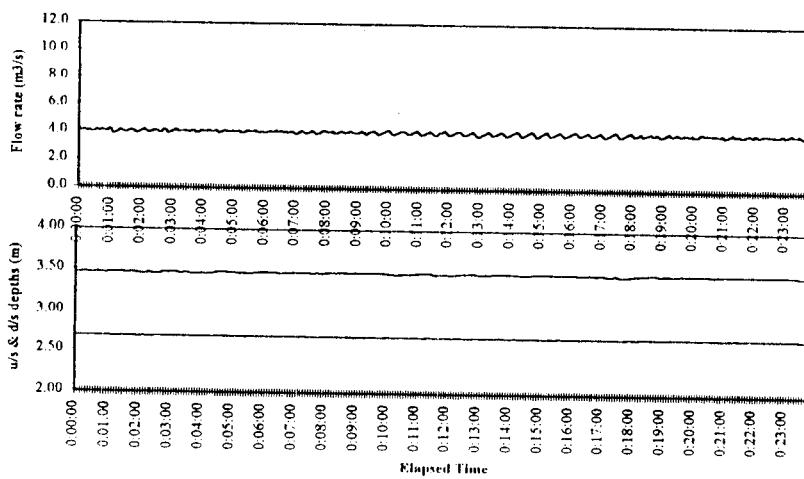


Figure 12. Hydraulic Response of PHLC for Case Study VIII.

BADRI
Twin AVIO 250/1000



AVIS25
Twin AVIS 180/335



MACHAI
Dummy Weir

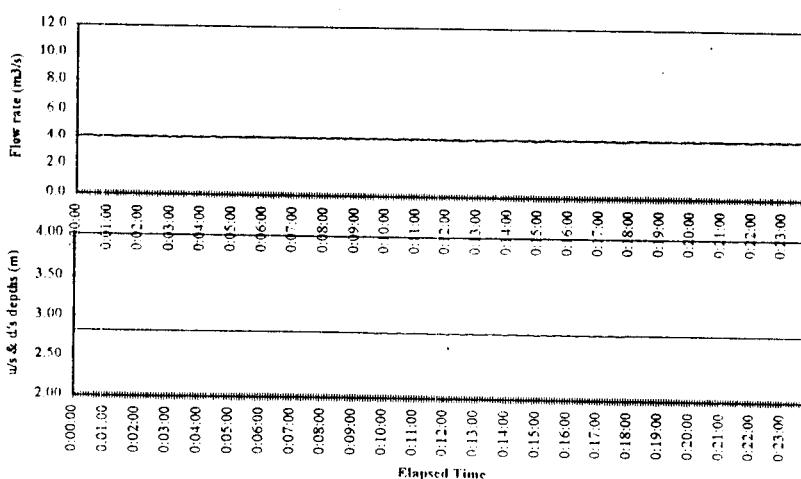


Figure 12. (Contd.)

Table 7. Water Levels for Design Discharge Rates along PHLC.

Reach Name: KUNDAL					
Node Number	Distance (m)	Flow Area (m ²)	Flow Rate (m ³ /s)	Flow Depth (m)	Velocity (m/s)
-	-	25.198	27.979	2.855	1.110
1	113.9	25.450	28.111	2.875	1.105
2	227.8	25.696	28.176	2.894	1.097
3	341.7	25.939	28.200	2.913	1.087
4	455.5	26.187	28.222	2.933	1.078
5	569.4	26.437	28.223	2.952	1.068
6	683.3	26.691	28.213	2.972	1.057
7	797.2	26.954	28.208	2.992	1.047
8	911.1	27.224	28.207	3.013	1.036
9	1,025.0	27.502	28.205	3.034	1.026
10	1,138.9	27.785	28.192	3.055	1.015
11	1,252.7	28.073	28.170	3.077	1.003
12	1,366.6	28.366	28.144	3.099	0.992
13	1,440.3	28.559	28.128	3.114	0.985
14	1,441.8	28.680	26.905	3.123	0.938
15	1,480.5	28.788	26.897	3.131	0.934
16	1,574.3	29.052	26.884	3.150	0.925
17	1,575.8	29.060	26.839	3.151	0.924
18	1,594.4	29.113	26.838	3.155	0.922
19	1,708.3	29.442	26.831	3.179	0.911
20	1,822.2	29.779	26.833	3.204	0.901
21	1,874.3	29.936	26.836	3.216	0.896
22	1,875.8	29.942	26.814	3.216	0.896
23	1,936.0	30.126	26.818	3.230	0.890
24	2,049.9	30.477	26.826	3.255	0.880
25	2,163.8	30.835	26.832	3.281	0.870
26	2,277.7	31.201	26.833	3.308	0.860
27	2,391.6	31.572	26.830	3.335	0.850
28	2,505.5	31.949	26.824	3.361	0.840
29	2,549.3	32.095	26.822	3.372	0.836
30	2,550.8	32.127	26.462	3.374	0.824
31	2,619.4	32.358	26.462	3.391	0.818
32	2,733.2	32.742	26.471	3.418	0.808
33	2,847.1	33.129	26.485	3.445	0.799
34	2,961.0	33.521	26.494	3.473	0.790
Average		29.199	27.320	3.158	0.943

Reach Name: BAJA					
Node Number	Distance (m)	Flow Area (m ²)	Flow Rate (m ³ /s)	Flow Depth (m)	Velocity (m/s)
35	-	22.546	26.494	2.641	1.175
36	12.3	22.549	26.493	2.641	1.175
37	13.8	22.692	25.430	2.653	1.121
38	62.3	22.713	25.428	2.654	1.120
39	63.8	22.843	24.410	2.665	1.069
40	102.3	22.867	24.407	2.667	1.067
41	103.8	22.874	24.356	2.668	1.065
42	200.3	22.936	24.344	2.673	1.061
43	400.6	23.068	24.321	2.684	1.054
44	412.3	23.076	24.320	2.684	1.054
45	413.8	23.078	24.314	2.684	1.054
46	601.0	23.212	24.310	2.695	1.047
47	801.3	23.365	24.326	2.708	1.041
48	1,001.6	23.525	24.345	2.721	1.035
49	1,201.9	23.689	24.344	2.734	1.028
50	1,402.3	23.859	24.339	2.748	1.020
51	1,472.3	23.921	24.339	2.753	1.017
52	1,473.8	23.928	24.287	2.754	1.015
53	1,602.6	24.045	24.287	2.763	1.010
54	1,772.3	24.202	24.277	2.776	1.003
55	1,773.8	24.229	24.045	2.778	0.992
56	1,802.9	24.257	24.041	2.780	0.991
57	2,003.2	24.455	24.017	2.796	0.982
58	2,203.5	24.662	24.000	2.812	0.973
59	2,403.9	24.880	23.998	2.830	0.965
60	2,604.2	25.108	24.005	2.848	0.956
61	2,752.3	25.283	24.012	2.862	0.950
62	2,753.8	25.291	23.952	2.862	0.947
63	2,804.5	25.352	23.955	2.867	0.945
64	3,004.8	25.600	23.968	2.887	0.936
65	3,132.3	25.761	23.975	2.899	0.931
66	3,133.8	25.764	23.965	2.900	0.930
67	3,205.1	25.856	23.967	2.907	0.927
68	3,405.5	26.117	23.967	2.927	0.918
69	3,605.8	26.384	23.961	2.948	0.908
70	3,806.1	26.661	23.952	2.969	0.898
71	4,006.4	26.946	23.943	2.991	0.889
72	4,162.3	27.175	23.938	3.009	0.881
73	4,163.8	27.195	23.735	3.010	0.873
74	4,206.8	27.260	23.735	3.015	0.871
75	4,407.1	27.567	23.739	3.039	0.861
76	4,607.4	27.882	23.751	3.063	0.852
77	4,807.7	28.206	23.764	3.087	0.843
78	5,008.0	28.539	23.766	3.112	0.833
79	5,208.4	28.882	23.754	3.138	0.822
80	5,262.3	28.976	23.750	3.145	0.820
81	5,263.8	28.985	23.669	3.145	0.817
82	5,408.7	29.238	23.665	3.164	0.809
83	5,552.3	29.490	23.674	3.183	0.803
84	5,553.8	29.517	23.357	3.185	0.791
85	5,609.0	29.619	23.354	3.192	0.788
Average		25.414	24.168	2.869	0.959

Reach Name: AVIS15					
Node Number	Distance (m)	Flow Area (m ²)	Flow Rate (m ³ /s)	Flow Depth (m)	Velocity (m/s)
86	-	22.268	23.354	2.617	1.049
87	136.4	22.359	23.352	2.625	1.044
88	234.3	22.424	23.337	2.630	1.041
89	235.8	22.429	23.305	2.631	1.039
90	272.9	22.455	23.301	2.633	1.038
91	409.3	22.554	23.301	2.641	1.033
92	464.3	22.595	23.305	2.645	1.031
93	465.8	22.598	23.294	2.645	1.031
94	545.7	22.659	23.298	2.650	1.028
95	554.3	22.666	23.298	2.650	1.028
96	555.8	22.677	23.209	2.651	1.023
97	682.1	22.778	23.214	2.660	1.019
98	818.5	22.890	23.221	2.669	1.014
99	955.0	23.006	23.226	2.678	1.010
100	1,091.4	23.123	23.227	2.688	1.004
101	1,227.8	23.244	23.224	2.698	0.999
102	1,364.2	23.367	23.218	2.708	0.994
103	1,500.7	23.494	23.212	2.718	0.988
104	1,637.1	23.625	23.208	2.729	0.982
105	1,773.5	23.760	23.206	2.740	0.977
106	1,834.3	23.821	23.206	2.745	0.974
107	1,835.8	23.843	23.018	2.747	0.965
108	1,909.9	23.922	23.019	2.753	0.962
109	2,046.4	24.069	23.022	2.765	0.957
110	2,182.8	24.219	23.026	2.777	0.951
111	2,319.2	24.374	23.029	2.789	0.945
112	2,455.6	24.532	23.030	2.802	0.939
113	2,592.0	24.693	23.028	2.815	0.933
114	2,728.5	24.858	23.025	2.828	0.926
115	2,864.9	25.026	23.022	2.841	0.920
116	3,001.3	25.199	23.021	2.855	0.914
117	3,137.7	25.376	23.021	2.869	0.907
118	3,214.3	25.477	23.021	2.877	0.904
119	3,215.8	25.488	22.921	2.878	0.899
120	3,274.2	25.567	22.921	2.884	0.897
121	3,410.6	25.754	22.922	2.899	0.890
122	3,547.0	25.944	22.923	2.914	0.884
Average		23.760	23.148	2.739	0.977

Reach Name: BADRI					
Node Number	Distance (m)	Flow Area (m ²)	Flow Rate (m ³ /s)	Flow Depth (m)	Velocity (m/s)
123	-	19.802	22.923	2.407	1.158
124	164.2	19.809	22.923	2.408	1.157
125	328.3	19.816	22.922	2.409	1.157
126	492.5	19.824	22.922	2.409	1.156
127	656.6	19.832	22.921	2.410	1.156
128	820.8	19.841	22.921	2.411	1.155
129	984.9	19.850	22.921	2.412	1.155
130	1,017.3	19.852	22.921	2.412	1.155
131	1,018.8	19.868	22.816	2.413	1.148
132	1,149.1	19.879	22.816	2.414	1.148
133	1,313.2	19.894	22.815	2.415	1.147
134	1,477.4	19.910	22.815	2.417	1.146
135	1,641.5	19.927	22.813	2.418	1.145
136	1,805.7	19.945	22.812	2.420	1.144
137	1,969.9	19.964	22.811	2.421	1.143
138	2,134.0	19.984	22.812	2.423	1.142
139	2,192.3	19.991	22.813	2.424	1.141
140	2,193.8	20.001	22.743	2.425	1.137
141	2,298.2	20.016	22.744	2.426	1.136
142	2,462.3	20.040	22.746	2.428	1.135
143	2,626.5	20.065	22.747	2.430	1.134
144	2,790.6	20.093	22.747	2.433	1.132
145	2,954.8	20.122	22.746	2.435	1.130
146	3,118.9	20.152	22.747	2.438	1.129
147	3,283.1	20.184	22.748	2.441	1.127
148	3,447.2	20.218	22.747	2.443	1.125
149	3,611.4	20.257	22.738	2.447	1.122
150	3,775.5	20.299	22.723	2.451	1.119
151	3,939.7	20.339	22.726	2.454	1.117
152	4,103.9	20.377	22.737	2.457	1.116
153	4,268.0	20.416	22.752	2.461	1.114
Average		20.018	22.809	2.426	1.140

Reach Name: AVIS25					
Node Number	Distance (m)	Flow Area (m ²)	Flow Rate (m ³ /s)	Flow Dept (m)	Velocity (m/s)
154	-	22.569	22.752	2.642	1.008
155	151.6	22.694	22.742	2.653	1.002
156	303.2	22.826	22.712	2.664	0.996
157	454.9	22.957	22.718	2.671	0.991
158	606.5	23.095	22.706	2.686	0.983
159	758.1	23.240	22.712	2.698	0.977
160	909.7	23.391	22.723	2.710	0.971
161	1,061.3	23.547	22.737	2.723	0.966
162	1,212.9	23.707	22.746	2.736	0.959
163	1,364.5	23.870	22.750	2.749	0.953
164	1,516.2	24.037	22.746	2.762	0.946
165	1,667.8	24.207	22.739	2.776	0.939
166	1,819.4	24.382	22.736	2.790	0.932
167	1,971.0	24.563	22.737	2.805	0.926
168	2,122.6	24.749	22.738	2.819	0.919
169	2,274.2	24.940	22.739	2.835	0.912
170	2,425.9	25.135	22.741	2.850	0.905
171	2,577.5	25.336	22.744	2.866	0.898
172	2,729.1	25.541	22.747	2.882	0.891
173	2,880.7	25.751	22.746	2.899	0.883
174	3,032.3	25.965	22.742	2.915	0.876
175	3,183.9	26.184	22.734	2.932	0.868
176	3,335.5	26.407	22.727	2.950	0.861
177	3,487.2	26.635	22.721	2.967	0.853
178	3,638.8	26.868	22.718	2.985	0.846
179	3,790.4	27.105	22.720	3.003	0.838
180	3,899.3	27.279	22.723	3.017	0.833
181	3,900.8	27.282	22.723	3.017	0.833
182	3,942.0	27.348	22.724	3.022	0.831
Average		24.883	22.734	2.829	0.917
Reach Name: MACHAI					
Node Number	Distance (m)	Flow Area (m ²)	Flow Rate (m ³ /s)	Flow Dept (m)	Velocity (m/s)
183	-	21.211	22.724	2.529	1.071
184	31.3	21.226	22.724	2.530	1.071
185	62.6	21.242	22.724	2.531	1.070
186	93.9	21.258	22.725	2.533	1.069
187	125.2	21.274	22.725	2.534	1.068
188	156.5	21.291	22.725	2.535	1.067
189	187.8	21.307	22.725	2.537	1.067
190	219.1	21.324	22.726	2.538	1.066
191	250.4	21.341	22.726	2.540	1.065
192	281.7	21.358	22.726	2.541	1.064
193	313.0	21.375	22.726	2.542	1.063
194	344.4	21.392	22.727	2.544	1.062
195	375.7	21.409	22.727	2.545	1.062
196	407.0	21.427	22.727	2.547	1.061
197	438.3	21.444	22.727	2.548	1.060
198	469.6	21.462	22.727	2.550	1.059
199	500.9	21.480	22.727	2.551	1.058
200	532.2	21.498	22.727	2.553	1.057
201	563.5	21.516	22.727	2.554	1.056
202	594.8	21.534	22.727	2.556	1.055
203	626.1	21.553	22.727	2.558	1.054
204	657.4	21.571	22.727	2.559	1.054
205	688.7	21.590	22.727	2.561	1.053
206	699.3	21.596	22.727	2.561	1.052
207	700.8	22.600	11.427	2.645	0.506
208	720.0	22.640	11.427	2.648	0.505
Average		21.497	21.857	2.553	1.019

7. Conclusions

1. Functioning of AVIO and AVIS gates

1. Based on the results from Case I to Case VIII listed in Table 5 & 6 and shown in Figs. 5 to 12, the AVIO and AVIS gates present no problems.

Typically a series of automatic gates in multiple canal reaches, (e.g. PHLC) the effect of gates responding to changing flow conditions will usually carry from one location to another and perhaps create hydraulic instability in the system. Fortunately, there is enough available storage volume and sufficient mild slope in the PHLC so that hydraulic disturbances in the series of twin AVIO and AVIS gates do not interfere (or at least have very little interference) with each other.

As explained above, this suggests that the twin AVIO and AVIS gates are adequate for this canal if properly operated.

2. Effect of roughness and sedimentation

Since the PHLC system used downstream control, the water depth just downstream of the automatic control gates are maintained almost constant with changing flow rates. The slope of the water surface profile will be changed according to the flow rate; -- as the flow rate increases, so does the negative slope. Either various values of "n" or cross-sectional area (weed and sediment in canal) will affect the flow rate and also the slope of the water surface profile; however, the flow depth at the upstream end of most reaches will be (almost) constant. Figures 13 to 15 show upstream and downstream gate depths and flow rates (about 4-5 m³/s) for each reach in the PHLC when the hydraulic roughnesses are 0.016 (Figure 13) and 0.021 (Figure 14). A roughness of 0.021 was also used in Figure 15, but the pivot depths of the automatic gates were modified. Table 8 summarizes the flow rate, depths and velocity at the upstream and downstream end of each reach.

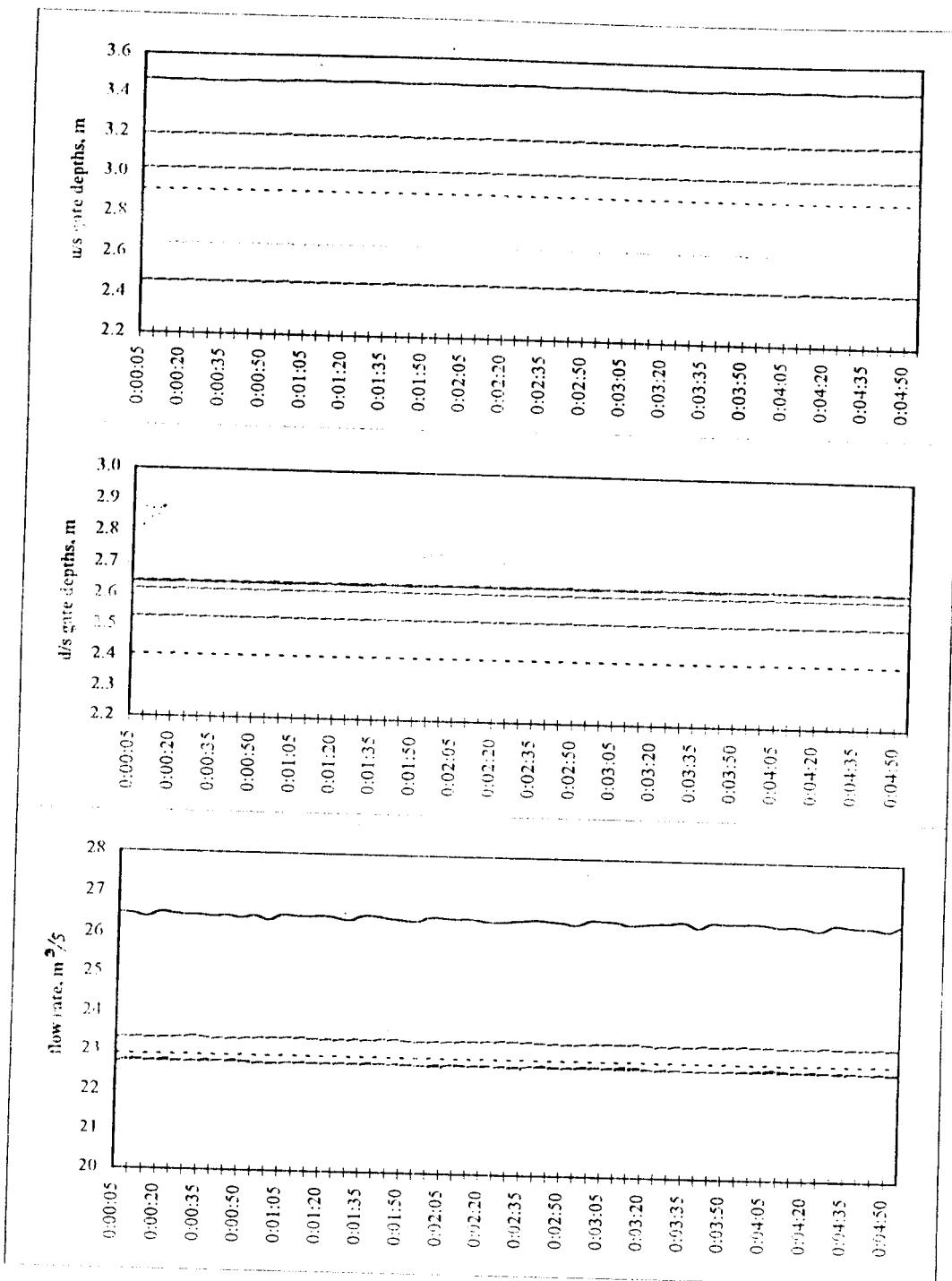


Figure 13. Flow Conditions for the 0.016 roughness value.

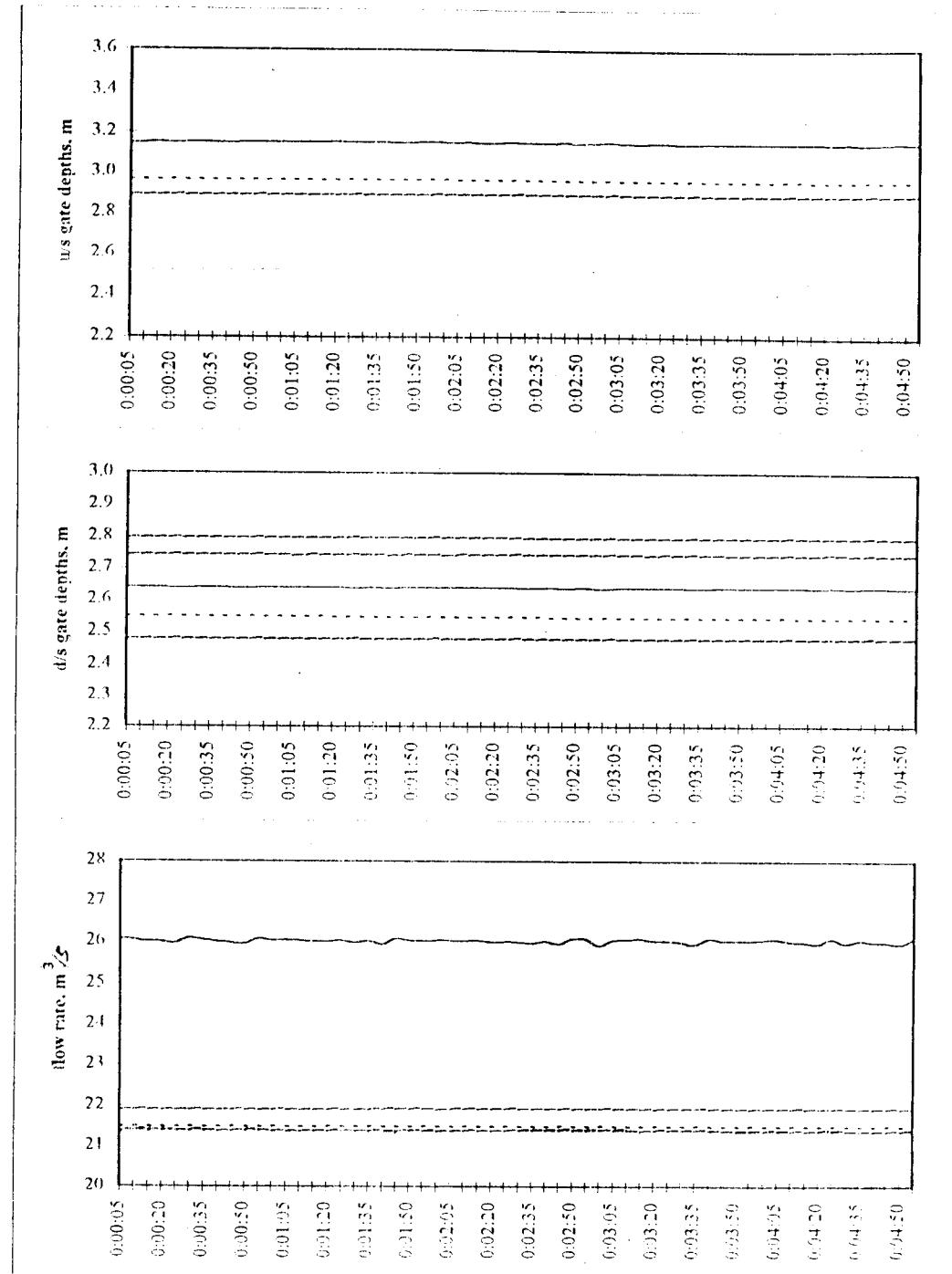


Figure 14. Flow Conditions for the 0.021 roughness value.

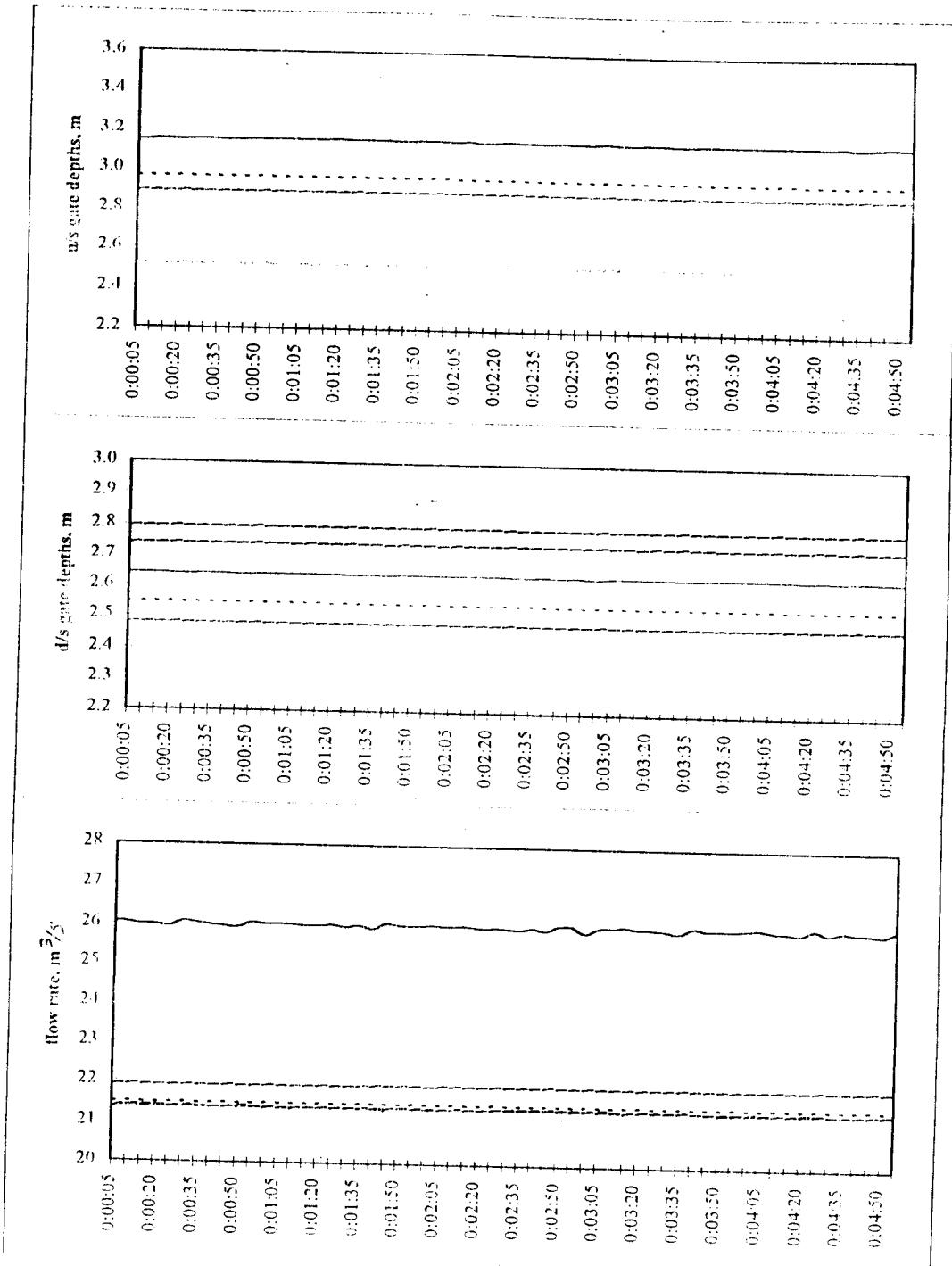


Figure 15. Flow Conditions for the 0.021 roughness value with modified pivot depths.

Table 8. Summarized Flow Conditions.

Reach Name	Manning's n along the PHLC = 0.016					
	Flow Rate (m ³ /s)		Flow Depth (m)		Flow Velocity (m/s)	
	U/S Reach	D/S Reach	U/S Reach	D/S Reach	U/S Reach	D/S Reach
KUNDAL	28.29	26.47	2.86	3.47	1.12	0.79
BAJA	26.47	23.36	2.64	3.19	1.17	0.79
AVIS15	23.36	22.92	2.62	2.91	1.05	0.88
BADRI	22.92	22.75	2.41	2.46	1.16	1.11
AVIS25	22.75	22.73	2.64	3.02	1.01	0.83
MACHAI	22.73	11.43	2.53	2.65	1.07	0.50

Reach Name	Manning's n along the PHLC = 0.021					
	Flow Rate (m ³ /s)		Flow Depth (m)		Flow Velocity (m/s)	
	U/S Reach	D/S Reach	U/S Reach	D/S Reach	U/S Reach	D/S Reach
KUNDAL	27.62	26.04	2.86	3.15	1.10	0.90
BAJA	26.04	21.91	2.64	2.12	1.16	1.32
AVIS15	21.91	21.49	2.80	2.97	0.90	0.81
BADRI	21.49	21.41	2.55	1.94	1.00	1.45
AVIS25	21.41	21.37	2.74	2.89	0.90	0.83
MACHAI	21.37	10.07	2.48	2.52	1.04	0.48

Reach Name	Manning's n along the PHLC = 0.021					
	Flow Rate (m ³ /s)		Flow Depth (m)		Flow Velocity (m/s)	
	U/S Reach	D/S Reach	U/S Reach	D/S Reach	U/S Reach	D/S Reach
KUNDAL	28.22	26.51	2.86	3.17	1.12	0.91
BAJA	26.51	22.35	2.64	2.21	1.18	1.27
AVIS15	23.35	21.91	2.80	2.98	0.95	0.82
BADRI	21.91	21.74	2.54	1.91	1.03	1.51
AVIS25	21.74	21.72	2.74	2.90	0.91	0.84
MACHAI	21.72	10.07	2.47	2.52	1.06	0.48

This would have no effect on flow rate through the turnouts since they are mostly located close to the automatic control structures and they are assumed to have sufficient head (target depth must be set properly for the automatic gates). However, changing of the water surface profile slope will affect the flow depth immediately upstream of the automatic control gates. When higher flow rates are required and, consequently, the negative slope of the water surface profile increases (steepens), the depth upstream of the automatic gates, especially both locations of the twin AVIS gates, will decrease. If the head loss at these twin AVIS gates are not properly provided, the highest flow rate would be limited.

3. Effect of low flow conditions

The effect of low flow conditions in the PHLC were evaluated assuming that the downstream water demand in Machai Branch Canal is almost zero and the PHLC supplies water only for the head regulators and outlets along the PHLC canal. The results for Cases VII and VIII show that the automatic gates will maintain this low flow with acceptable flow depths along the canal, but the canal system will be less stable as compared with the higher flow rates. This is normal in automatic control of small canals or small flow rates. Low flow rates are more difficult compared with high flow rates since they have a larger percentage of flow changes.

IIMI-PAKISTAN PUBLICATIONS

CONSULTANCY REPORTS

S.No.	Title	Author	Year
C-1	Consultancy inputs for the preparation of project inception report on social organization in irrigation management	P. Ganewatte P. Pradhan	Jan 1995
C-2	Regional Salinity - Sodicity Issues in Punjab, Pakistan	Dr. James W. Biggar	April 1996
C-3	Study of Water and Salt Balances for Eight Sample Watercourse Commands in Chishtian Sub-division, Punjab, Pakistan	E.G. van Wayjen	June 1996
C-4	Unsteady Flow Simulation of Pehur High-Level Canal including Automatic Downstream Water Level Control Gates	Dr. Kobkiat Pongput	June 1996