Modeling and Simulation of Irrigation Canals with Hydro Turbines

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***Abstract* - Monitoring and control of irrigation canal operation is necessary for effective water management particularly at the farm level. In addition, the flow of water in the canals has tremendous potential to generate power by using small scale hydro turbines. Modeling and simulation of these irrigation canals with hydro turbines enables to develop monitoring and control solutions while exploring the amount of power that can be generated using hydro turbines at the same time. The proposed study addresses modeling and simulation of the irrigation canals that have hydro turbines. It consists of developing models for individual components of canal structures (such as canal reaches, weirs, gates and hydro turbines), and then integrating them. The simulation results are verified with one of the standard software (SS) available in the market. Further, optimization is also performed via simulations for two different scenarios.**

Keywords - irrigation canal; modeling; simulation; optimization

I. INTRODUCTION

With ever increasing demand for water, the need for improved management of available water resources is of utmost importance. Irrigation canals are artificial systems developed to transport water from main water reservoirs to several water-demanding agricultural farms during irrigational seasons. Generally, they cover very long distances, ranging from hundreds of meters to hundreds of kilometers. Along these canals, different end users like agricultural farms, municipalities, industries etc., are located close to them and water is distributed to these end users all along the way. Water flow to these end users is controlled by modifying the openings of several gates situated at different lengths of the canal. Further, irrigation canals also have a potential of producing green energy. The natural flow of rushing water in irrigation canals can be used to produce several Watts to Mega Watts of electricity by placing hydro-turbines in the canal.

Developing mathematical models for these irrigation canals facilitate to understand and develop monitoring and control solutions for effective water management solutions for irrigation canals. There are several studies in the literature [1] [2] addressing the modeling of irrigation canals. However, there are no/limited studies [3] on modeling of irrigation canals that have hydro turbines. The current study addresses developing a mathematical model for irrigation canal that has hydro turbines. Models are developed for individual canal structures and then integrated.

The paper is organized as follow. In Section II, modeling of individual components and integrated model of irrigation canal system is presented. Section III provides the simulation results, and their comparisons with one of the SS. Conclusions are provided in Section IV.

II. MODELING OF IRRIGATION CANAL

Irrigation canal systems draw water mainly from rivers, lakes and reservoirs and this water is distributed across the vast agricultural fields by lengths of canals, sub-canals and further branches. The irrigation canal system starts with a main intake structure built at the entry to the canal system. Its purpose is to direct water from the original source of supply (lake, river, reservoir etc.) into the irrigation system.

The conveyance system takes water from the intake structure and supplies it over long distances through canals and sub-canals. The water is finally supplied to the fields via branches and ditches in the sub-canals. Apart from the canals and sub-canals, the conveyance system also includes various canal structures to regulate the flow. These mainly comprise of gates (which are used to control and regulate the flow in canals), and flow measurement structures such as weirs in the canal system.

Therefore, modeling of canal reaches (canal, sub-canal or branch), canal junctions (between canal and sub-canal or sub-canal and branch), gates, weirs and hydro turbines are required for monitoring and control of irrigation canal system.

A. Canal Reach

A canal reach is basically a straight length of canal with constant cross-section and slope. The flow model assumes one-dimensional unsteady flow. In general, length of the reach is significantly large as compared to the width, and hence variations across the cross-section are negligible. Flow in a canal reach is modeled [4] by Saint Venant's Equations which are a system of non-linear hyperbolic partial differential equations. The flow is assumed to be one-dimensional and gradually varying. The canal slope is assumed to be negligible and the fluid is assumed to be incompressible i.e. the density remains constant. Following are the model equations:

Conservation of mass is described using continuity equation

$$\frac{\delta A}{\delta t} + \frac{\delta Q}{\delta x} - q_l = 0 \qquad (1)$$

Where A is the area of flow in m^2, q_l is the seepage loss in m^2/s, Q is the flow rate in m^3/s and x is the position along the length of the canal.

The rate of change in momentum of the flow is equal to the external forces acting on the system.

$$\frac{\delta Q}{\delta t} + \frac{\delta (VQ)}{\delta x} + gA\left(\frac{\delta Z}{\delta x} + S_f\right) = 0 \qquad (2)$$

Where V is the velocity in m/s and S_f is the friction slope which can be calculated using Manning's equation.

B. Canal Junction

A canal junction is a point where two or more canal reaches combine into one or diverge into more reaches. The junction length is assumed negligible which eliminates the consideration of energy losses. The total flow [4] entering into the junction is equal to the flow leaving the junction.

$$\sum_1^n S_i Q_i = 0 \qquad (3)$$

Where S_i is the flow coefficient (-1 for upstream and +1 for downstream) and Q_i is the flow rate at junction in i^{th} canal reach.

C. Weir

A weir is a barrier across a river designed to alter flow characteristics. In most cases, weirs take the form of a barrier, smaller than most conventional dams. A Weir installed across a river causes water to pool behind the structure and allows water to flow over the top. Weirs are used to prevent flooding, and measure discharge. There are several types of weirs such as broad crested and sharp crested etc. The discharge equation [4] of the weir gives a relation between the flow rate and the head upstream of the weir.

$$Q = CBH^{\frac{3}{2}} \qquad (4)$$

Where Q is the discharge through the weir in m^3/s, C is the weir discharge coefficient (varies between 2.6 to 4.2 depending upon the shape), B is the weir width in meters, and H is height of the upstream flow above the weir crest in meters.

D. Gate

A gate is a flow control structure that regulates the amount of water flowing in a particular canal reach. As it affects the flow into or out of the reach at a junction, the flow in other reaches is also affected. By installing gates at certain strategic locations we can control flow in the entire canal system. A gate basically poses as an obstruction in the path of flow. It completely blocks the flow when the opening is zero and as the gate opening is increased it lets more water to pass through. There are several types of gates such as sluice gate, radial gate etc. The model equations [4] used in this study are of sluice gate type, and are given below.

If the submergence of the sluice gate is less than 0.67 it is said to be free flowing, and the discharge through the gate is given as follows:

$$Q = CWB\sqrt{2gH} \qquad (5)$$

If the submergence is in the range 0.67 to 0.8, the flow is said to be in transition, and the discharge through the gate is given as follows:

$$Q = CWB\sqrt{2g^3H} \qquad (6)$$

If the submergence is greater than 0.8, the discharge through the gate is given by the following equation

$$Q = CA\sqrt{2gH} \qquad (7)$$

Where Q is flow through the gate in m^3/s, C is gate discharge coefficient, W is gate width in meters, B is the gate opening in meters and H is difference in the heights of the upstream and downstream levels in meters.

E. Hydrokinetic Turbine

A hydrokinetic turbine converts the kinetic energy of flowing water into electrical energy. It is different from traditional turbines that convert the potential energy or head of water stored in a dam into electrical energy. Hydrokinetic turbines do not require any additional infrastructure development and can easily be installed in flowing streams. There are several types of turbines based on rotor orientation (such as axial, cross flow and inclined turbines). However, the power equation [5] is same for all of them, and is given below.

$$P = \frac{1}{2}\rho\eta C_p V^3 \qquad (8)$$

Where P is the output power of the hydro turbine in Watts, ρ is the density of fluid in kg/m^3, η is the efficiency, C_p is the coefficient of performance of turbine and V is the velocity in m/s.

III. RESULTS AND DISCUSSION

The models developed for various components (such as canal reach, weir and gate) of the canal structure are simulated, and the results are compared with one of the open source canal simulation software. The geometrical parameters and the coefficient values used in the simulation are given below.

TABLE I. PARAMETERS AND COEFFICIENTS

Parameter/Coefficient (unit)	Value
Canal width, w (m)	120
Distance step, Δx(m)	1000
Time step, Δt(s)	3600
Simulation time, T (s)	72000
Manning's coefficient, n	0.23
Friction slope, S_0	0.00061
Sub-canal width, w' (m)	120
Weir width, B (m)	120
Weir crest height, h (m)	2
Weir coefficient, C	2.6
Gate width, g_w (m)	40
Gate coefficient, g_C	0.6
Hydro-kinetic turbine diameter, D (m)	2.2

The initial condition of flow at upstream of the junction is given by equation (9) for simulation

$$Q(x,0) = 100 \quad (9)$$

The downstream depth is taken as 0.86m, and the depth at rest of the points is computed using energy equation while the weir discharge equation is applied across the weir to obtain the upstream depth. The upstream boundary condition is defined as follows.

$$Q(0,t) = 100sin\left(\frac{\pi t}{5} - \frac{\pi}{2}\right) + 200 \; if \; t \leq 5 \; hrs \quad (10)$$

$$Q(0,t) = 100\cos\left(\frac{\pi(t-5)}{10}\right) + 200 \; if \; 5 < t \leq 15 \; hrs \quad (11)$$

$$Q(0,t) = 100 \; if \; t > 15 \; hrs \quad (12)$$

The downstream boundary condition for the main canal is given by a stage hydrograph which is defined as follows:

$$y(10000,t) = 0.86 \quad (13)$$

Coding is done in Matlab, and the results are compared with those of SS.

A. Canal Reach

The length of the canal is assumed to be 16 km for this simulation. The depth and velocity profiles (represented as -D and -V in the diagram) of canal reach are given in *Fig. 1*. The profiles are determined at different times and at different locations (x=0 km and x=8 km) along the length of the canal. As shown, the depth of the flow is higher between 5 to 10hrs, and then is decreasing between 10 to 20 hrs. Similar profile (increase in the velocity at times between 5 to 10hrs) is observed even with velocity. This is mainly due to the characteristic of flow which is assumed to be sinusoidal wave (boundary conditions in equations 10 and 11). Further, as expected, the velocity and depth profiles are propagating along the length of the canal (can be observed at x =0 and 8 km) with some delay. It can also be observed that the simulated results are in close agreement with SS results.

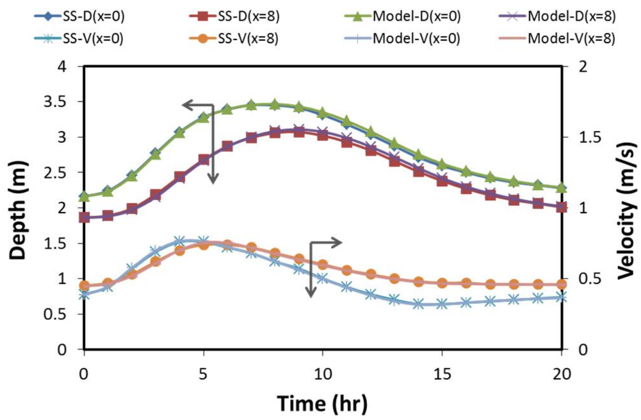

Fig. 1: Depth and velocity profiles - Canal reach

B. Canal Weir

The length of the canal is assumed as 5km and the weir is located at 2.5km downstream of the canal. Note that there is no branch in the canal. *Fig.* 2 shows the results of canal weir. It can be observed that the depth profile of weir downstream is lower than that of weir upstream. This is due to the presence of weir which is not submerged. Further, it can also be noticed that the velocity profile of weir downstream is higher than that of weir upstream due to change in depth because of weir. It can also be observed that velocity profiles of both upstream and downstream are slightly decreased between t= 5 to 10hr due to the higher depth in that time period.

C. Canal Junction

The length of the main canal is considered as 4km while the sub-branch of length 2km is considered at 2km downstream of the main canal.

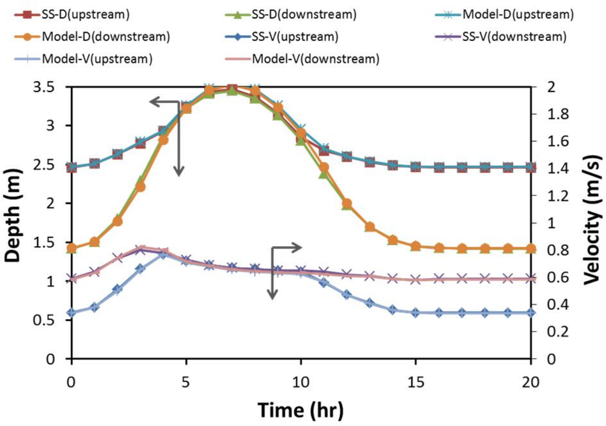

Fig. 2: Depth and velocity profiles - Canal weir

Fig. 3 shows the results of canal junction. It can be observed that the depth profile of branch upstream is lower than that of canal upstream since the flow divides into two branches. Further, the velocity profile of branch upstream is also lower than that of main upstream since the flow is divided across two branches.

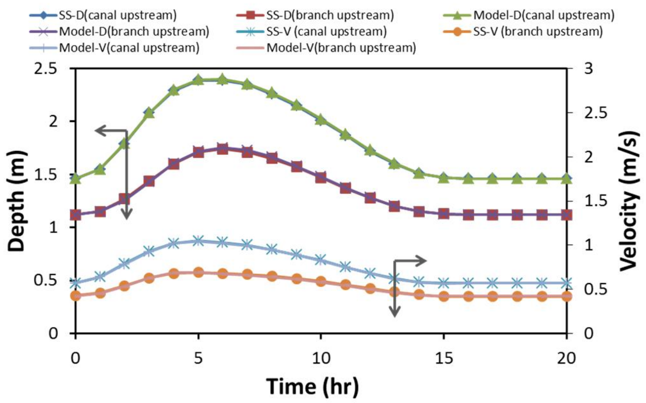

Fig. 3: Depth and velocity profile - Canal junction

D. Canal Gate

The length of the main canal is considered as 10km while the gate is located at 4.5km downstream of the main canal. Note that there is no branch in the main canal. Further, gate is kept opened during 0 to 15hr, and then closed slowly between 15 to 20hr during this simulation. *Fig. 4* shows the results of canal gate. As shown, the depth profiles of gate upstream and gate downstream are following sinusoidal behavior till 15hr (i.e., when gate is fully opened). As the gate is closed gradually between 15 to 20hr, the depth in the upstream is increasing while it is decreasing in the downstream. Similarly, the velocity profiles of both upstream and downstream are decreasing after 15hr since the flow is decreasing due to gate closure.

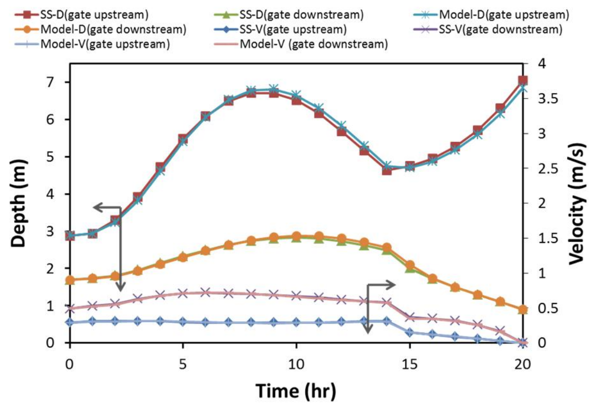

Fig. 4: Depth and velocity profiles - Canal gate

E. Integrated Model for Canal System

It involves modeling of a main canal of length 10 km. The canal has branches at 10 kilometers where it divides into two sub-canals: reach 1 and reach 2 each of 5 km in length as shown in *Fig. 5* .

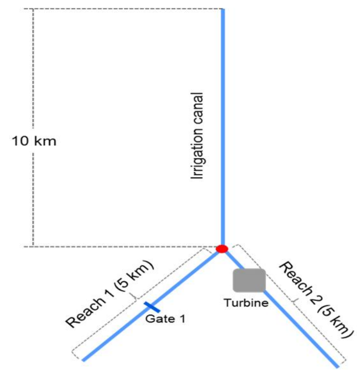

Fig. 5: Canal system for integrated model

Reach 1 has gate to supply the water to the end users (farmers) while Reach 2 links to the sub-canal (*Fig. 5*). Simulations are performed with and without turbine in Reach 2. Further, gate opening in Reach 1 is changed (i.e., kept opened during 0 to 15hr, and then closed slowly between 15 to 20hr) during this simulation. *Fig. 6* and *Fig. 7* shows the depth and velocity profiles of the integrated model without turbine. Depth (*Fig. 6)* is varying with time at canal upstream, branch gate downstream (Reach 1 in *Fig. 5*) and main canal junction downstream (in Reach 2 in *Fig. 5*). The depth at canal head is higher than the other points at all times while the depth in branch (Reach 1) is less than that in the main canal downstream (Reach 2) due to flow restriction by gate. The sinusoidal nature of the curves is due to the similar nature of upstream flow rate. The gate downstream curve suddenly falls at 15hr due to the reduced gate opening.

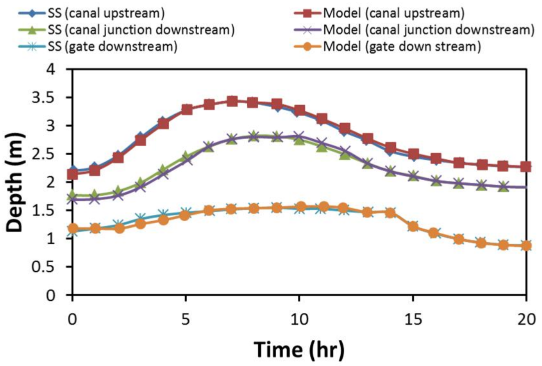

Fig. 6: Depth profile - Integrated model

Variation of flow velocity with time at canal upstream, branch gate downstream and main canal junction downstream points is shown in *Fig. 7*. The velocity profile in all the streams is sinusoidal up to 15hr. After 15hr, velocity in the gate downstream falls due to reduced gate opening, and it becomes zero at 20hr when gate is fully closed. It can also be observed that there is an increase in velocity profile of canal upstream from 15hr.

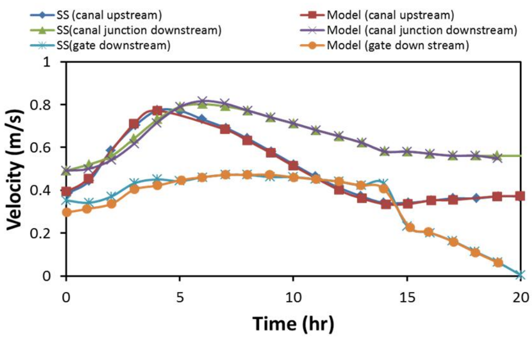

Fig. 7: Velocity profile - Integrated model

Fig. 8 shows simulation results of the integrated model with turbine in reach 2. During this simulation, the gate opening in Reach 1 is assumed to be fully closed. Since the output power is proportional to the cube of flow velocity, the variation in power profile is sinusoidal (i.e., power is maximum when the velocity is high as shown in *Fig. 7*) which is same as the canal upstream flow. Further, the power is very small (~2 KW) since the flow assumed in the canal is low and there will be several such turbines in the canal in general.

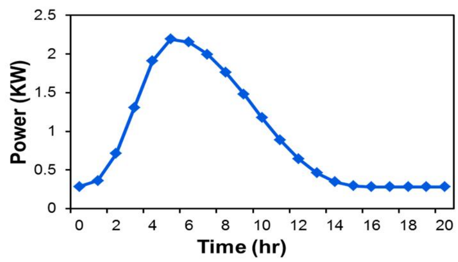

Fig. 8: Variation of turbine power with time

F. Optimization via simulation

Optimization is also performed using the integrated model for different scenarios. Scenario 1 refers to meeting the water demand in Reach 1 by manipulating gate openings. Scenario 2 refers to meeting water demand in Reach 1 while meeting power demand in Reach 2. *Fig. 9* shows the results of scenario 1 which includes water demand, water flow rate and the associated gate openings in Reach 1. It can be observed that the output flow rate is always higher than the water demand indicating that the demand is being met at all the times. Further, the trend of gate opening is similar to the flow demand which is expected as higher flow demand needs higher gate opening.

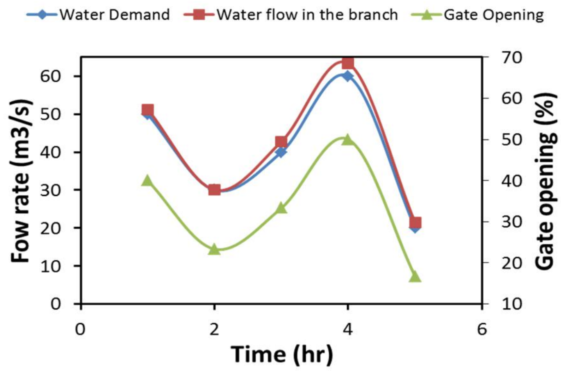

Fig. 9: Optimal gate opening - Scenario 1

Fig. 10 shows the results of scenario 2 which includes the trends of water demand, power demand, actual water flow rate, associated gate opening and the power that is generated. Equal weights are assumed for both the objectives (i.e., for both water and power demand). As shown in *Fig. 10*, the power demand is closely met while the water demand is slightly violated at times since there is trade-off between the two. However, several scenarios can be tested with different weights given to these objectives.

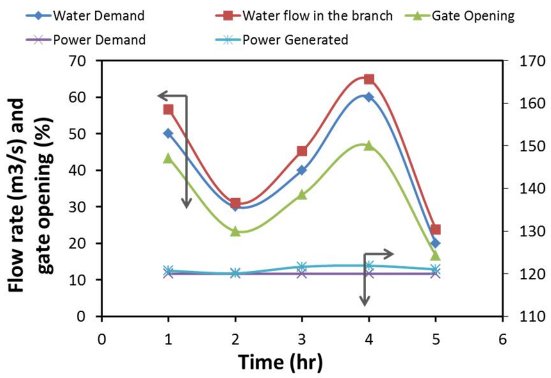

Fig. 10: Optimal gate opening - Scenario 2

IV. CONCLUSION

Models are developed for the individual components of irrigation canal structure which include canal reach, weirs, junctions and gates. Subsequently, an integrated model is developed for the canal system that has a hydrokinetic turbine. The simulation results show that they are in close agreement with standard software available in the market. Further, optimization is performed with the developed model for two different scenarios via simulation. This paper focuses on a single objective optimization of irrigation canal system. However, multi objective optimization (MOO) approach can be explored to achieve various conflicting objectives like meeting flow and power demands. This can also be extended to an online optimization problem with more rigorous mathematical models. These would be topics of interest for future studies.

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