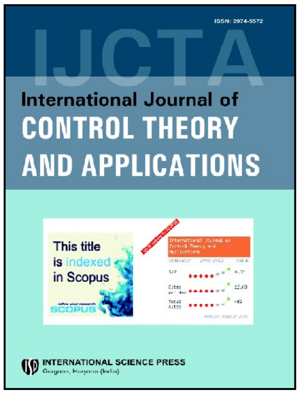

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Prediction of Reservoir Release using Genetic Programming and ANFIS Models Coupled with Wavelet Transform

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Abstract: Recent trends of application of machine learning techniques in real time reservoir studies is proving advantageous due to high success rate in providing satisfactory results with high accuracy in less time. This study therefore presents the application of genetic programming and ANFIS techniques in predicting water releases from reservoir at multi-time steps. Further the wavelet transform were combined with each developed models to form wavelet based hybrid models and compared to the single models. The study area chosen were for two multi-purpose reservoirs - Maithon and Panchet reservoir, located in Jharkhand, India. The comparision of models with each other is done using performance statistics, namely, root mean square error (RMSE), correlation coefficient (CC), mean absolute error (MAE) and Nash Sutcliffe efficiency (NSE). The results obtained from single prediction models using genetic programming was found to be better than single ANFIS models for all multi-time steps reservoir water releases. Further, wavelet hybrid models i.e. wavelet-ANFIS and wavelet based genetic programming models improved noticeably the prediction results of single ANFIS and genetic programming models. Overall, the results concluded that wavelet integrated genetic programming model is relatively more accurate and consistent among all models.

Keywords: wavelet transform, ANFIS, genetic programming, reservoir.

I. INTRODUCTION

For the optimal operation of reservoir systems, incorporation of accurate information of reservoir inflows, elevation and releases to the decision maker or reservoir operators is very essential. And an accurate knowledge of these parameters will be beneficial to water managers in appropriate management, planning and evaluation for water supply releases from the reservoir to meet the desired objectives. Also the operation of reservoir during seasonal period are of more concern to water managers due to risk of uncertain droughts or occurrence of adverse floods that affect reservoir operation policies. But, the prediction of reservoir releases is complicated, non-linear in nature and relatively difficult in determination. But due to the progress in modelling of reservoir operation systems, advanced computational tools like ANN, ANFIS, SVM, etc. are proving more advantageous in providing relatively accurate and better results in less time [6, 7, 10, 12]. The knowledge of how much water to release in advance at various multi-time steps helps the operators in maintaining optimal policies for water release. In recent years, various investigators have addressed the application of various advance computational techniques in solving complex non-linear problems related to reservoir operation studies. Genetic programming, as an evolutionary algorithm tool, has been applied for developing real time reservoir operation models and found to be very effective in determining rule curves along with inflow prediction [1]. Recognition of non-linear relationships of storage and discharge and routing of complex hydrographs in natural channels using genetic programming was also accurately achieved with extremely good results [2]. Reservoir studies with long-term operations based on ANN and Genetic Programming (GP) was carried out by [3] and their findings suggested that proposed GP formulation had a relatively better potential. It improved the operating rules of multi-reservoir systems as compared to ANN and standard operating rule curves. Furthermore, applications of genetic programming in determining local scour downstream gave genetic programming formulation results to be more accurate than experimental results and other scour depth equations [4]. Studies on modeling of reservoir operations using Artificial Neural Network (ANN) [5] in both reservoir water level forecasting and reservoir water release decision also provided excellent model performances with good computational efficiency. Wavelet transform nowadays, are also often hybridized with other computational intelligence tools like ANN, ANFIS, linear models, etc. as a data pre-processing technique [6]. It is found to capture useful information on various resolutions and significantly improved the results than using only single regular models [7]. The purpose of this study is, therefore, to develop real time models using genetic programming and ANFIS and their wavelet hybrid models that can provide useful information to the operator in the form of multi-time ahead release predictions for efficient reservoir operation.

In the present study, prediction of daily reservoir water release at multi-time steps is done using daily inflow, daily water elevation, outflow from reservoir and their lagged values for the seasonal period i.e. June to October for two reservoirs Maithon and Panchet located in Jharkhand, India. Finally comparision of all developed models i.e. single prediction models ANFIS and Genetic Programming (GP) with Wavelet hybrid models of genetic programming and ANFIS are compared to each other in determining the best model for the reservoirs.

II. STUDY AREA AND DATA

In this study, two major dams of Damodar valley i.e. Maithon dam and Panchet Dam are chosen for demonstrating the application of machine learning techniques as given in figure 1. Maithon dam is located on Barakar river in Jharkhand at a latitude of 23^0 47’ and longitude of 86^0 49’, while Panchet dam is located across Damodar river in Dhanbad district of Jharkand at a latitude of 23^0 40’ and longitude of 86^0 44’. Maithon dam is the biggest dam of Damodar Valley Corporation and the largest in Jharkhand and the reservoir came into being in 1957. Both the dams have been mainly designed for flood control, irrigation and power generation. Maithon dam is 4,789 m in length and 50 m in height with a catchment area spread of 6,249 square km. The average annual basin precipitation is 114 cm with average annual runoff of 2,616 million cubic meter. The Panchet reservoir has a catchment area of 10,961 square km. The average annual basin precipitation of Panchet reservoir is 114 cm with an average annual run off of 4540 million cubic meter. For generation of hydropower, the Maithon dam is installed with 3 units of 20 MW each, and it is two units of 40 MW for Panchet dam. The Maithon and Panchet dams have been able to significantly reduce daily and annual discharge and also largely eliminated the extreme flows in the Damodar valley. The daily observed data of inflow, reservoir water level and release of both Maithon and Panchet reservoir for a period of 16 years have been collected from Damodar Valley Corporation, Kolkata. The reservoir release prediction study is carried out only for the monsoon periods i.e. from June to October.

III. ADAPTIVE NEURO FUZZY INFERENCE SYSTEM

Adaptive Neuro fuzzy inference System (ANFIS) is one of the most widely used neuro fuzzy networks and is a powerful tool for analyzing complex non-linear processes with successful application to many hydrological problems. One of the most accurate fuzzy inference models used is Takagi-Sugeno (TS) fuzzy inference system

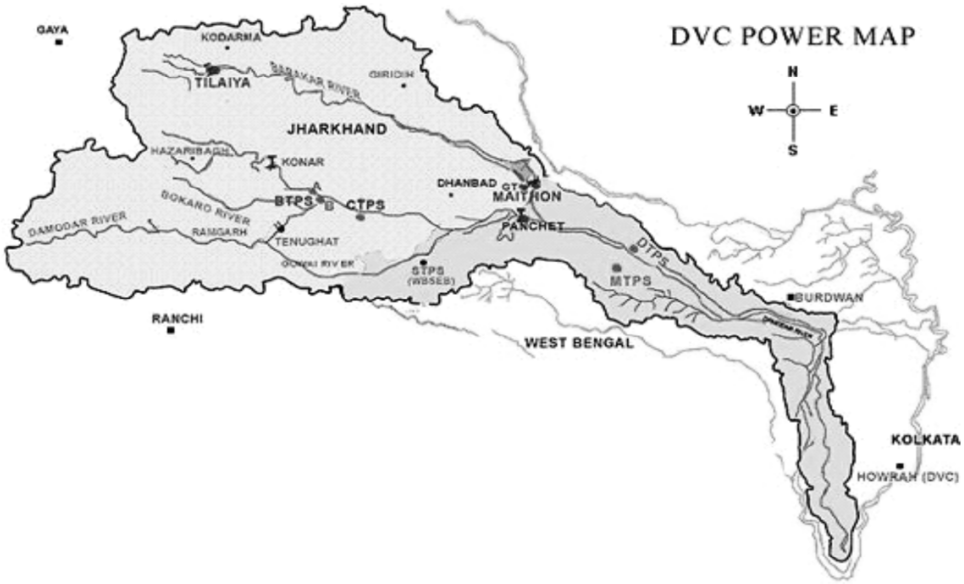


Figure 1: Map of Maithon and Panchet reservoir

models. In the TS fuzzy inference system, a fuzzy rule is constructed using a weighted linear compound of crisp inputs rather than a fuzzy set. In the first order TS fuzzy inference system, a common rule set of fuzzy IF-THEN rules is defined as follows:

$$\text{Rule1: IF } x \text{ is } A_1 \text{ and } y \text{ is } B_1 \text{ THEN } f_1 = p_1x + q_1y + r_1 \tag{1}$$

$$\text{Rule1: IF } x \text{ is } A_2 \text{ and } y \text{ is } B_2 \text{ THEN } f_2 = p_2x + q_2y + r_2 \tag{2}$$

where, A_1, A_2 and B_1, B_2 denote membership values of input variables x and y respectively; f_1 and f_2 are the output functions with p_1, q_1, r_1 and p_2, q_2, r_2 are the design parameters. In this study, triangular membership function was selected and employed to the models as input data. ANFIS consists of five layers, and the basic functions of each layer are input, fuzzification, rule inference, normalization and defuzzification. In the present study, each fuzzified inputs of ANFIS model was tuned with a hybrid method combining the back propagation gradient descent and least squares method in estimation of parameters.

IV. GENETIC PROGRAMMING

Genetic programming (GP) based on Darwin's theory has been extensively applied for solving symbolic regression problems and the main advantage is their ability in generating prediction equations without assuming prior form of the existing relationships. The algorithm generates initial population of solutions randomly by combining the elements from function and terminal sets. The elements like arithmetic operators (+, ×, ÷, or -), mathematical functions (sin, cos, tan, exp, tanh, log), Boolean operators (AND, OR, NOT, etc), logical expressions (IF, or THEN) or any other suitable functions defined by the user form the functional set. Using mutation and crossover, GP produces a new population of solution having better solution than their parents and the process in repeated till the end of a certain number of generations or till the best solution is reached. In this study, multi-gene GP a popular variant of GP is used for predictive modeling of Maithon and Panchet reservoir water releases. In multigene GP, the predicted value comprises of a summation of various genes with specific optimal weights plus a bias term to form the final formula of the best numerical model [8]. The mathematical expression of a multigene GP can be written as

$$Y = a_0 + a_1 \times gene_1 + a_2 \times gene_2 + ... + a_n \times gene_n \quad (3)$$

where a_0 is the bias term and a_i is weight of the ith gene. In the study, GPTIPS, an open source genetic programming toolbox in MATLAB that employs multigene GP for symbolic regression goals and is a linear combination of genes and is evolved according to standard genetic programming is utilized [8, 9]. Root Mean Square Error (RMSE) which is the default fitness function of GPTIPS is considered in all the models.

V. WAVELET TRANSFORM COUPLED GENETIC PROGRAMMING AND ANFIS MODELS

Wavelets are waves of zero mean and effectively of short duration. Wavelet transform are generally done to break a signal into shifted and scaled version of the original data. Sometimes, it is also called as multi resolution analysis. There are two types of wavelet transform: Continuous wavelet Transform (CWT) and Discrete wavelet transform (DWT). But researches in practical applications of hydrology have more access to a discrete time signal rather than continuous time signal and so in the present study discrete wavelet transform has been used. In the study, genetic programming is combined with discrete wavelet transform components to form wavelet-GP model for achieving a more powerful nonlinear prediction model. And in wavelet based ANFIS model (WANFIS), wavelet decomposed components are taken as inputs to ANFIS model for predicting current day, one-day and two-day ahead reservoir water releases. The daily inflow, water level and outflow of reservoir were decomposed into sub-components (approximation A3, details D1, D2, and D3) with daubechies-3 (db3) as the mother wavelet using a MATLAB code which includes Mallat's DWT algorithm [11]. Each input combinations were created in ANFIS and wavelet-ANFIS using three numbers of triangular membership functions. For using wavelets with ANFIS and GP, the input time series have been decomposed in three resolution levels based on the formula [12], $L = \text{int}\left[\log\left(N\right)\right]$, where L,N are decomposition level and number of time series data respectively. Four statistical methods were selected to analyse the performance of models namely root mean square error (RMSE), correlation coefficient (CC), mean absolute error (MAE) and Nash-Sutcliffe Efficiency (NSE) and is expressed mathematically in Table 1.

Table 1
Statistical criteria for evaluation of models

Performance Measure	*Mathematical definition*
Root Mean Square Error (RMSE)	$\sqrt{\frac{I}{n}\sum_{i=1}^{n}\left(Q_i - \hat{Q}_i\right)^2}$
Correlation coefficient (CC)	$\frac{\sum_{i=1}^{n}\left(Q_i - \bar{Q}_i\right)\left(\hat{Q}_i - \bar{\hat{Q}}_i\right)}{\sqrt{\sum_{i=1}^{n}\left(Q_i - \bar{Q}_i\right)^2 \sum_{i=1}^{n}\left(\hat{Q}_i - \bar{\hat{Q}}\right)^2}}$
Mean Absolute Error (MAE)	$\frac{1}{n}\sum_{i=1}^{n}\left\vert\hat{Q}_i - Q_i\right\vert$
Nash-Sutcliffe Efficiency (NSE)	$1 - \frac{\sum_{i=1}^{n}\left(Q_i - \bar{\hat{Q}}_i\right)^2}{\sum_{i=1}^{n}\left(Q_i - \bar{Q}_i\right)^2}$

where, Q_i = observed data, $\hat{Q}_i$ = predicted data, $\overline{Q_i}$ is average of observed data, $\overline{\hat{Q}_i}$ is average of predicted data, n is the number of data length.

VI. MODEL FORMULATION AND PARAMETERS

The gamma test was carried out before selecting the required data length of inputs in training and testing. The best gamma test results was found for a combination of 80% training and 20% testing with gamma test score of 0.0932 and v-ratio 0.3729. Hence, this proportion of data partitioning is used for all the developed models in comparing model performances. The auto correlation function and partial auto correlation function were conducted on each input time series and the lags associated with each variables were determined. Nine numbers current day prediction models was developed using inputs I_t, I_{t-1}, I_{t-2}, H_t, H_{t-1}, H_{t-2},Q_{t-1},Q_{t-2},Q_{t-3}; ten numbers for one-day ahead using I_t, I_{t-1}, I_{t-2}, H_t, H_{t-1}, H_{t-2},Q_t, Q_{t-1},Q_{t-2},Q_{t-3} and ten numbers for two-day ahead prediction models using I_t, I_{t-1}, I_{t-2}, H_t, H_{t-1}, H_{t-2},Q_t, Q_{t-1},Q_{t-2},$Q_{t-3.}$ Here, I, H and Q represents inflow to reservoir, reservoir water level and outflow from reservoir respectively. Subscript t denotes current day time and lags denoted by t-1, t-2 and t-3 respectively associated with all variables. The total data set of inflow, water level and outflow from reservoir were all scaled in the range 0 and 1 for all ANFIS, Genetic Programming, wavelet based ANFIS and wavelet based genetic programming models. For developing the GP and wavelet-GP models, the population size was varied between 500 to 3000, maximum depth of tree was kept 5, maximum number of genes was 4 and the functional set used were +, - , power, times, × , sin, cos, exp.

VII. RESULT AND DISCUSSIONS

Tables 2 and 3 shows the statistical performances of Maithon and Panchet reservoir in training and testing for the ANFIS, WANFIS, GP and wavelet-GP prediction models for current day, one-day ahead and two-day ahead reservoir water releases. From the comparisions of all models based on statistical criteria, it can be seen that wavelet-ANFIS and wavelet-GP are more precise models in predicting reservoir water release for current day and multi-step ahead forecasts. Overall, the statistical results of wavelet hybrid models indicate that the application of wavelet decomposed inputs further provides a more potential improvement over the single ANFIS and GP models. This may be related to the fact that single models use only raw time series data as input values for modeling, whereas wavelet hybrid models use subcomponents which include various information about non-linearity, non-stationary and seasonality behaviour in input time series. Considering these findings, it can be concluded that the new wavelet-GP and WANFIS are more robust models. From table 2, though the wavelet hybrid models performed better but gave relatively gave reduced performances for one-day and two day ahead prediction in comparision to current day prediction. Of all the models, wavelet-GP gave the best consistent performance in both training and testing periods for both Maithon and Panchet reservoirs. And thus wavelet-GP can be chosen to be the best prediction model for both the reservoirs. The WANFIS models was developed using all the wavelet decomposed components for all input variables, whereas in GP and wavelet-GP models, the insignificant decomposed components of input variables got eliminated automatically after mutation and crossover processes in the final formula of GP and wavelet-GP prediction models. For example, the best wavelet-GP model for current day reservoir release of Panchet reservoir obtained with four number of genes is given below by equation (4) as :

$$Q_t = -1.404 + 0.2325 \times (A3\_I_t + D2\_I_{t-2} + D1\_I_t - D2\_Q_{t-1}) + 0.7189 \times D2\_Q_{t-1} + 1.171 \times D3\_Q_{t-1} + 0.2539 \times (D2\_I_t - D1\_Q_{t-2}) - 0.1926 \times (A3\_Q_{t-3} - D1\_I_{t-1} - D3\_I_{t-1}) + 0.2325 \cos(D3\_I_{t-2} + D2\_Q_{t-1} + D3\_I_{t-1}) + 1.171 \cos(\sin((D3\_Q_{t-2})^\wedge 0.5)) - 0.1926 \sin(\sin(\sin(D2\_Q_{t-2}))) + 0.9941 \sin(A3\_Q_{t-1}) - 0.4464 \sin(D2\_Q_{t-2}) \quad (4)$$

Here, only the significant component of each input variable time series is taken and the rest of decomposed components of the input time series is discarded. Figure 2 presents the comparison of the observed and predicted reservoir releases using the optimal WANFIS and Wavelet-GP with Daubechies (db3) mother wavelet and single ANFIS and GP models for current day in training and testing period of Maithon and Panchet reservoirs. From the scatter plots, it can be observed that the estimates of the WANFIS and wavelet-GP and single ANFIS and GP models for current day release prediction are less scattered and closer to the line of perfect fit both in training and testing. The agreement of fit seems to be better for Panchet reservoir than Maithon reservoir. Also from table 2 and table 3 for Maithon and Panchet reservoir, the root mean square error (RMSE) values obtained for wavelet-GP were the least among all models both in training and testing and for all lead time forecasts. The Nash-Sutcliffe Efficiency (NSE) values of wavelet-GP model was also consistent and the highest both in training and testing. Single models ANFIS and GP gave very low performances of NSE values for one-day ahead and two-day ahead forecasts of Maithon reservoir in the range of 0.729 to 0.861 and 0.416 to 0.470 respectively. Whereas with the integration of wavelet decomposed components to these models, the NSE values got improved noticeably with values ranging from 0.827 to 0.970 in one-day ahead forecasts and 0.855 to 0.906 for two-day ahead forecasts respectively. In case of Panchet reservoir also, similar improvements due to wavelets were noticed as compared to single ANFIS and GP models. The single ANFIS and GP models for Panchet reservoir

Table 2
Comparision of performances of best ANFIS, Genetic Programming, WANFIS and Wavelet-Genetic Programming models for Maithon reservoir

Lead Time	*Criterion used*	*ANFIS*		*Wavelet -ANFIS*		*GP*		*Wavelet - GP*	
		Training	*Testing*	*Training*	*Testing*	*Training*	*Testing*	*Training*	*Testing*
Current	RMSE	0.017	0.015	0.007	0.024	0.013	0.109	0.013	0.009
Day	CC	0.960	0.920	0.993	0.861	0.975	0.955	0.977	0.966
Forecast	MAE	0.009	0.009	0.004	0.009	0.006	0.006	0.007	0.005
	NSE	0.921	0.816	0.985	0.545	0.951	0.908	0.955	0.933
One-day	RMSE	0.027	0.021	0.010	0.030	0.023	0.049	0.013	0.020
ahead	CC	0.888	0.832	0.985	0.670	0.923	0.517	0.976	0.828
forecast	MAE	0.011	0.009	0.005	0.013	0.009	0.013	0.006	0.008
	NSE	0.788	0.729	0.970	0.901	0.852	0.861	0.952	0.827
Two-day	RMSE	0.045	0.029	0.018	0.025	0.043	0.027	0.018	0.013
ahead	CC	0.656	0.624	0.951	0.773	0.686	0.725	0.952	0.937
forecast	MAE	0.015	0.014	0.009	0.015	0.013	0.013	0.008	0.007
	NSE	0.430	0.416	0.905	0.855	0.470	0.432	0.906	0.876

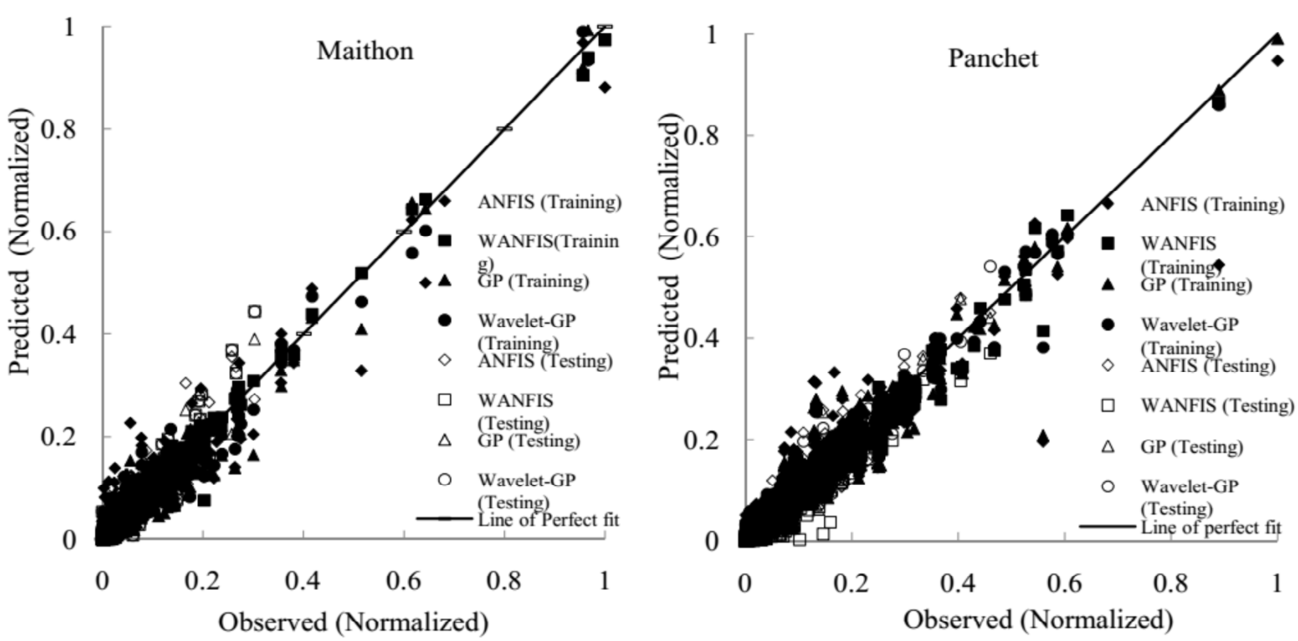
Table 3
Comparision of performances of best ANFIS, Genetic Programming, WANFIS and Wavelet-Genetic Programming models for Panchet reservoir

Lead Time	*Criterion used*	*ANFIS*		*Wavelet -ANFIS*		*GP*		*Wavelet - GP*	
		Training	*Testing*	*Training*	*Testing*	*Training*	*Testing*	*Training*	*Testing*
Current	RMSE	0.022	0.018	0.012	0.021	0.020	0.017	0.012	0.015
Day	CC	0.957	0.945	0.981	0.949	0.966	0.952	0.983	0.961
Forecast	MAE	0.011	0.010	0.007	0.013	0.011	0.010	0.008	0.009
	NSE	0.916	0.890	0.974	0.848	0.934	0.904	0.976	0.919
One-day	RMSE	0.026	0.023	0.018	0.021	0.027	0.021	0.016	0.014
ahead	CC	0.939	0.915	0.976	0.939	0.938	0.923	0.989	0.959
forecast	MAE	0.013	0.012	0.006	0.015	0.012	0.012	0.009	0.009
	NSE	0.882	0.813	0.979	0.946	0.879	0.838	0.982	0.915
Two-day	RMSE	0.044	0.036	0.018	0.041	0.043	0.035	0.023	0.021
ahead	CC	0.815	0.773	0.971	0.804	0.828	0.775	0.955	0.916
forecast	MAE	0.020	0.018	0.011	0.029	0.019	0.018	0.012	0.013
	NSE	0.664	0.545	0.942	0.824	0.686	0.570	0.929	0.838

obtained were RMSE (0.017 to 0.686) and NSE (0.545 to 0.979) which got improved to RMSE values (0.012 to 0.023) and NSE values (0.824 to 0.924). The mean absolute error for the reservoirs were also found considerably reduced with the application of wavelets. The highest and lowest correlation coefficients for Panchet reservoir was obtained for one-day ahead release forecast (0.989 in training and 0.959 in testing) with wavelet-GP model and two-day ahead release forecast (0.815 in training and 0.773 in testing) with ANFIS model respectively. For Maithon reservoir, wavelet-GP gave the highest correlation coefficient (CC) with good consistency in training and testing; and ANFIS gave the least correlation coefficient (CC) with values in the range 0.624 to 0.656. From the results, it can be further inferred that the wavelet transform has the ability to improve the prediction results with those of observed with higher correlations than single models.

VIII. CONCLUSION

In this study, the capabilities of adaptive neuro fuzzy inference system (ANFIS), Genetic Programming (GP), Wavelet based ANFIS(WANFIS) and wavelet based Genetic Programming (wavelet-GP) model in determining the current day, one-day ahead and two-day ahead reservoir water release prediction were evaluated. From the obtained results, GP in conjunction with wavelets outperformed the standard ANFIS and GP models. It may be related to the ability of wavelets to handle non-linearity, non-stationary and seasonality behavior in input time series. The ANFIS model also satisfactorily predicted the reservoir water release. ANFIS failed mostly in predicting the two day ahead release but performed consistently overall with very low root mean square error and mean absolute error. As deduced from results, single prediction models using genetic programming was found to be better than single ANFIS models for all multi-time steps reservoir releases. Further, wavelet hybrid models i.e. wavelet-ANFIS and wavelet based genetic programming models improved considerably the prediction results of single ANFIS and genetic programming models by a greater margin for all statistical criterias. Overall results concluded that wavelet integrated genetic programming model is relatively more accurate and consistent among all models.



(a) (b)

Figure 2: Scatter plots of predicted and observed reservoir water releases for current day using ANFIS, WANFIS, Genetic Programming (GP) and Wavelet-GP of (a) Maithon and (b) Panchet reservoirs

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