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## SUSTAINABLE DEVELOPMENT OF WATER RESOURCES, WATER SUPPLY AND ENVIRONMENTAL SANITATION

**A system dynamics simulation model for the assessment of water resources in Sri Lanka***K. D. W. Nandalal and S. B. A. D. Semasinghe, Sri Lanka*

*Ability to accurately predict water availability in a country is vital in planning its water resources development activities. Traditional approach used is based on a water balance and a demand projection. The projections are variant of current trends and subject to considerable uncertainty. Besides, they do not capture dynamic character of climatic, socio-economic and environmental change etc., and their impact on water use. Thus, the traditional approach is subject to a wide margin of error. In contrast, a novel approach, "system dynamics" offers a new way of modeling future dynamics of complex water systems increasing the ability to correctly assess and predict availability and use of water. This paper presents a system dynamics based simulation model to predict water resources in Sri Lanka. Using the model water availability was predicted and Sri Lanka will have sufficient water in the year 2025. However, in several districts water availability will decrease rapidly while others will not get much affected.*

**Introduction**

Sri Lanka is a country rich in water resources. The mean annual rainfall ranges between 900 mm and 6000 mm, with an island wide average of about 1,900 mm, which is about two and a half times more than the world annual mean of 750 mm. Thus, the total volume of fresh water received annually is 13,230 million m<sup>3</sup>. Though Sri Lanka has abundant water resources in aggregated terms this overall picture is misleading owing to the high degree of variation in the availability of water, both seasonally and regionally.

Sri Lanka is an agricultural country and therefore, water is the key ingredient in its development programmes. Thus, an accurate assessment of available water resources and prediction of its use is vital in planning and implementing such activities. Ability to accurately assess and predict availability of water resources based on the traditional approach that relies on water balance and demand prediction is quite limited since it does not capture temporal and spatial dynamics of main variables such as climatic change, socio-economic change, institutional change, environmental change, etc., and how they affect water use. Besides, future water projections are variants of current trends and as such are subject to considerable uncertainty (Gleick, 2000). Therefore, the prediction of future water use and balance is subject to a wide margin of error. In contrast, a novel approach, "system dynamics" offers a new way of modelling the future dynamics of complex systems increasing the ability to correctly assess and predict availability, use and balance of water, which enhances sustainable management of water resources.

This paper presents a system dynamics simulation approach

for integrated analyses of Sri Lanka's water resources through the development of a model. The model considers the dynamic interactions between quantitative characteristics of the available water resources and water use that are determined by the socio-economic development, population, agricultural development and food production in the country.

**System dynamics in water management**

System Dynamics (SD) is a complex method of system description that facilitates analysis of alternative decision policies on system behavior (Forrester, 1961; Sterman, 2000). Development of a SD model includes the following steps in sequence: (a) understanding of the system and its boundaries; (b) identifying the key variables; (c) representation of the physical processes in terms of variables through mathematical relationships; (d) mapping the structure of the model and simulating the model for understanding its behaviour; and, (e) interpretation of the simulation results for efficient decision making.

Application of SD modeling for global, regional and basin-level water resources systems has proven to yield remarkable results, though not many applications are found in literature. TARGETS (Rotmans and deVries, 1997) and WorldWater (Simonovic, 2002) are such two global water resources assessment models in which the water resources sector has been linked to other pertinent development and policy issues related to demography, economy, energy, pollution and non-renewable resources. A basin-level model ErhaiSD (Guo et al, 2001) has been developed to manage the environmental issues of the Lake Erhai Basin in China. Simonovic et al (1997) investigated the applicability of SD

modelling in the framework of water resources planning and management in Egypt. A water resources system dynamics model WRSD (Xu et al, 2002) for the Yellow river basin in China has been developed to analyze the sustainable water resources management in the basin. Simonovic (2002) provides a very comprehensive description of various global water resources assessment models. Simonovic and Rajasekaram (2004) developed an integrated water resources management model for Canada, CanadaWater based on the system dynamics simulation approach.

### System dynamics simulation model development

#### Model structure

Sri Lanka is divided into twenty five units in the model and they are called water units. The administrative district boundaries are their boundaries. Since the availability of data is at district level, this division was used in the model. Each unit comprises of four sectors, viz., water quantity, population, agriculture and food sectors. All twenty five units, each with the above four sectors, are integrated to build the overall model for the whole country. The model has been developed using the Vensim (Ventana Systems Inc., 2004) modelling environment.

The developed model for Sri Lanka includes water quantity, population, agriculture and food as the major sectors. All these sectors use water in one form or the other, hence they directly or indirectly depend on each other. Figure 1 provides the basic model structure of different sectors including the main variables with their multiple dynamic feedback causal links. Key issues of the water quantity sector of the model are; water inflow, water outflow, water demand and water use. Growth of population, birth, death and net migration mainly depict as key issues of the population sector. Cultivated lands, land development, harvested land and agricultural productions are considered as key issues in the agricultural sector. The key components of the food sector in the model are food production, foreign trade (export and import), availability and consumptions. However, certain issues in the sectors are not modelled at district (water unit) level but at country level only. For example, the migration of people in the population sector, the consumption of food in the food sector are modelled at country level only.

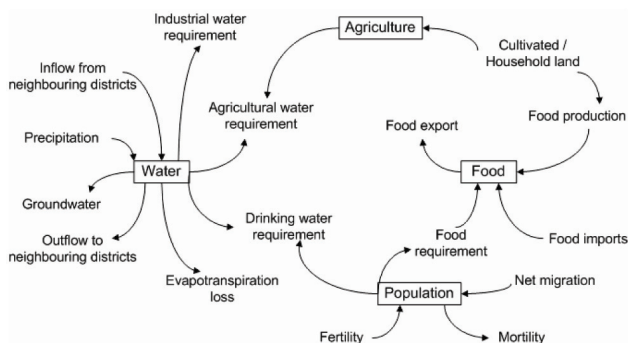


Figure 1. Basic model structure

### Water quantity sector

The water quantity sector in each water unit (district) is independently developed and hydraulically connected via inflow and outflow streams. The sector has three basic components; water inflow, water use and water outflow.

The principal sources of water inflow to a unit are precipitation and streamflows from neighbouring water units. Precipitation data available at several gauging stations in each water unit were averaged using the Gridding method. The precipitation either recharges groundwater zone or flows overland to streams to become streamflow. The model does not provide the quantity of groundwater in a water unit since the quantity of groundwater available underground at the beginning of a simulation period is unknown. However, the model shows the changes in groundwater storage during a simulation period. The model tries to satisfy the demand for water with the available surface water. The surface water comprises of streamflow coming from neighbouring water units and the precipitation over the water unit less groundwater recharge. If the demand exceeds the available surface water quantity, the additional amount is drawn from the groundwater zone.

Water use in a unit consists of agricultural, industrial, domestic, commercial water requirements and water losses due to evapotranspiration. Water demand for agriculture, forestry and grassland are estimated using crop coefficient, Kc (FAO Irrigation and Drainage Papers No. 24 and 33) and reference crop evapotranspiration (ETo). The pan evaporation data are used to calculate ETo.

Rural and urban populations have different per capita domestic water demands and this is considered in the model. Commercial and industrial water uses are available at provincial level. The model distributes these uses to district level based on industries, schools, hospitals, etc., in a district. However, the industrial and commercial water uses in Sri Lanka are very low compared with water demands for agriculture and forestry.

Inland water area of a district is considered for computation of evaporation loss and the model neglects the monthly variation of inland water surface area. The area without cultivated land, inland water and forest is taken as build-up and grass land for computing evapotranspiration. The Kc value of grass is used for both grass and build up land.

The water outflow from a water unit to another unit or sea is only through streams. The difference between the total surface water inflow and water use is the excess water resources in a water unit and it flows out through streams. If the water demand of a unit exceeds the total district water inflow, there will be no water outflow. However, perennial rivers have a flow throughout the year. In such cases, the model assumes that the ground water is extracted by the perennial rivers to suit their minimum flows.

As mentioned previously, the outflow from a certain unit becomes inflow to another unit or escapes to the sea. For example, the outflow from the Nuwara Eliya district through the Kelani river becomes inflow to the Kegalle district.

Similarly, outflow from Kegalle through the Kelani river becomes inflow to the Colombo district. Finally, the Kelani river carries outflow from the Colombo district to the sea. Due to such interconnectivity, the water quantity sectors of all the units are finally hydraulically interconnected.

### Agricultural sector

The agricultural sector is developed at water unit level. Each component in the sector in all the water units are linked to form the overall country scale model. Thus, the model has the ability to investigate the agricultural activities at both district and national levels. The major cultivation crops considered in the model are paddy, tea, rubber, coconut and highland crops.

The model estimates water requirement for paddy using crop coefficient,  $K_c$  (FAO Irrigation and Drainage Papers No. 24 and 33) and reference crop evapotranspiration,  $E_{To}$ . Further, it takes into account the variation of  $K_c$  values of paddy for the different growth stages; initial, development, midseason and late season. Though the date to start paddy cultivation in different areas can be different, the model assumes them to be the same (November and May for Maha and Yala seasons, respectively) throughout the country.

The model uses midseason values of  $K_c$  for tea, rubber, and coconut during the entire period of simulation in the estimation of water requirements. Upland crops considered in the model are Kurakkan, Maize, Meneri, Sorgham, Green, Cow pea, Gingelly, Ground nuts, Manioc, Sweet Potatoes, Potatoes, Chilies, Mustard, Red onion, Big onion, Ginger, Turmeric, Vegetables and fruits.

### Food sector

Though food production is available at district level in the model, food imports and exports can not be integrated to the model at that level. Therefore, the food sector is developed for the entire country by integrating the district productions. The food sector covers 11 commodities: Cereals include Rice, Kurakkan, Maize, Meneri, Sorghum and Wheat flour; Roots and tubers include Potatoes, Manioc and Sweet potatoes; Sugar includes Refined (Sugar) and Jaggery; Pulses and nuts include Green gram, Soya bean, Cowpea, Dhal, Ground nuts and T.V.P; Vegetables include Vegetables (Excl. onion), Onion; Fruits include Fresh and Dried fruits; Meat includes Beef, Pork, Mutton and Poultry; Eggs; Fish includes Fresh fish, Dried and salted fish and Tinned fish; Milk includes Cow milk, Buffalo milk, Tinned, Condensed milk and Milk food; Oil and fats include Coconut, Gingelly, Margarine, Butter and Cheese. These commodities are linked together based on calories, proteins and fats of these foods. Imported and country produced calories, proteins and fats are estimated for each food separately and aggregated to determine the availability at the national level. At the end, per capita availability of calories, proteins and fats are obtained by deducting the food used as seed and animal feed, food waste and food export from the national availability.

### Population sector

This sector is modelled at the water unit level. Fertility and mortality are considered at this level. The model does not consider migration among the water units, but it is modelled at the national level. The population is directly related to the food and drinking water requirements.

### Model calibration and verification

There are two parameters to be calibrated in each water unit. The two parameters are groundwater recharge factor (the portion of the water infiltrated from the precipitation) and groundwater contribution factor to perennial rivers. These two were calibrated based on monthly data for 10 years from 1991 to 2000. The data used include the meteorological data such as rainfall, evaporation etc., and land use. The calibration assumed that the groundwater stock in each district can not be continuously increased or decreased with the time. The verification of it was carried out by comparing the flows obtained from the model with the observed data in several main rivers during the verification period from 2001 to 2004. Figure 2 presents the comparison of the Kelani river flow at Hanwella and the Kalu river flow at Putupaula for both calibration and verification periods, for example.

Using the model, per capita water availability in each district was estimated. It is the annual usable water contribution to the direct runoff divided by the population of the district.

Falkenmark et al (1989) have used annual per capita water availability to define water scarcity thresholds and this paper uses that definition. In their criterion of water scarcity, a country is considered water-scarce if the per capita annual water supply falls below 1700 m<sup>3</sup>. Above this level of per capita water supply, water scarcities are considered to be rare and, if they exist, they are only problems within a few localities and this condition is called little or no water scarcity. Between 1700 m<sup>3</sup> and 1000 m<sup>3</sup>, a country faces seasonal or regular water-stressed conditions, which is called moderate condition of water scarcity.

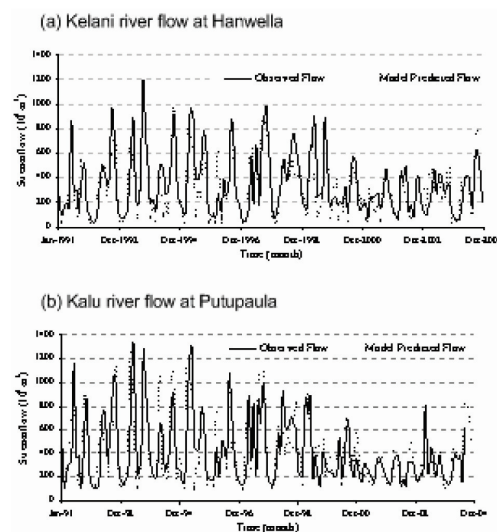
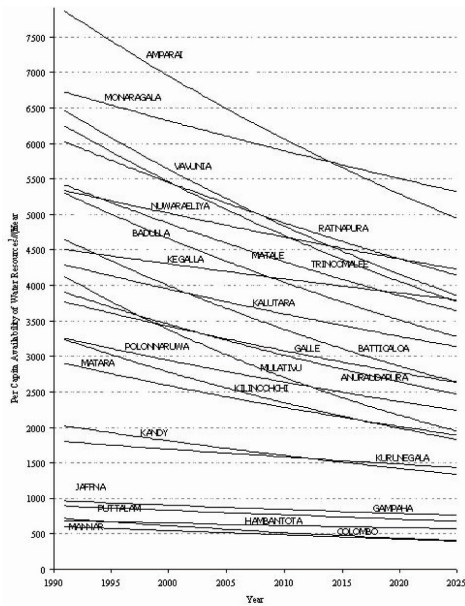


Figure 2. Comparison of flow during verification



**Figure 3. District level per capita water availability**

If the annual per capita water supply is between 1000 m<sup>3</sup> and 500 m<sup>3</sup>, water shortages begin to hamper the health and well being of human beings and it is called the medium to severe condition. If it falls below 500 m<sup>3</sup>, shortages are severe constraints to human life. Figure 3 depicts the estimated per capita water resources availability at district level for the period from 1990 to 2025.

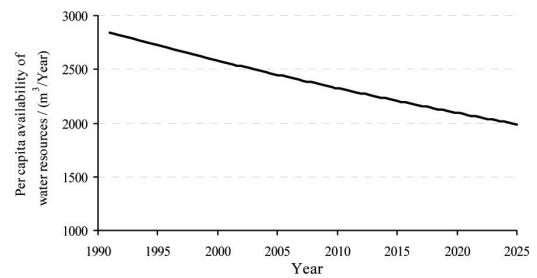
According to the Falkenmark water scarcity criterion, the districts of Puttalam, Gampaha, Hambantota, Mannar and Colombo are in the medium to severe water scarcity condition. Colombo and Mannar districts will fall to severe condition by the end of the year 2025. Water scarcity condition of the Jaffna district will be moderate up to 2025 while Kurunegala and Kandy districts fall to the condition from little or no to moderate after the year 2014. All the other districts fall into the little or no water scarcity condition.

Though the water scarcity conditions of districts show different conditions with respect to water scarcity, the whole country will have little or no water scarcity upto the year 2025 as shown in Figure 4.

**Conclusions**

A system dynamics based simulation model that integrates water with population, agriculture and food sectors is developed to assess and predict water resources in Sri Lanka at district and national level. The model was calibrated and verified based on relevant observed data for a period of 15 years. Subsequently, the model was used to predict water availability in Sri Lanka at district level and national level up to the year 2025.

The results indicate that in several districts water availability will decrease rapidly while others will not get much affected. During the period analyzed, Sri Lanka will have abundant water resources in aggregated terms, but this overall picture is misleading, as some districts will face water scarcity conditions.



**Figure 4. Per capita water availability in Sri Lanka**

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