Utility of Climate Information Based Reservoir Inflow Forecasts in Annual Water Allocation – Ceara Case Study

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ABSTRACT

A dynamic water allocation framework for a multipurpose, single reservoir is formulated to utilize climate information based reservoir inflow forecasts to quantify the reliability of use for the given demand. Based on the semi-parametric approach of De Souza and Lall [2003], 12 months lead retrospective reservoir inflow forecasts were developed for the period July 1990-June 2000 for the Oros reservoir utilizing the climatic conditions available up to June of that year. Based on the actual annual demand to be supplied by the Oros reservoir for the JMH system, the utility of climate forecasts for multipurpose water allocation is assessed utilizing the adaptive forecasts developed for the period 1990-2000. Since Oros reservoir is a multi-year storage reservoir, the initial storage available in July of every year was adequate enough to supply water for all the uses even under zero inflow assumption thereby reducing the utility of climate forecasts during normal inflow years. On the other hand, climate information based reservoir inflow forecasts is more beneficial in meeting the annual demands of the Oros system for different uses during above-normal and below-normal inflow years than during normal inflow years. Analysis of the results suggests that the utility of climate information based reservoir inflow forecasts is more pronounced for systems with high demand to storage ratio.

1. Introduction

Recent advances in understanding the linkages between exogenous climatic conditions such as tropical sea surface temperature (SST) anomalies to local/regional hydroclimatology offer the scope of predicting the rainfall/streamflow potential on a season ahead and long-lead (12 to 18 months) basis [Hamlet and Lettenmaier, 1999; Sharma, 2000; De Souza and Lall, 2003]. This information could be effectively utilized to develop an adaptive reservoir management and operation strategy. Traditionally, reservoir rule curves that specify the volume of water to be kept in the reservoir at a particular time of the year to meet the future demand are often obtained based on the driest envelope in the entire historical record, thereby adhering to the same rule curve every year for reservoir operation. In this regard, a commonly adopted strategy in the U.S. is to lower the reservoir to a prespecified level every year during the winter to accommodate the later winter and spring peak flows. This unconditional/static risk management strategy could be modified to evolve a dynamic risk management strategy based on the winter and spring climate information based streamflow forecasts. Several investigators have emphasized the importance of exploiting this improved hydrologic predictability to enhance operation and management of water supply systems [Cayan et al., 1999; Arumugam et al., 2003].

But, few studies have focused on the utility of climate forecasts in improving reservoir operation and system management.

The main intent of this study is to assess the utility of climate information based reservoir inflow forecasts in improving multipurpose bulk sector water allocation over the long-term. For this purpose, we utilize 12 months lead, retrospective reservoir inflow forecasts obtained based on exogenous climatic indices for allocating water annually for multiple uses. In this context, we adopt the dynamic water allocation framework developed by [Sankarasubramanian et al., 2003] to obtain yields for multiple uses contingent on the climate information based reservoir inflow forecasts. The study site considered is the Oros reservoir, Ceara, North East Brazil [De Souza and Lall, 2003].

2. Formulation of a Single Reservoir, Multipurpose Water Allocation Model

The water allocation model presented here is an optimization model that obtains the maximum yield with a specified reliability of supply from the reservoir by meeting policy and physical constraints for the ensemble inflow sequences. A single site, multi purpose reservoir is considered with an objective to maximize the net income from different uses based on ensemble streamflow forecasts. The model encompasses a contract structure for each use that quantifies the yield (R_i) for the user specified reliability of supply ($1-pf_i$, pf_i = failure probability) along with a maximum allowable restriction volume (w_i) that could be enforced as part of contract specification if actual flows were drier than the forecasted flows. The decision variables are the releases/yields, R_i, for each use having an associated reliability of supply. For more details on contract specification, see Sankarasubramanian et al., [2003]. The following section briefly describes the system of reservoirs and the water allocation process in the Jaguaribe-Metropolitano Hidrossytem (JMH) in Ceara, North East Brazil.

2.1 Study Site Description

Ceara, a semi-arid state in the North East Brazil, is a drought prone region that is heavily influenced by the anomalous conditions in SST over tropical Atlantic and Pacific. Figure 1 shows the six major reservoirs and different irrigation districts in the JMH. This study considers the largest reservoir in the JMH system, Oros, for the purpose of assessing the utility of climate information based reservoir inflow forecasts in improving annual water allocation. The first three reservoirs in Jaguaribe Basin primarily supply water for irrigated areas, while the rest in the Metropolitan Basin serve towards the municipal and industrial demand of the largest metropolitan area, Fortaleza. The Jaguaribe Basin water demand is 80% Irrigation and 20% urban. The Metropolitan Basin water demand is mainly towards urban and industrial use. Hence, the demands in the Metropolitan basin are relatively uniformly distributed during the year, while those in the Jaguaribe basin are concentrated during the irrigation season (August-November). Rainfall records for each basin are available since 1911. But, streamflow records at different reservoirs vary in their starting date. Consequently, calibrated rainfall-runoff models have been used to reconstruct the inflow at each reservoir. The quality of the inflow data is expected to be the best for the Oros reservoir, and weakest for Pacoti-Riachão. Table 1 gives the monthly evaporation rate for the Oros reservoir. The annual inflows into the Oros reservoir were nearly zero in several of the years with the flow being highly variable and skewed. Ninety-five percent of the annual inflow typically occurs during January through June. Thus, the storage at the end of June in the Oros reservoir primarily specifies the water that is available for human and animal needs as well as for irrigation. Though agriculture contributes only 5.6% of the state's gross domestic product, it accounts for 40% of the livelihood of the state's population. Thus, even a marginal improvement in water allocation would have substantial benefit in terms of improving the livelihood of the society as well as in setting priorities among competing uses of water and in instituting appropriate contingency measures.

Water allocation process in the JMH basin, Ceara usually occurs at the end of wet season, in July every year in each sub basins (Figure 1). The annual water committee meeting coordinated primarily by the water allocation agency, COGERH, with members representing different water user groups (predominantly Municipal, agricultural and industrial use). The user groups deliberate upon water sharing based on the simulated water levels (prepared by COGERH) in the major six reservoirs, which is obtained for different release pattern by assuming zero inflow for the next 12 months. This strategy (zero inflow assumption) basically allocates water for different uses based on the storage available in June. In this process, priority in water allocation is given to municipal use followed by industrial use with the remaining storage water is allocated for irrigation. As an outcome of this negotiation, both COGERH and each user group agrees upon the volume of water to be supplied over the next 12 months (July-June) as well as on the end of the year target storage (June in the ensuing year) to be kept in the six reservoirs (Figure 1). Thus, the timeline of the water allocation process described above basically necessitates the development of reservoir inflow forecasts for the period July-June (lead time of 12 months) based on the climatic information available up to June to facilitate annual bulk sector water allocation. The following section briefly describes the water allocation framework suggested by Sankarasubramanian et al., [2003] to obtain releases for multiples uses contingent on climate information based reservoir inflow forecasts.

2.2 Water Allocation Model for Bulk Sector Contracts using Ensemble Forecasts

Given the ensemble streamflow forecasts q_{tk}, where t=1,2,…,T denoting the period of operation (usually months, hence T = 12) and k = 1,2,…, N is the index representing a particular ensemble out of 'N' ensembles and the initial reservoir storage, S_{0*}, at the beginning of the year, the water allocation model described in this section determine the annual releases (R_i) for each use 'i' that can be obtained from the reservoir for the given reliability ($1-p_{fi}$) . The water committee specifies the target storage S_{T*} to be kept in the reservoir at the end of June and the minimum and maximum releases from the reservoir for each use.

2.2.1 Objective Function

The goal is to maximize the annual yield (R_i) for different uses from the reservoir with reliability ($1-p_{fi}$) such that the end of year storage is less than S_{T*}, with probability p_s. Hence, the decision variables are the annual releases R_i for 'n' different uses. Expressing this, the objective is to maximize the net benefit from multiple uses

$$O = \sum_{i=1}^{n} \phi_i R_i \qquad \ldots(1)$$

where ϕ_i denotes the marginal net benefit from each use.

2.2.2 Constraints

In most seasonal/annual water allocation decisions, water that is needed for basic services like domestic water supply, ecosystem services is allocated separately by assigning high priorities that could be set by assigning appropriate marginal net benefit, ϕ_i, for each use. The constraints that are enforced to maximize (1) can be grouped into (a) Contract/water use level constraints (b) Reservoir level constraints. Contract level constraints enforce physical bounds of supply as well as target reliability of supply ($1-pf_i$) for each use. On the other hand, reservoir level constraints ensure the end of the year target storage with associated failure probability p_s, and the probability of enforcing a particular restriction level. During drier periods, Sankarasubramanian et al., [2003] propose enforcing restriction levels (if the actual flows are drier than the forecasted flows) as part of water allocation model formulation. Restriction levels imposed at the reservoir level specify the reduced supply of water, $\alpha_{il} R_i$, that is signified by the restriction fraction, α_{il} (i denotes user, l denotes restriction level) for each contract/use. Higher levels of restrictions could be imposed as the severity of the deficit/shortfall increases.

Constraint 1: Reliability of supply for each use

The target reliability ($1- p_{fi}$) of supply of the contracted quantity, R_i is enforced by specifying that the likelihood of actual restrictions, w_i, for each contract being greater than maximum allowed restriction volume, w_i^{*}, should be lesser than the contract failure probability, p_{fi} (2). The maximum allowed restriction volume, w_i^{*} and the contract reliability ($1- p_{fi}$) act together to provide a safety/protection mechanism for both the user as well as the supply agency.

$$P(w_i \geq w_i^{*}) \leq p_{fi} \qquad \ldots(2)$$

Constraint 2: Bounds on the Allocation for each use

Policy or physical considerations may enforce the annual release from the reservoir to be constrained between an upper and lower bound. This could be either based on the agreement in the water committee meeting or based on the minimum recommended supply for each use.

$$R_{i,min} \leq R \leq R_{i,,max} \qquad \ldots(3)$$

Constraint 3: End of the Year Target Storage

To ensure, adequate storage is maintained in the reservoir at the end of contract period as per the water committee decision, a probability constraint on the end of the year storage is introduced. A typical year-end target storage that is commonly adopted in Ceara is to ensure 18 months of municipal water demand beyond the allocation period.

$$P(S_T \leq S_{T*}) \leq p_s \qquad \ldots(4)$$

Constraint 4: Restriction Enforcement

To ensure restriction levels are not enforced too frequently, the probability of each restriction level 'l' being enforced in the upcoming year should be lesser than pr_l, which could be again specified through deliberations between the water users and the agency. This could be expressed as,

$$P(RL_l) \leq pr_l \text{ where } l = 1,2,\ldots, n_r \qquad \ldots(5)$$

where RL_l denotes the restriction level 'l'. Note that S_t, $t = 1,2,\ldots, T$ are not decision variables. These state variables are evaluated during each iteration of the optimization model using simple reservoir simulation as functions of the current value of releases for each use. The probability constraints (2), (4) and (5) are evaluated by counting the number of times the respective inequalities are satisfied in 'N" ensembles. Monthly storage computations are basically updated using a simulation model based on simple continuity equation. For more information, see Sankarasubramanian et al., [2003]. The optimization solver, Fortran Feasible Sequential Quadratic Programming (FFSQP) developed at the University of Maryland that maximizes the net value in (1) from the reservoir by satisfying the constraints in section 2.2.2.

3. Retrospective Streamflow Forecasts for the Oros reservoir

The main objective of this study is to assess the utility of climate information based inflow forecasts in improving the reservoir performance over the long-term and illustrate the usefulness of generic water allocation framework developed by Sankarasubramanian et al., [2003] towards bulk sector water allocation. The reservoir performance in reducing system losses (spill and evaporation) utilizing K-NN retrospective forecasts is compared with the system losses under zero inflow forecast that is currently pursued for water allocation in JMH, Ceara. Using the semi-parametric K-nearest neighbor (K-NN) resampling algorithm of De Souza and Lall [2003], ensembles of retrospective monthly streamflow forecasts for each year from July 1990- June 2000 is developed based on the April-June average of East Atlantic Dipole (EAD), Nino 3.4. For more information about K-NN resampling approach, see De Souza and Lall [2003].

NINO 3.4, the most commonly used index to represent ENSO condition in the tropical Pacific, is defined as the average Sea Surface temperature anomaly in the region bounded by the eastern equatorial Pacific 150 degrees W to 90 degrees W and 5 degrees S to 5 degrees N. The other climatic index, East Atlantic SST Gradient (EAD), is defined as the difference in the monthly average of the SST anomaly in the region bounded by North Atlantic (5-20N, 60-30W) and the monthly average of the region bounded by South Atlantic (0-20S, 30W-10E). Figure 2 shows the ensemble average and median of adaptive forecasts developed for the period July 1990- June 2000 obtained using the respective years April-June conditions of Nino3.4 and Dipole. The data available for the period July 1949- June 1990 was employed for resampling the flows. The correlation between the ensemble average of forecasted flows and the observed annual flows at Oros for the period July 1990-June 2000 is 0.7. Figure 2 basically shows that the resampled flows using the approach of De Souza and Lall [2003] correlate well with the observed annual flows and preserves the monthly correlation structure.

3.2 Zero Inflow Policy

Since the entire state of Ceara North East Brazil is a semi-arid, drought prone region, COGERH, the water allocation agency for the Jaguaribe Metropolitan Hydro System assumes zero inflow for the next twelve months (July-June) to allocate water for different uses. In other words, this approach allocated water purely based on the currently available storage to ensure maximum possible storage in the reservoir that can protect the system from multiyear droughts. This is presumably a conservative approach with an underlying reliability of supply being equal to 100%. We have included this as a scenario/candidate forecast and analyzed the reservoir yields for multiple uses based on this assumption.

4. Assessment of the Utility of Long-Lead Streamflow forecasts

In this section, we assess the utility of retrospective reservoir inflow forecasts (developed in section 3) towards potential improvement in annual water allocation for multipurpose use in the JMH basin, Ceara. The multipurpose water allocation experiment is run using the adaptive forecasts developed for the period July 1990-June 2000. The actual recorded volume in Oros reservoir on July 1, 1990 was 1914.17 hm3. Using this initial storage for year 1990 and the adaptive forecasts developed for the period July 1990-June 1991, we obtain annual reservoir yields for the above period for each use with municipal being given the highest priority. Table 2 gives the maximum annual demand to be supplied by the Oros for the JMH system for the considered three uses. The experiment is run only for 90% reliability ($1-pf_i$) for each use. Since Ceara is a semi-arid region having experienced multi-year droughts, the currently adopted strategy is to fix the end of the year storage so that the resulting storage can supply 18 months of municipal demand (including evaporation losses) even if zero inflow occurs for that period. To be precise, by assuming such a high target end of year storage, the system is protected from failure to supply municipal demand for almost 30 months. For the annual municipal demand given in Table 2, the end of year target storage to supply 18 months of municipal demand under zero inflow assumption including evaporation losses is 260 hm3. Based on this end of year storage constraint, the annual reservoir yields for the three uses are obtained using the adaptive forecasts July 1990-June 1991. Based on the yields obtained from the water allocation model, releases were made from the reservoir using the observed flows for the period July 1990-June 1991 and the shortfall, spill and evaporation were noted. The resulting end of year storage was assumed to be initial storage for the next year (July 1991- June 1992). This procedure was repeated for all the 10 years (July 1990-June 2000) using the end of year target storage constraint based on the prioritized strategy. Similarly, the same experiment was carried out using the zero inflow assumption and the shortfall, spill, evaporation and annual yields were noted.

Table 2 gives the annual average yields for human, industrial and municipal use using the K-NN forecasts and the zero inflow forecasts along with the maximum annual demand for each use. Table 2 also summarizes the annual average shortfall, spill and evaporation in meeting the target yield based on both the approaches. As we can see from Table 2, there is no difference in annual allocation for municipal and industrial use using either of the two approaches. But, average annual yield for agriculture could be considerably increased using the K-NN forecasts, which is mainly obtained by reduction in spill and evaporation. Table 2 also quantifies the variability in annual yields, evaporation and spill from the reservoir. Note that the variability in agriculture yield using the K-NN forecasts is lesser than the variability in agriculture yield obtained using the zero inflow assumption. Figure 3 shows the difference between yields obtained using K-NN forecasts and yields obtained using Zero inflow assumption along with the observed annual flows in that particular year. The only difference is in year 1993 for agriculture use during which yield obtained using K-NN forecasts are higher than the Zero inflow assumption. Note that there is no shortfalls (Table 2) in supplying these target releases. This is mainly because the initial storage is continuously depleting and the forecasted inflow into that particular year is very close to zero. Hence, the utility of climate forecasts is much more pronounced during critical drought periods.

Table 2 also gives the system losses in terms of evaporation and spill for the period July 1990-June 2000. We understand that the evaporation using K-NN forecasts is lower than the zero inflow assumption, since K-NN forecasts draw more water in year 1993 by reducing the reliability of supply of each use to 90%. Table 2 shows the reduction in spill (around 40 hm3) that was achieved using K-NN forecasts over the zero inflow assumption. The tropical Pacific was going through a La Nina phase in year 1996-1997 that usually leads to above normal inflows into Oros reservoir. Once the reservoir builds up sufficiently with high initial storage conditions, then there is no difference in reservoir yields using climate information based reservoir inflow forecasts and zero inflow assumption. From this view point, if ENSO cycle enters first La Nino conditions followed by El Nino conditions, then water management during drought periods (during El Nino conditions) becomes relatively easy since sufficient storage is built up during La

Nino conditions. Reversal of this scenario (with El Nino first followed by La Nina conditions) would be difficult from short-term water management point of view.

4.0 Summary and Conclusions

Results from this exercise suggest that the utility of climate forecasts for multi purpose water allocation from the Oros reservoir is more pronounced during above-normal and below-normal inflow years. Since Oros is a multi-year storage reservoir that ensures sufficient initial storage conditions in July, the reservoir yields obtained using both K-NN forecasts and zero inflow assumption do not differ during normal conditions. Comparison of these results with the single purpose water allocation exercise that assumes unbounded annual demand show that the climate forecasts are more beneficial in water allocation from a within-year reservoir system than over a multi-year storage system [Sankarasubramanian et al., 2003]. Thus, reservoir yields obtained using climate information based forecasts of even moderate predictive skill essentially reduce the losses from the reservoir system that actually results in increased yields over the long-term. The currently pursued strategy of zero inflow assumption only leads to increased losses from the system. Hence, climate information based forecasts offers scope towards short-term water management for the semi-arid region Ceara since the entire Jaguaribe-Metropolitan system is quite vulnerable to recurrent droughts that affects the livelihood of majority of population in JMH, Ceara.

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Table 1: Monthly evaporation rate, ψ_t in m, for the Oros reservoir used for simulation. The total annual evaporation is 1.590 m.

	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
ψ_t	0.151	0.174	0.175	0.189	0.172	0.170	0.129	0.091	0.072	0.069	0.081	0.118

Table 2: Utility of Reservoir Inflow forecasts towards improving Bulk-Sector Water Allocation for multipurpose use and in reducing System Losses. Priority based allocation was pursued with human consumption having the highest priority followed by industry and agriculture assuming a 90% reliability of supply for each use. The end of year target storage was assumed to be 260 hm3 to supply 18 months of municipal demand even if zero inflow occurs during that period. All values are in hm3.

	K-NN Forecast		Zero Inflow		Annual Demand
	Mean	Standard Deviation	Mean	Standard Deviation	
Yield (Human)	130.0	0.0	130.0	0.0	130.0
Yield (Agriculture)	130.5	45.9	120.2	53.3	145.0
Yield (Industry)	81.0	28.5	81.0	28.5	90.0
Deficit/Shortfall	0.0	0.0	0.0	0.0	-
Evaporation	239.6	98.6	245.6	92.8	-
Spill	46.2	146.2	50.5	159.7	-

Figure 1. Location of Ceara, Brazil and the Reservoir Inflow Locations. 1=Oros, 2=Banabuiu, 3=Pedras Branca, 4=Pacajus, 5=Pacoti Riachao, 6=Gaviao. The major irrigation demand areas are indicated by squares and the municipal and industrial demand areas served are indicated by filled circles. Only features of the Jaguaribe and Metropolitan basins are filled in. Other basin boundaries are marked.

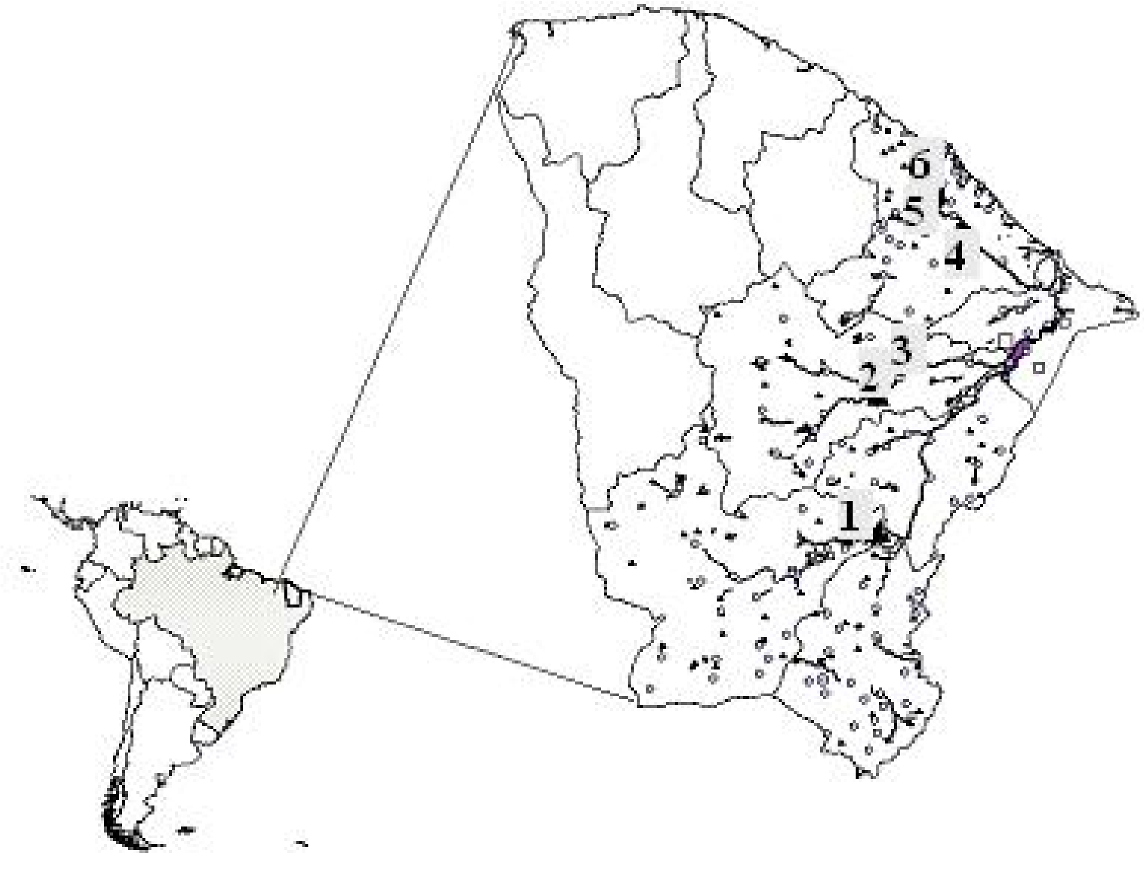

Figure 2: Performance of the K-nearest neighbor-resampling algorithm in simulating the observed flows at the Oros reservoir. Adaptive forecasts for the period 1990-1999 obtained using the flow values and predictors available for the period 1949-1989. The correlation between the observed flows and the average of the ensembles is 0.7.

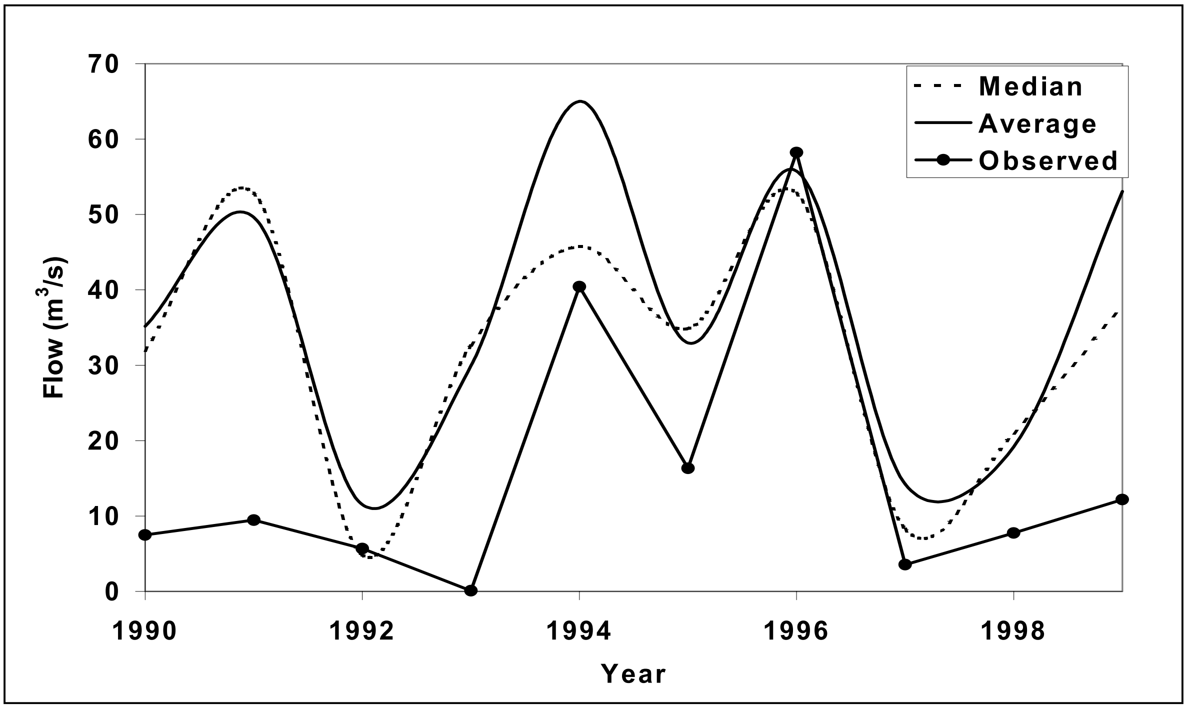

Figure 3: Performance of adaptive K-NN forecasts for multipurpose water allocation showing the difference in Forecasted Yield and Zero Inflow Yield for three uses. Note the difference is only in agriculture use in year 1993 during a drought year.