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Hydraulic and Sediment Handling Performance Assessment of Rani Jamara Kulariya Irrigation Project (RJKIP) by Conjunctive Use of 1D and 3D Simulation Models

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Abstract - **Many water resources related hydraulic structures have been suffering economical loss due to poor performance of the designed components. In depth study of the design must be done before implementation of such projects. The main objective of this study was to check the hydraulic capacity and behavior of the head/works of Rani Jamara Kulariya Irrigation Project under inflow conditions of high concentration of sediments together with the design discharge. Possible changes in design, without decrease of the performance, were checked, to see if the project could be economized. A one dimensional model HEC-RAS (version 4.1.0) was used for the major portion of the study and a three dimensional model SSIIM (version 1) was used in the analysis of the settling basin. The results were then compared. The results suggest that the flow capacity of the system could decrease to 71 m^3/s from the designed capacity of 80 m^3/s when checked under 'minimum sustained river water level' conditions at the head/works. The sediment simulation in HEC-RAS showed that, all particles of size greater than or equal to 0.125 mm would be trapped in the settling basin. For intermittent flushing mechanism, the D_{50} of active particles downstream of the settling basin was found to be 0.030 mm whereas the size was found to be 0.035 mm for continuous flushing (with a flushing discharge of 20 m^3/s). Other scenarios of operations along with some design modifications to the settling basin were checked in HEC-RAS. Further, the hydraulic and sediment studies were done for the settling basin using SSIIM by which the flow vectors, flow velocities and trap efficiency valuess were studied.**

Keywords - HEC-RAS, SSIIM, Hydraulics, Sediment, Manning's n, Trap efficiency, Flushing

1. INTRODUCTION

Water is a natural resource supporting the economy of Nepal. The agriculture sector, which is dependent on the availability of water, contributes about 35% of GDP and provides employment for more than 74% of the work force [1]. Hydropower generation contributes to the national economy and is considered as one of the main focuses for the future economic progress of Nepal. All such projects, however, mostly rely on flow of the rivers of the country. Most of these rivers are glacier fed and characterized by young and fragile geology with steep catchment areas. Steep topography, fragile geology and intense rainfall have led to large volume flows and exceedingly high sediment transported by these rivers during the rainy season [2, 3]. This poses a significant challenge to the Irrigation and Hydropower Projects with respect to sediment handling and which also might make them unfeasible.

Figure 1 Head/works of RJKIP (Taken 6/21/2014)

The Rani Jamara Kulariya Irrigation Project (RJKIP) envisions irrigating about 20,300 ha of land in the Kailali District of Nepal through the construction of a permanent side intake at Chisapani. The project intends to construct a settling basin at about 4+950 km, a main canal up to 8+875 km: the bifurcation point of a new 14.4 km branch canal, and a feeder canal 11.09 km long, to feed three existing systems, the Rani, Jamara and Kulariya systems

[1]. This intake (figure 1) will have a capacity of 100 m^3/s. The main canal up to the settling basin has been designed for 100 m^3/s capacity with a flushing capacity of 20 m^3/s in the settling basin. The design discharge up to the new branch canal is 80 m^3/s. The intake bottom crest level has been fixed to divert discharge of 80 m^3/s: corresponding to 80% of the reliable water level in the river during the month of April. It is the period with the lowest amount of flow in the river [1]. The conveyance system is mostly a trapezoidal canal with many parts being an enclosed rectangular canal, referred to as the barrels.

1.1 Physical and Numerical Simulation Model

Undertaking a physical modelling test to understand the hydraulic and sediment handling properties of Hydraulic structures is a trusted method. This method has been around for centuries [4]. However, there are drawbacks to this method. They are quite expensive and lack flexibility for modifications. Due to the advancement of computer technology in the recent times, mathematical modeling has evolved as a useful tool in hydraulic engineering problems [5]. Mathematical models play an important and increasing role in designing such Hydraulic structures, but they require good input data with careful calibration and validation [6]. However, a validation and calibration process was not possible in this particular study as the project itself was under construction during the period of study.

1.2 Objectives of Study

The objectives of this study were to check the Hydraulic and Sediment handling properties of the head/works of RJKIP using numerical simulation models, HEC-RAS and SSIIM. By using parallel simulation models in this way, the results can be compared.

2. METHODOLOGY

2.1 Hydraulic and Sediment Analysis Using Hydraulic Engineering Centers – River Analysis System (HEC-RAS, version 4.1.0)

The one-dimensional modeling system used in HEC-RAS is a mainly physically based modeling system applied to the analysis of river flow dynamics, sediments, and water quality [7]. This is a widely used tool and appropriate for this kind of study. Using the geometrical editor tool of HEC-RAS, the whole system from head/works to the settling basin was constructed based on design data of the RJKIP (figure 2). Manning's n value was selected as 0.016 for the open channel and 0.015 for the barrel part of the conveyance system. Its value for the settling basin was set to 0.03. The HEC-RAS flow model has advantages over other models in modeling the effects of hydraulic structures (e.g. bridges, weirs, and culverts). This feature was used in the study for modeling the regulating gates at the head/works and the flush gates at the end of settling basin.

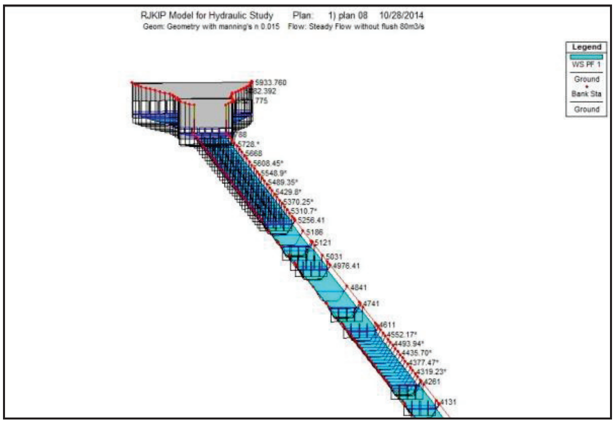

Figure 2 Geometric plot of the system in HEC RAS

Under quasi-unsteady flow data, the model requires a discharge hydrograph for unsteady flow simulation. In the model, as the flow is a controlled diverted flow, discharge values used are the design discharges i.e., 80m^3/s during normal operation and 100m^3/s, during flushing. For intermittent flushing, design is based on a weekly flush, so the time series is formed accordingly.

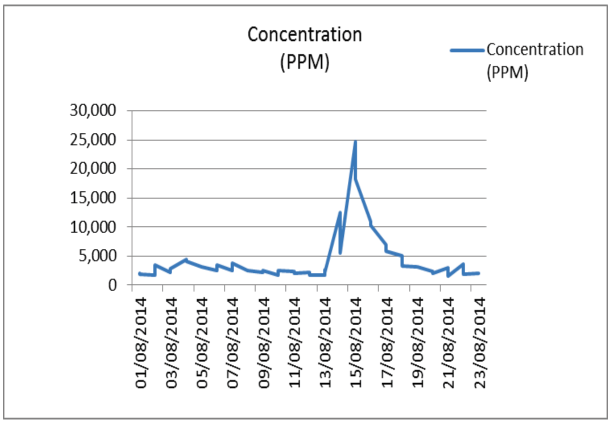

Figure 3 Sediment concentration (Source: Hydro Lab Pvt. Ltd.)

For sediment data, the measured suspended sediment concentration (ppm) is shown in graphical form (figure 3) as an example of flow during August, 2014 at Chisapani, Karnali. The inflow sediment discharge has to be provided for each time step of the run.

The 'England-Hansen' for 'Transport function', 'Active Layer' for 'Sorting Method' and 'Van Rijn' for 'Fall Velocity Method' was used for this study.

2.2 Hydraulic and Sediment Study Using Simulation of Sediment in Intakes with Multi Block Options (SSIIM, 1)

SSIIM is a general sediment transport model which has been applied to different form of hydraulic structures such as intake, settling basin, reservoir, etc. The model uses a finite method to compute the Navier-Stokes equations in three dimensions on a general non-orthogonal grid. For the sediment calculations, the model uses the diffusion/advection equation and a bed-load transport formula [5].

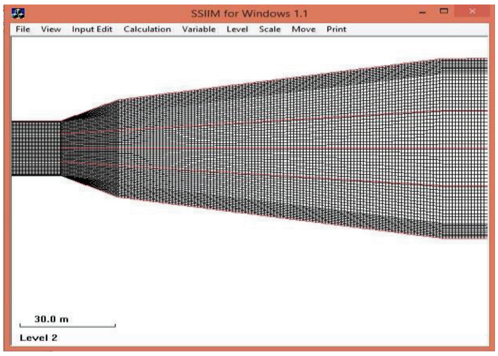

Figure 4 Grid of the settling basin at level 2 in SSIIM

The Settling Basin for intermittent flushing is only modeled and simulated here in SSIIM. The grid of the settling basin shown in figure 4 is constructed in SSIIM with fine resolution i.e, Grid of size 796x66x13.

3. RESULTS AND DISCUSSION

3.1 Results from HEC-RAS

The capacity of the barrels and open channels were checked (table 1) for discharges of 80 m^3/s and 100 m^3/s. Barrels and Open channels are designed with a depth of 3m and freeboard equal to 1 m.

Table 1 Capacity check for barrel and open channel

Discharge	Highest flow depth (Canal/Barrel)	Min. flow depth (Canal/Barrel)	Avg. depth	Remarks
80 m^3/s	2.65	2.32	2.55	OK
100 m^3/s	3.02	2.17	2.83	OK

The minimum water surface elevation required for diversion of 80 m^3/s and 100 m^3/s was first calculated from simulation with multiple hits and trials. The amount of discharge that is diverted to the system under the same water surface elevation and increased Manning's n was checked (figure 5, table 2). The trapezoidal portion and the barrel portion were designed with Manning's n values of 0.016 and 0.015 respectively.

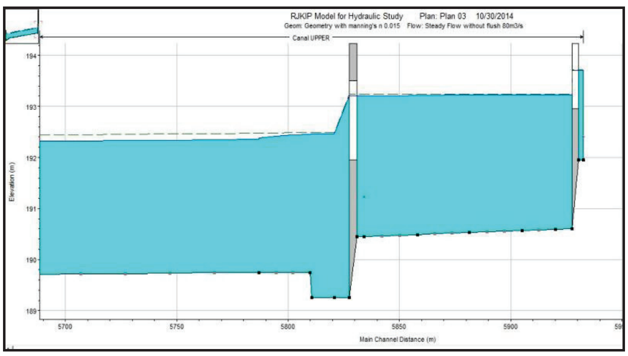

Figure 5 Headworks – Intake and regulators in profile plot, HECRAS

Table 2 Capacity decrease due to increase in n

Water surface elevation (m)	Discharge for n (0.015/0.016)	Discharge for n (0.020)	% Decrease in capacity
193.71	80	71	11.25
193.84	100	88	12

The Geometry from the Intake to the Settling Basin, after running for hydraulics, was run for sediment analysis. The Bed gradation was inserted and suspended sediment PSD was supplied as a boundary condition at uppermost section. The scour able depth was inserted as zero as the concrete floor is not supposed to scour under controlled design discharge. Different cases of operation and design change (change in length of settling basin) were simulated in the HEC-RAS, referred here in as Cases A through E.

CASE A: When the flushing of the settling basin is intermittent (the discharge value is equal to 80 m^3/s up to the settling basin and 100 m^3/s will be used only during flushing) (figure 6)

- The sections between the intake and the discharge regulator were found to deposit a lot of sediment and the initial trap efficiency was found to be 45%.
- The trap efficiency of the settling basin for size 0.125mm was found to be 100%.
- The D_{50} of the sediment unsettled in the settling basin was found 0.03mm.
- The sediment concentration after settling basin was 1030 mg/l when the average concentration entering from the intake was 3800 mg/l for the August month flow.
- The rate of filling of the settling basin (figure 7) was calculated as 128.374m^3/hr.
- The trapping of sediment in the conveyance system i.e. the open channel and barrel, was studied and compared with Case B. The value of the trap% was 4.52 after 40 hour run.

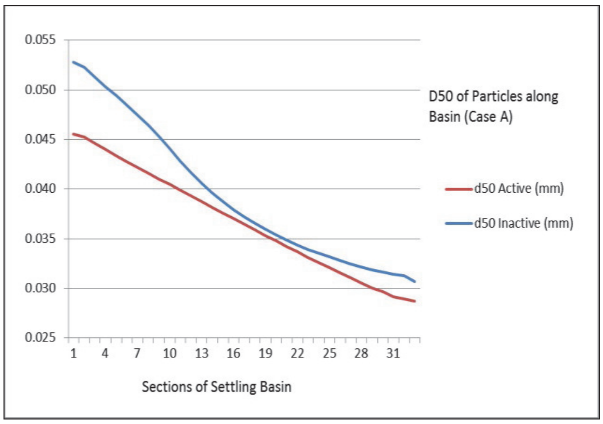

Figure 6 Sediment size along basin (Case A)

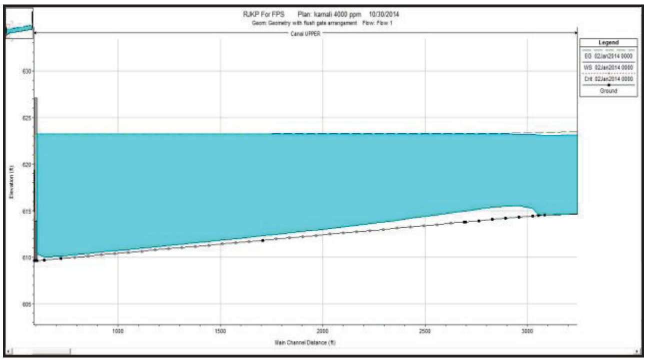

Figure 7 Settling basin filled with sediment

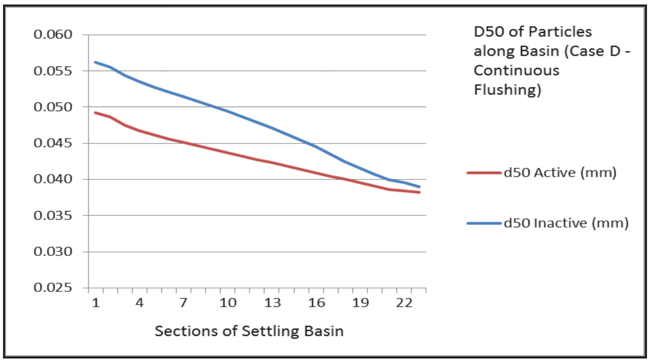

Figure 8 Sed. Size along Settling Basin (Case D – continuous flush)

CASE B: With continuous flushing of the settling basin: (flush discharge 20 m^3/s, which means that the discharge up to the settling basin would be 100 m^3/s)

- The initial trap efficiency of the sections between the intake and discharge regulator were found to be about 32%.
- The trap efficiency of the settling basin for size 0.125mm was 99.99%.
- The D_{50} of sediment unsettled in the basin was 0.035 mm.
- The sediment concentration after settling basin was 1130 mg/l.
- The rate of filling of the settling basin was 171.88 m^3/hr.

The trapping of the sediment in the conveyance system was less in case B than in case A which might be due to the increased velocity along the system because of higher discharge rates. In addition, the rate of filling of the settling basin in case B was 54% greater than that in case A. This indicates that a greater amount of sediment is carried to the basin instead of being deposited in the conveyance system; a desirable outcome. However, the value of D_{50} and sediment concentration at end of basin is increased.

CASE C: When the length of the settling basin is decreased to 500 m and then checked for intermittent flushing (as in Case A)

- The trap efficiency of settling basin for particle size 0.125 mm in found to be 99.997%. D_{50} of sediment unsettled in basin was found to be 0.032 mm, slightly higher than Case A.
- The basin filling rate was 119.39 m^3/hr and sediment concentration after settling basin was 1089.842, higher by almost 60 mg/l compared to Case A.

CASE D: When the length of the settling basin was decreased to 400 m and with a dividing wall dividing the basin into two, intermittent and continuous flushing were then checked.

In intermittent flushing, trap efficiency for size 0.125 mm particles was found to be 99.995%. The D_{50} of unsettled particles (figure 8) was found to be 0.036 mm. The rate of filling of the basin was 107.90 m^3/hr and the sediment concentration after settling basin was 1158 mg/l.

In the continuous flushing, the trap efficiency for particles of size 0.125 mm was 99.996%. The rate of filling of the basin was 142.532 m^3/hr and concentration after basin was 1266.811 mg/l.

CASE E: Hydraulic Flushing of 400 m Settling Basin with Complete Drawdown

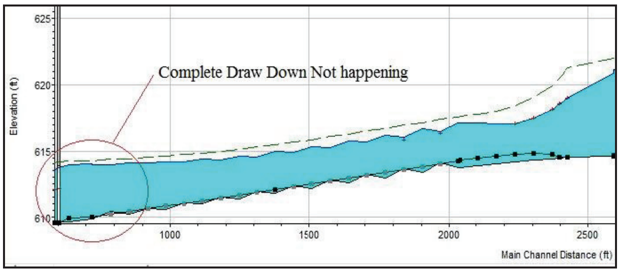

Figure 9 Hydraulic Flushing (Note: 1 m = 3.281 ft)

In this case the flushing was checked for a 400 m long basin without the dividing wall. It was found that flushing started at almost a velocity of 1.9m/s. The complete drawdown was required for this velocity to be developed throughout the basin. However, the gate opening capacity was not enough to allow the flow velocity to increase to that extent (figure 9).

3.2 Results from SSIIM

The output from SSIIM shows eddy formation in the transition zone of the settling basin. It is not formed abruptly as the zone is quite long.

The average velocity of flow along the settling basin decreases gradually from 1 m/s at the start then decreases to 0.617 m/s, 0.5822 m/s and 0.3352 m/s at end.

Figure 10 shows a table in which the velocity from SSIIM and HEC-RAS was simulated with the intermittent flushing option.

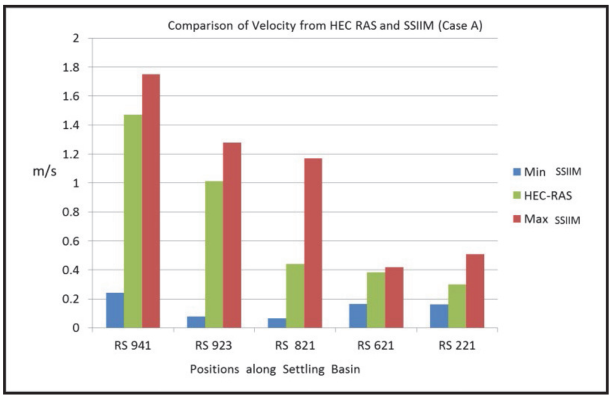

Figure 10 Comparison of velocity from HEC RAS and SSIIM

This result shows that the velocity in HEC RAS, which is a section averaged value, falls well within the range of max and min velocity in SSIIM (figure 10).

The same file was then assigned sediment control file to simulate sediment deposition. The output after a complete run is presented in graphical form in figures 11(a) and 11(b).

The trap efficiency of the settling basin for a condition similar to Case A was calculated using SSIIM. It shows 100% trap efficiency for particles up to 0.15mm. Trap efficiency was 98.51% for 0.1mm particles, 82.91% for 0.06mm particles and 41.45% for 0.03mm particles (table 3).

Table 3 Trap % for intermittent flushing in SSIIM

Particle group	Size(mm)	Trap%
1	0.5	100
2	0.4	100
3	0.3	100
4	0.2	100
5	0.15	100
6	0.1	98.51
7	0.06	82.91
8	0.03	41.45

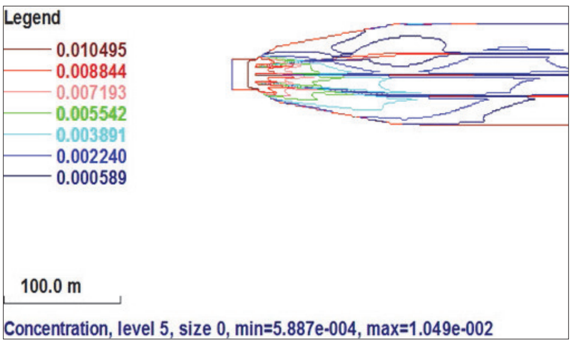

Figure 11 Concentrations at level 5 as seen in the Plan of the Settling Basin (SSIIM) – (a)

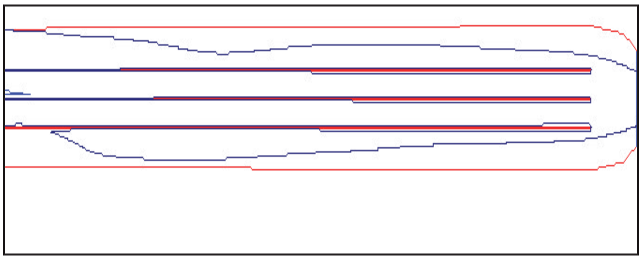

Figure 11 Concentrations at level 5 as seen in the Plan of the Settling Basin (SSIIM) – (b)

The HEC RAS simulation for Case A showed trap efficiency of 100% for particle size 0.125mm and D_{50} of unsettled particles were 0.03 mm. In this way, it was seen that the results in 1D simulation was very similar to those in the 3D simulation from the perspective of trapping efficiency. So the analysis done in the HEC RAS for testing of the system under increased discharge and dimensionally decreased length (of settling basin) under the different cases can be predicted to be similar to the output that could have occurred in SSIIM.

4. CONCLUSIONS

The study of the head/works of RJKIP, using 1D and 3D analysis models, showed that such tools can be applied for design decisions. They are flexible and easily modified and easy for interpretation. The application of SSIIM for the study of settling basin showed that the trapping of different sizes of particles were very similar to that from the study with HEC-RAS. This means that for such kind of geometrical reach, the 1D model HEC-RAS performs comparably with the 3D model SSIIM, although it may not be the case for other complex scenarios. However, SSIIM can be very useful in understanding the flow vectors and to see if there is any kind of eddy formation. Also, its capacity to find the velocity at different vertical levels is very useful in visualizing the real life performance of the project. This 3D analysis capability makes it very useful in sediment related studies.

The simulation in HEC-RAS showed that, in the project, the complete drawdown (by full opening of flush gates) initiated scouring at parts of the settling basin with higher velocity. Increased width of gates could increase flow velocity throughout the basin during flushing and make hydraulic flushing possible. A dividing wall would allow half of the basin to be flushed with the other half continuing in normal use. The length of the settling basin was decreased and checked in HEC-RAS and the performance was not much compromised even when the length was decreased to 400 m instead of the designed length of 600 m. This would be important in decreasing the cost of project.

In addition to these findings, there are some other conclusions which we can draw from this study. The value of Manning's n has a significant impact on flow capacity, so its value must be carefully fixed. The long term sediment concentration data must be available for simulation. This then gives overall performance of the system as a whole. Also the long term river stage data of for the intake can be very helpful in determining flow diversion capacity of the project over the whole year. There are different methods to choose for calculating Fall velocity, Sorting method and Transport mechanism in HEC-RAS, hence an in depth study is required for choosing the appropriate one according to condition.

It is a difficult task to completely model a natural phenomenon that occurs in an artificial structure so the parameters used in the model must be optimized and validated for flow depths and sediment depositions. If validation is done and parameters are optimized accordingly, the results can be highly trusted.

5. ACKNOWLEDGEMENT

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7. BIOGRAPHIES

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