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Spatial Modelling of Water Availability and Choice of Crop Production in a River Basin

Chellattan Veettil P.¹, and van Huylenbroeck G.¹

¹ Department of agricultural economics, Gent University, Gent, Belgium

Abstract— This paper analyze the problems of water resource allocation and crop choice in a river basin using spatial analytical tools. Spatial variability of water availability is modelled by the product sum model. Here the water availability at any farm $Z(x_i)$ is a joint spatio-temporal environment and socioeconomic process. Water availability is estimated using spatial econometric tool. Here the spatial weight matrix (W) is constructed by taking water user associations (WUA) as boundaries. The choice of a crop is explained using *spill over* model in which the choice of a crop is influenced by the choice of neighbouring farmers. Here the spatial lag model is modified to adapt the latent variable (y^*) which has a binary outcome.

Keywords—Riverbasin, Spatio-temporal process, spatial water institutions

I. INTRODUCTION

India is one of the world's major irrigating countries in the world with rapidly increasing demand for water for agricultural and non-agricultural uses. Water is a scarce and precious national resource to be planned, developed, conserved and managed on an integrated and environmentally sound basis, keeping in view the socio-economic aspects and needs of the region and States. It is one of the most crucial elements in developmental planning [1,2]. Indian water scenario showed an acute water scarcity. Of the water available to India, the agricultural sector consumes 85 percent of the supply [3]. Complex issues of equity and social justice with regard to water distribution for different uses are required to be addressed. The development, and overexploitation of groundwater resources in certain parts of the country have raised the concern and need for judicious and scientific resource management and conservation. While the gross irrigation potential is increased from 19.5 million hectare at the time of independence (1947) to 95 million hectare by 1999-2000, further development of a substantial order is necessary if the food and fiber needs of the country's growing population are to be met with. The drinking water needs of people and livestock, demand for water for hydro and thermal power generation and for other industrial uses, etc. are taken into consideration while water allocation is designed, which is lacking at present. Water resources

development and management will have to be planned for a hydrological unit such as drainage basin as a whole or for a sub-basin, multi-sectorally, taking into account surface and ground water for sustainable use incorporating quantity and quality aspects as well as environmental considerations. The spatial, temporal and institutional aspects are vital while designing water sharing.

Krishna River Basin, India

Krishna, a South Indian river originates in Western Ghat hills at an altitude of 1,337m above mean sea level flows through the states of Maharashtra, Karnataka and Andhra Pradesh to the Bay of Bengal totalling a length of around 1,400km and a catchment area of 258,948 km². This river basin comprise of 8% of total geographical area of the country and supply water to 23 large cities. Majority of the area coming under arid or semi arid regions of the country which lead to high water scarcity and very low percapita water availability.

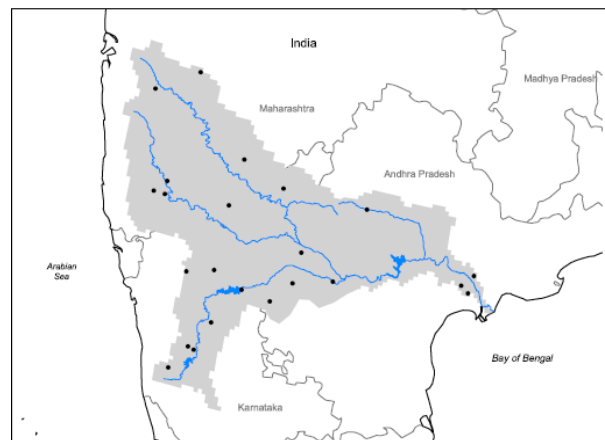


Fig 1. Map of Krishna river basin

There are five principal tributaries joining Krishna: Ghataprabha, the Malaprabha, the Bhima, the Tungabhadra and the Musi. The important soil types found in the basin are black soils, red soils, laterite and lateritic soils, alluvium, mixed soils, red and black soils and saline and alkaline soils with the main crops are rice, corn, sugarcane, sorghum, cotton, millet and horticultural crops. The river

basin has an average annual surface water potential of 78.1 km³ of which, 58.0 km³ is utilisable water. 77% of the total basin area is cultivable (203,000 km²), which is 10.4% of the total culturable area of the country. Current scenario shows a near complete closing of the basin as the total water storage capacity has already been achieved for Krishna basin. Moreover the discharge has reduced drastically not only at the delta region but also at sub basin level, hence facing an acute shortage of water in the near future. But sarcastically, the widely cultivated crops in this region include wetland crops such as rice, and sugarcane.

Spatial and temporal dimensions of water allocation

Water allocation in an irrigation system should be done with due regard to equity and social justice. Government of India in its water policy pointed out that disparities in the availability of water between head-reach and tail-end farms and between large and small farms exists and it should be obviated by adoption of a rotational water distribution system and supply of water on a volumetric basis subject to certain ceilings and rational pricing [2]. For each 500Ha of irrigated land one Water User Association (WUA) is required [1]. There should be a close integration of water-use and land-use policies (water policy of India, water framework directive of EC [4]). Because large areas of India are relatively arid, mechanisms for allocating scarce water are critically important to the welfare of the country's citizens. In India many rivers cross state boundaries, constructing efficient and equitable mechanisms for allocating river flows has long been an important legal and constitutional issue. Numerous inter-state river-water disputes have erupted since independence. Conflicts in water sharing found peak when monsoon fails or during summer and pacify when the rains are plenty.

Concept of spatial water institutions

According to USAID, “a Water Users Association (WUA) is a voluntary, nongovernmental, nonprofit entity established and managed by a group of farmers located along one or several watercourse canals. It is a self-managing group of farmers working together to operate and maintain their irrigation and drainage network to ensure fair and equitable water distribution and increase crop yields. Water users consist of farmers, peasants and other owners who combine their financial, material and technical resources to improve the productivity of irrigated farming through equitable distribution of water and efficient use of irrigation and drainage systems”. It is evident that water user association represent a particular geographical area along one or more canals. Present study uses this spatial

characteristic of the water institution while developing spatial water models in the following sections.

II. MODELING WATER AVAILABILITY

Spatial econometric model incorporates the spatial effects in econometric models. Anselin proposed *spatial lag* or *spatial autoregressive* (SAR) and *spatial error* (SEM) model [5,6] which follow a general prototypical regression form [7] as follows

$$\begin{aligned} y &= \rho W y + X \beta + v, \\ v &= \lambda W v + \varepsilon, \\ \varepsilon &\sim f^{MN} \left(\varepsilon \mid 0_N, \sigma^2 I_N \right), \end{aligned}$$

where $y \equiv (y_1, y_2, \dots, y_N)'$ denotes an $N \times 1$ vector of dependent variable (water availability); ρ spatial autoregressive parameter, W the $N \times N$ spatial weight matrix; $X \equiv (x_1, x_2, \dots, x_N)'$, $x_1 \equiv (x_{11}, x_{12}, \dots, x_{1k})'$, $x_2 \equiv (x_{21}, x_{22}, \dots, x_{2k})'$ $x_N \equiv (x_{N1}, x_{N2}, \dots, x_{Nk})'$ denotes observations on exogenous variables; $\beta \equiv (\beta_1, \beta_2, \dots, \beta_k)'$ a $k \times 1$ vector of regression coefficients; $v \equiv (v_1, v_2, \dots, v_N)'$ is the $N \times 1$ vector of random disturbances; λ is the correlation across v ; $\varepsilon \equiv (\varepsilon_1, \varepsilon_2, \dots, \varepsilon_N)'$ $N \times 1$ vector of error terms and $f^{MN} \left(\varepsilon \mid 0_N, \sigma^2 I_N \right)$ denotes the multivariate normal probability distribution function defined over the vector ε , with mean 0_N and covariance $\sigma^2 I_N$. If $\lambda = 0$ we get the spatial lag model or SAR model [8] $y = \rho W y + X \beta + \varepsilon$; and if $\rho = 0$ we have spatial error model SEM: $y = X \beta + \lambda W v + v$

Geostatistical analysis of spatial water availability

The structural analysis in geostatistics provide spatial structure of the variable where as spatial estimation methods (widely known as kriging) interpolate the variable at the nonsampled locations using the variogram developed in the first part. Environmental problems are mainly treated as realization of space-time random fields [9,10]. When geostatistics is extended to environmental problems, often we face the process both in space and time

dimensions. So models explaining only space or time is not complete in environmental and agricultural problems. Literature suggested mainly two types of models to deal with spatio-temporal processes: Separable model [11, 12,

$$\gamma_{st}(h_s, h_t) = [k_2 + k_1 C_t(0)] \gamma_s(h_s) + [k_3 C_s(h_s) + k_4 C_t(h_t)] \frac{Var[Z(x_j + h_s, t + h_t) - Z(x_j, t)]}{2}$$

13] and Non separable model [14, 15, 16]. Since water availability at a particular geographical location is a joint process of space and time interaction, here a non-separable model is used to analyse spatio-temporal mechanism of water resource allocation. In the analysis of geostatistical run off and precipitation model [17], compared four types of joint spatio-temporal model at catchment scale. They used a fractal component in the variogram models to capture the spatial and temporal fractalities.

Spatio-temporal model

Let $Z = \{Z(x, t), (x, t) \in D \times T\}$ be a second order stationary spatio-temporal random field (De Cesare et al, 2001) where $D \subset R^d$ and $T \subset R^t$, d is the physical spatial dimension ($d \leq 3$) and t the time dimension ($t=1$). $Z(x_j, t_i)$ denotes the water availability at a particular spatial location x_j and time t_i .

The spatio-temporal variograms are the combination of spatial $[\gamma_s(h_s)]$ and temporal $[\gamma_t(h_t)]$ variograms. The spatial and temporal variograms are

$$\gamma_s(h_s) = \frac{Var[Z(s + h_s) - Z(s)]}{\forall t, t + h_t \in T}$$

$$\gamma_t(h_t) = \frac{Var[Z(s, t + h_t) - Z(s, t)]}{2}$$

$$\hat{\gamma}_{st}(h_s, h_t) = \frac{1}{2 \sum_{j=1}^{m(h_s)} n_j(h_t)} \sum_{j=1}^{m(h_s)} \sum_{i=1}^{n_j(h_t)} \left[z(x_j + h_s, t_i + h_t) - z(x_j, t_i) \right]^2$$

The spatio temporal variogram is

The estimated sample variogram [17] is

But this model depend on lag vector h not the exact location or time [15]. The product sum model is an improvement on the traditional models.

where C_s and C_t are covariance functions, $C_{st}(0)$ is the sill of $\gamma_{st}(h_s, h_t)$, $C_s(0)$ is the sill of $[\gamma_s(h_s)]$ and $C_t(0)$ is the sill of $[\gamma_t(h_t)]$. In case of separable models (product model or linear model) the space and temporal variograms are separable. But the estimation of spatial $[\gamma_s(h_s)]$ and temporal $[\gamma_t(h_t)]$ variograms from $\gamma_{st}(h_s, h_t)$ is possible using $\gamma_{st}(0, h_t)$ and $\gamma_{st}(h_s, 0)$.

Modeling the choice of crop production

The choice of type of crop and extent (area) of crop cultivation is affected by choice made by neighbouring farmers in addition to resources available and characteristics of the farm and farmer which is termed as exogenous variable (x_i). The *spill over* model [18] explain that the farmer i chose a decision about the crop y_i is affected by the values of y chosen by other farmers (y_{-i}).

The objective function of the farmer i is

$$U(y_i, y_{-i}, x'_i)$$

the solution of this objective function maximization yields to the reaction function[8]

$$y_i = R(y_{-i}, x'_i)$$

when we restrict the reaction function to the 'neighbours' which yield a spatial weight matrix \mathbf{W} (Here the spatial weight matrix \mathbf{W} is constructed taking water user association as the spatial boundry or 'neighbour'), the corresponding spatial lag model reveals a global range of spill-overs

$$y^* = (I - \rho W)^{-1} X\beta + (I - \rho W)^{-1} \varepsilon$$

where y^* is a latent variable of the choice of crop. Since the choice is a binary variable, then

$$y_i^* = \sum_j a_{ij} x'_j \beta + u_i$$

where $u_i = \sum_j a_{ij} \varepsilon_j$; a_{ij} is the element i, j of the Leontief inverse matrix $(I - \rho W)^{-1}$

III. CONCLUSION

The choice of crop production is an outcome of the existing water allocation and governance structure. But a reallocation model is essential for a riverbasin like Krishna which is mainly flowing through water scarce areas. This paper propose a spatio temporal model for efficient water allocation based on water availability, taking into consideration of spatial variability and the choice of crop.

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Corresponding author's address

chellattan veettil P, Department of Agricultural Economics,
Gent university, coupurelinks 653, gent 9000,
Belgium

Email: prakashan.chellattanveettil@ugent.be