

WATER RESOURCES MANAGEMENT UNDER DROUGHT: CLIMATE CHANGE ISSUES

P P Mujumdar
IISc Bangalore

Introduction

Climate change, in as much as it affects the common man, is in fact hydrologic change. The three prominent signals of climate change, viz., increase in global average temperature, rise in sea levels and change in precipitation patterns convert into signals of regional scale hydrologic change in terms of modifications in water availability, evaporative water demand, hydrologic extremes of floods and droughts, water quality, salinity intrusion in coastal aquifers, groundwater recharge and other related phenomena. Increase in atmospheric temperature, for example, is likely to have a direct impact on the river runoff in snow-fed rivers and on the evaporative demands of crops and vegetation apart from its indirect impacts on almost all other processes of interest in hydrology. Similarly a change in the regional precipitation pattern could have direct implications on water availability, groundwater recharge, floods and droughts. While these facts are understood and accepted fairly well on a global scale, a major research focus in hydrologic sciences in recent years has been on assessing the impacts of climate change at regional scales, such as a river basin scale. An important research question that needs to be addressed in at the catchment scale, is the one related to the responses of water fluxes on a catchment scale to the global climatic variations.

A commonly adopted methodology for assessing the regional hydrologic impacts of climate change is to use the climate projections provided by the General Circulation Models (GCMs) for specified emission scenarios in conjunction with the process-based hydrologic models to generate the corresponding hydrologic projections. The scaling problem arising because of the large spatial scales at which the GCMs operate compared to those required in most distributed hydrologic models, is commonly addressed by downscaling the GCM simulations to hydrologic scales. This procedure of impact assessment is burdened with a large amount of uncertainty introduced by the choice of GCMs and emission scenarios, small samples of historical data against which the models are calibrated, downscaling methods used and several other sources. Development of procedures and methodologies to address such uncertainties is a current area of research in hydrology. Vulnerability assessment, adaptation and policy issues also form logical extensions of the basic research to provide the water resources managers, both at local, administrative scales and at larger, river basin scales with options for adaptive responses.

The specific questions that need to be addressed at a basin scale are the following:

- a) How is the rainfall pattern likely to change in the basin in the next three to five decades?
- b) How is the water availability (through both surface water and ground water resources) likely to be affected by climate change?
- c) How is the recharge pattern likely to change?
- d) How are the irrigation demands likely to change, as a cascading effect through temperature, radiation and evapotranspiration?, and
- e) Can we develop adaptive water use and allocation policies – through conjunctive use of surface and ground waters - to account for the climate change impacts?

These questions need to be addressed through mathematical modeling of the surface-ground water systems, downscaling from GCM simulations and optimization of conjunctive use of surface and ground water.

In this talk, an overview of the climate change issues for water resource management under drought conditions is provided, along with an overview of models developed for conjunctive use of surface and ground water, with crop yield optimization as an objective to produce maximum crop yield in the face of extreme water stresses.

Sustainable Water Resources Management

Sustainability of development refers to ensuring a high reliability of meeting future demands without compromising on the hydrologic, environmental and physical integrity. In the Indian context, large scale changes – due to changes in land use patterns as well as due to climate change – may have serious implications on sustainability of development of water resources. India is endowed with rich surface water resources but an extremely uneven spatial and temporal distribution of the rainfall, which is the primary source of surface waters, frequently results in severe water scarcity in some regions and, flood hazards in others. Under drought situations, it is critical to manage the water resources to optimize the productivity of water and to increase the efficiency of water use. Irrigated agriculture being the largest consumptive user of water in India, it is therefore important to address maximization of crop yield through conjunctive use of surface and ground waters, especially under the uncertainties in water availability, introduced by climate change.

Conjunctive Use Model for Surface and Ground Water

Modeling for conjunctive use will provide a handy tool for planning and operational purposes. Models for conjunctive use may be used for developing adaptive responses to climate change. The following paragraphs provides a brief description of a conjunctive use model developed (Vedula et al., 2005).

A mathematical model is developed to arrive at an optimal conjunctive use policy for irrigation of multiple crops in a reservoir-canal-aquifer system. The integration of the reservoir operation for canal release, ground water pumping and crop

water allocations during different periods of crop season (intra-seasonal periods) is achieved through the objective of maximizing the sum of relative yields of crops over a year considering three sets of constraints: mass balance at the reservoir, soil moisture balance for individual crops, and governing equations for ground water flow. The conjunctive use model is formulated with these constraints linked together by appropriate additional constraints as a deterministic linear programming model. A two-dimensional isotropic, homogeneous unconfined aquifer is considered for modeling. The aquifer response is modeled through the use of a finite element ground water model. A conjunctive use policy is defined by specifying the ratio of the annual allocation of surface water to that of ground water pumping at the crop level for the entire irrigated area. A conjunctive use policy is termed stable when the policy results in a negligible change in the ground water storage over a normal year.

Model overview

A schematic diagram of the conjunctive use system is presented in Fig. 1. The system is characterized by three main components: the reservoir, the irrigated area and the underlying aquifer with the associated dynamic relationships defining the interactions among them. A mathematical formulation is developed to arrive at an optimal conjunctive use policy of ground and surface waters for the irrigation of multiple crops in an irrigated area under the command of reservoir. The model considers varying soil moisture conditions and soil types and takes into account the dynamic response of the aquifer in the reservoir command area to surface application, pumping and recharge. The integration of decision making in reservoir operation, ground water pumping and crop water allocations during the different periods of crop season (intra-seasonal periods) is achieved through optimization with the objective of maximizing the sum of relative yields of crops over a year, and considering three sets of constraints: mass balance at the reservoir, soil moisture continuity for individual crops, and governing equations for ground water flow. These sets of constraints are linked together appropriately by additional constraints. The reservoir release and the ground water are optimally allocated to achieve the maximum annual relative yield of crops. A two-dimensional, isotropic, homogeneous unconfined aquifer is considered. The aquifer response is modeled through the use of a finite element ground water model.

The study area is discretized into a number of elements for this purpose. A given crop is assumed to grow in integral number of elements. The soil moisture continuity is considered for each cropped area which consists of several elements. Thus, the variables in the soil moisture balance equation for a given period will assume the same values over all the elements of a given cropped area. The governing partial differential equations representing the groundwater flow are transformed into linear algebraic equations using Galarkin method of weighted residuals. These equations are written for each node, and are embedded into the optimization model as constraints. The aquifer parameters (specific yield and transmissivity) are assumed to be known. A study area larger than the canal command area is considered such that the boundary conditions along the boundary of the study area can be assumed to be unaffected by the

irrigation operation within the command area. The boundary conditions specified correspond to those of a normal year. To specify the initial conditions at each node in the study area, ground water contours are drawn from the data of observation wells in and around the study area, and the initial conditions are specified accordingly. The recharge to the aquifer from an element consists of the recharge due to rainfall, canal seepage and the deep percolation from the root zone of the crop grown in the element. The waterlogging condition in the study area is avoided by imposing an upper bound on the ground water level at each node. The objective of maximizing the sum of relative crop yields is expressed using an additive crop production function. The conjunctive use model is formulated as a deterministic linear programming model. Reservoir inflow and rainfall in the canal command area in each time period are assumed deterministic. The decision variables in the model for each intraseasonal period are: reservoir release, reservoir storage, groundwater pumping required for each crop, surfacewater allocation for each crop, deep percolation, if any, from the root zone of the crop, actual evapotranspiration of each crop, ground water head at each node in the study area and the soil moisture at the beginning of the period for each crop.

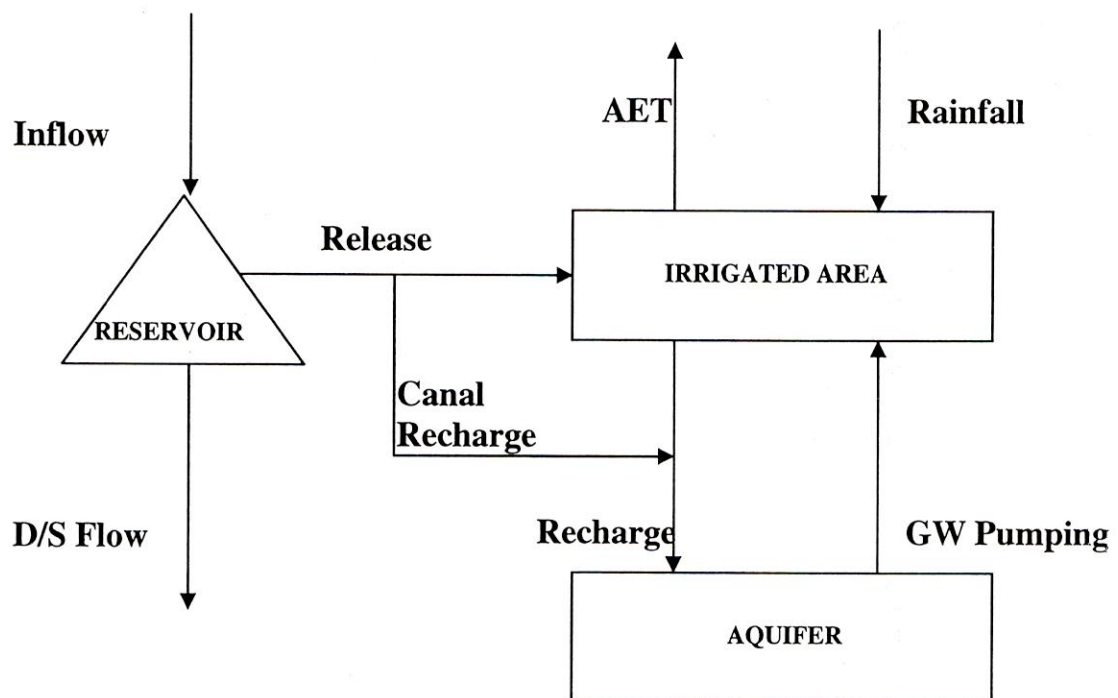


Fig. 1 Schematic diagram of the conjunctive use system.

A conjunctive use policy is defined by specifying the ratio of the annual allocation of surface water to that of ground water pumping at the crop level for entire irrigated area. A given policy is characterized by the ratio of annual irrigation water application at crop level from surface to ground sources. For example, a 70:30 policy refers to one in which 70% of the annual irrigation application, at the crop level, comes from surface source and 30% from ground water pumping. A policy is termed stable when it results in negligible change in the ground water storage over a normal year. The conjunctive use model is run for different pre-

determined ratios of annual surface and ground water applications at the crop level (i.e. for different conjunctive use policies). Ground water balance components over the entire study area are computed for each of these runs, and an examination of annual ground water balance is made in each case. The policy for which the annual change in ground water storage is negligible for a normal year is considered as the "stable policy". Optimal temporal allocation patterns are derived from the results of the stable policy for the specific case considered and applied to examine the aquifer storage response over years for stability. The derived stable conjunctive use policy aids in planning the total crop water allocation for irrigation in the study area.

Sample results from the model for the Vanivilas Sagar reservoir are presented as an example in Table 1. Details are available in Vedula et al., (2005). With such models in place, it is possible to examine the implications of climate change on water resource management. For example, if the surface water availability is likely to decrease, the conjunctive use policy may be re-examined with the revised streamflows and recharge estimates to provide the 'adaptive' responses to climate change.

Table 1 Summary Results of Conjunctive Use Model for Different Policies

Ratio	Sum of relative yields (seven crops)	GW storage change (mm)
a	7.000	- 265.39
10:90	7.000	- 252.95
30:70	7.000	- 164.64
40:60	7.000	-112.83
50:50	7.000	-87.29
60:40	6.964	-48.89
65:35	6.317	- 20.15
68:32	5.987	- 6.42
69:31	5.857	- 2.65
70:30	5.746	+0.69
71:29	5.614	+4.10
80:20	4.098	+23.86

a Run with unspecified policy.

Ratio : Volume Ratio of Surface to Ground Water Usage

Adaptive Reservoir Operating Policies under Water Stress Conditions due to Climate Change

Impact of climate change on reservoir performance is studied for the 'business-as-usual' case as well as with optimal operating policies, for the Hirakud reservoir in Mahanadi River. Adaptive policies for mitigation of hydrologic impacts in terms of performance criteria are suggested for future scenarios. Climate change effects on monthly power generation and four performance criteria (reliability, resiliency, vulnerability and deficit ratio) are studied initially with the standard

operating policy (SOP) using current rule curves. The results show that using current operations, annual hydropower and reliability will decrease and vulnerability will increase as a result of climate change for future scenarios. A stochastic dynamic programming (SDP) model which addresses the uncertainty associated with inflow is then applied to derive optimal monthly operating policy with the objective of maximizing annual power generation. The optimal operation also shows a decrease in hydropower and increase in vulnerability for the future. Adaptive policies are tested for two extreme cases from future scenarios.

Projections of future streamflow

Figure 2 shows the flow duration curves for monsoon streamflows projected using the CRF-downscaling model [Raje and Mujumdar, 2010a, b, c] for 2045-65 and 2075-95 for the range of GCM-scenario combinations with Fourth Assessment Report (AR4) projections. The GCMs used are CGCM2 (Meteorological Research Institute, Japan), MIROC3.2 medium resolution (Center for Climate System Research, Japan) and GISS model E20/Russell (NASA Goddard Institute for Space Studies, USA). It is seen that for most future scenarios, there is a decrease in middle level flows (equaled or exceeded 20 to 70 percent of the time). This decrease becomes more prominent by years 2075-95. High flows increase in most scenarios for 2045-65, but the number of scenarios showing an increase in high flows also decreases by years 2075-95. Low flows show a slight increase for 2045-65 (above 80 percent flows) but a smaller range of low flows increase for 2075-95 (above 90 percent flows only).

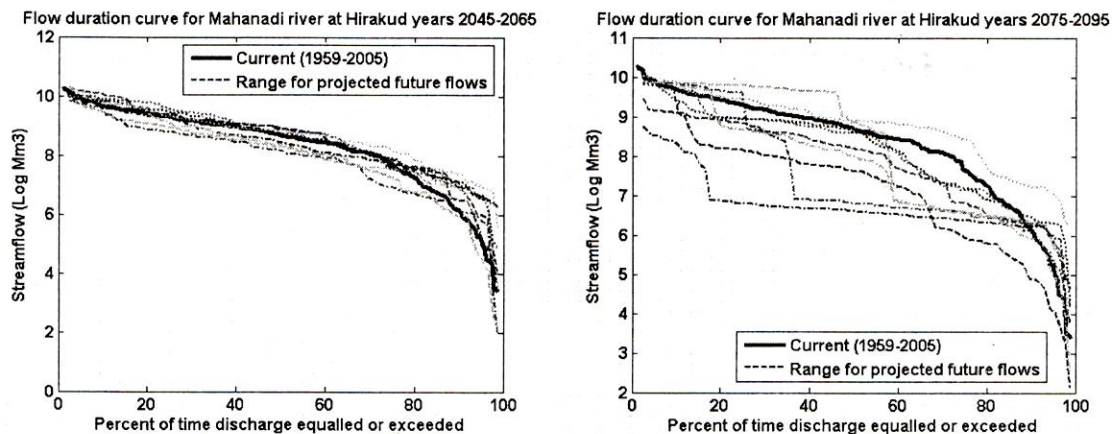


Fig. 2 Range of projected future flow duration curves for monsoon inflows at Hirakud for two time slices, 2045-65 and 2075-95.

The effect of changes in streamflow on future reservoir performance are quantified for the "business-as-usual" case using current rule curves and standard operating policy (SOP) and the optimized case using Stochastic Dynamic Programming (SDP). Another SDP optimization (referred to as SDP-1) with penalization for monthly hydropower deviations below firm power was also used to derive optimal operating policy. The SOP and SDP optimal policy derived for each scenario are applied to inflows for current (1959-2005) years, years 2045-65 and years 2075-95 for each GCM-scenario combination. For both SOP

as well as both SDP formulations, in most (six out of nine) scenarios in 2045-65, there is a decrease in annual hydropower. There is a further decrease in hydropower generation for years 2075-95 (eight out of nine scenarios). This decrease is due to the decrease in mid-level flows. Penalized SDP (SDP-1) policy has an intermediate hydropower generation between SOP and SDP, since it has to achieve a tradeoff between optimizing hydropower and reliability.

Adaptive policies are tested for the reservoir for two extreme scenarios showing largest reductions in hydropower generation for years 2045-65, viz. MIROC B1 scenario and CGCM2 A1B scenario. The first policy aims to restore performance with respect to power generation by decreasing other demands – in this study, irrigation demands. Hence, in this policy (adaptive policy 1), irrigation demands are reduced to half the current monthly values. For the same total release, this policy would increase release for power generation since the irrigation release is halved. The second policy explores how changes in flood control rules could be used to restore performance. Since maximum inflows occur in the monsoon season, changes in these rules would be expected to appreciably impact power generation. In this policy (adaptive policy 2), irrigation demands are reduced to half while also simultaneously relaxing flood control rules marginally. Hence, storage deviations from flood control defined storages upto 2000 Mm³ are allowed in this policy (the live storage capacity of the reservoir is 4650Mm³). The third policy extends the limits of changes in flood control rules. In this policy (adaptive policy 3), irrigation demands are reduced to half while flood control rules are further relaxed from policy 2 upto 3000 Mm³.

Figure 3 shows the impact of applying the above three adaptive SDP policies on performance measures for years 2045-65 for MIROC B1 scenario. Adaptive policy 1 decreases the vulnerability and deficit ratio and increases resiliency, but does little to increase hydropower or reliability. This can be expected, since irrigation demands are a small fraction of minimum power demands for Hirakud. Hence, reduced irrigation demands lead to only small increases in power releases, and power generation is not increased substantially. Adaptive policy 2 is able to restore reliability and deficit ratios to current values, though vulnerability is increased as compared to policy 1. This policy is also able to significantly increase annual hydropower as compared to policy 1. Application of adaptive policy 3 increases reliability, and decreases the deficit ratio and vulnerability as compared to policy 2 for one of the two extreme scenarios (MIROC B1), but they remain constant for the other extreme scenario considered (CGCM2 A1B) (Results not shown here) . It increases hydropower generation as compared to policy 2, but is unable to restore it to current levels.

Concluding Remarks

Climate change is likely to have impacts on all aspects of hydrology and water resources. It is necessary to understand the impacts of climate change on river basin and regional scales and develop adaptive responses. Water stress conditions projected by climate change impact models must be addressed

through appropriate water management strategies. Systems modeling is a powerful tool to develop such water management policies. Conjunctive use models and reservoir operation models should be used in conjunction with climate change projections provided along with quantification of uncertainties associated with the projections.

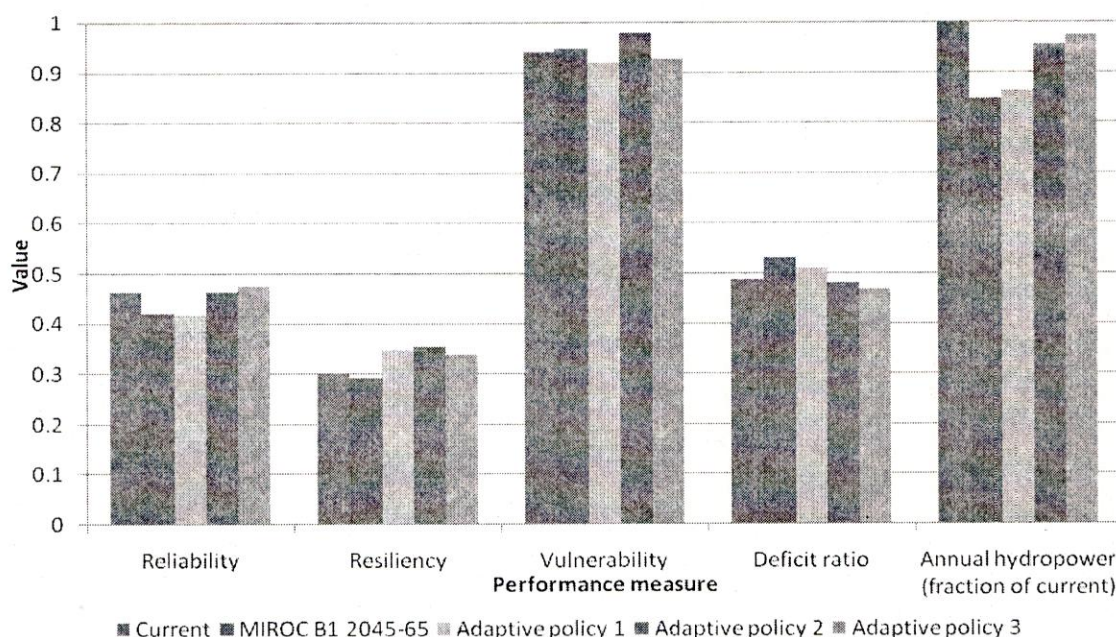


Fig. 3 Effect of applying adaptive SDP policies on performance measures for years 2045-65 for MIROC B1 scenario.

References

- Raje, D., and Mujumdar, P. P., (2009), "A conditional random field based downscaling method for assessment of climate change impact on multisite daily precipitation in the Mahanadi basin", *Water Resources Research*, 45, W10404. doi: 10.1029/2008WR007487.
- Raje, D., and Mujumdar, P. P. (2010a), "Constraining uncertainty in regional hydrologic impacts of climate change: nonstationarity in downscaling", *Water Resources Research*, 46, W07543, doi:10.1029/2009WR008425.
- Raje, D., and Mujumdar, P. P. (2010b), "Reservoir performance under uncertainty in hydrologic impacts of climate change", *Advances in Water Resources*, 33(3), 312-326. doi:10.1016/j.advwatres.2009.12.008
- Raje, D., and Mujumdar, P. P. (2010c), "Hydrologic drought prediction under climate change: Uncertainty modeling with Dempster-Shafer and Bayesian approaches." *Advances in Water Resources*, doi: 10.1016/j.advwatres.2010.08.001
- Vedula, S., Mujumdar, P P and Chandrasekhar G (2005) "Conjunctive Use Modeling for Multicrop Irrigation", *Agricultural Water Management*, 73 (2005) 193–221.