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WATER BALANCE MODEL TO PREDICT CLIMATE CHANGE IMPACTS IN THE WATERSHED EPITÁCIO PESSOA DAM– PARAÍBA RIVER - BRAZIL

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ABSTRACT

Climatic change has great implications for hydrological cycle and water resources planning. In order to assess this impact, a semi-distributed monthly water balance model was proposed and developed to simulate and predict the hydrological processes. GIS techniques were used as a tool to analyze topography, river networks, land-use, human activities, vegetation and soil characteristics. The model parameters were linked to these basin characteristics by regression and optimization methods.
The model development will also be used to obtain an appreciation of the process controls of water balance in large heterogeneous catchments in semi-arid climates.
The semi-arid regions, such as Taperoá and Caraúbas River basins in State Paraíba – Brazil the runoffs of these basins are small or even zero during dry season (from Aug. to Jan) and are very sensitive to temperature increase and rainfall decrease. Results of the study also indicated that runoff is more sensitive to variation in precipitation than to increase in temperature. Climate change challenges existing water resources management practices by additional uncertainty. Integrated water resources management will enhance the potential for adaptation to change.

Key-words: Climatic change; hydrological cycle, Semi-arid; Paraíba River-Brazil

1. Introduction

Global climatic change caused by growing atmospheric concentration of carbon dioxide and other trace gases has become evident (IPCC, 1995;Houghton et al., 2001; Kamga, 2001). Climate change or its increased variability is expected to alter the timing and magnitude of runoff. As a result it has important implications for existing water resources systems as well as for future water resources planning and management. For instance, under the climate change in recent years, the imbalance between water supply and water demands has been increasing, which has given rise to great attention from both the relevant authorities and the general public to water resources planning programs. Hence, urgent action is required for understanding and solving potential water resources problems for human's existence and well-being, especially, quantitative estimates of hydrological effects of climate change are essential (Guo et al., 2002).

Currently there are many different monthly water balance models and many researches in this field have been intensively conducted. In the 1940s and 1950s, Thornthwaite and Mather (1955) developed a set of deterministic monthly water balance models, in which only two parameters were used. In developing an index of meteorological drought, Palmer (1965) suggested a model that divides the soil moisture storage into two layers. In 1981, Thomas proposed a four parameter abcd water balance model. Alley (1984) reviewed and examined the Thornthwaite-Mather models, the Palmer (1965) model, and the Thomas (1981, 1983) abcd models in considerable detail. He concluded that predication erros were relatively similar among these models. Gleick (1987) developed a monthly water balance model specifically for climate impact assessment and addressed the advantages of using water balance type models in pratice. In the 1990s, more monthly water balance models were developed for stunding the impact of climate change on the hydrological balance and for general water resources planning and management (Mimikon et al., 1991; Vandewiele et al.,1992; Guo, 1995; Guo and Yin, 1997; Panagoulia and Dimou, 1997; Xu and Singht, 1998; Xiong and Guo, 1997,1999).

In 2001, Jothityangkoon et al., examined the process controls on water balance at the annual, monthly and daily scales. Asystematic "downward" approach for the formulation of models of appropriate complexity is presented based on an investigation of the climate, soil and vegetation controls on water balance. The overall conclusion is that in this semi-arid catchment, spatial variability of soil depths apper to be the most important control on runoff variability at all time and space scales, followed by the spatial variability of climate and vegetation cover.

In 2006, Galvíncio and Sousa, superficial water balance developed at Epitácio Pessoa river basin, in the state of the Paraíba-Brasil. In this study the authors demonstrated the impact of climate, vegetation, and topography of land use in the runoff. The model developed responded very well to these variables.

In 2007, Galvíncio and Sousa, evaluated the performance of the water balance model developed for years of El Nino and La Nina in the sub-basin of Caraúbas. The authors also concluded that the water balance model developed was able to make estimates of daily discharges, for years of La Niña, El Niño moderate and normal years.

For the purpose of water resources assessment and study of climate change impacts, a water balance model was proposed and developed in this paper to simulate and predict the hydrological process and water resources in the Epitácio Pessoa – Paraíba river - Brazil watershed. GIS techniques were used as a tool to analyze topography, river networks, land-use, human activities, vegetation and soil characteristics.

2. Material and methods

2.1 Region Studied

The waters of the Epitácio Pessoa river basin it flows for the Epitácio Pessoa dam, known as Boqueirão dam. This river basin is geographically located in the center of an area, composed by a fragmented mountain range. The water contribution to the dam comes from the Upper Paraíba subbasin and Taperoá subbasin. The courses of natural waters that benefit the soil and the agricultural production are: Paraíba river, and the streams: Marinho Velho, Perna, Canudos, Ramada, Relva and Feijão. According to the

Executive Agency and Water Administration of the Paraíba state - AESA, the Epitácio Pessoa dam has volume capacity of 411,7x106 cubic meters of water. The Fig. 1 shows the Epitácio Pessoa river basin location.

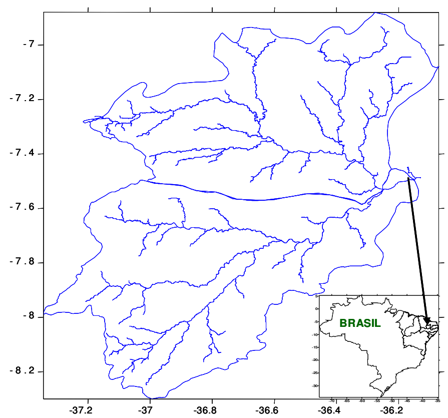

Figure 1. Location of the Epitácio Pessoa river basin

2.1.1 Climate, hydrology and soil

The river basin in investigation is formed by rocks of the precambrian period. The main soil in the Paraíba sub-basins and Taperoá is the polish no-calcic of little depth, on whole existent crystalline. The soils of these sub-basins are almost impervious.

In the semiarid of the Northeast of the Brazil, the precipitated annual total, on average, is from 520 to 660 mm. This is the same amount that precipitates in European cities, for instance, Berlin and Paris, but nobody speech of disastrous droughts in those cities. The difference between the European rainfall and of the semiarid region is the evaporation rate, that here is high, besides rainfall irregularities relative to space-time. Those are the causes that control the quantity of water that it will be to people's disposition, animals and plants.

The temperatures in the semiarid are high during whole the year because it is placed close to the Equator, and register strong winds and low air humidity. These atmospheric variables contribute for high evaporative rates. Case a dam is not deep enough; it will empty in few months after the rainfall period. The water of the rain that infiltrates in the terrain is absorbed in part, and protected of the evaporation. After weeks, and until months, of strong rainfall, the plants roots can still get the necessary humidity.

The river basin hydrography is poor because of the rainfall absence in the long period. Its rivers and lakes are irregular and with intermittent characteristics. Some general features that characterize the basin are: low cultures productivity, fewer choices of cultivations; little agricultural technology, absence of soil conservation, low use of natural resources, limited and irregular water resources disponibility and natural preservation areas limited. Those features are of fundamental importance to assure the farmers' survival, in a region subject to drought. In the Brazilian semiarid, the widespread cattle are the main activity; the great owner accumulates stocks, when the weather is favorable. In otherwise, the owner transfers the animals for more favorable areas. On other hands, the small producer practices the subsistence agriculture, producing: corn, bean and rice. Those cultures represent the main sources of income and food for the rural community.

2.2 Software and data

For accomplishment of the tasks of this study were necessary the materials following: satellite image of the Landsat TM-5, 1999 October 17, 215 orbit, 65 point; terrain elevation data with resolutions of 1.0 kilometer and 90 meters.
The Supervision of the Northeast for Development - SUDENE and Extraordinary Secretariat of Environment, Water Resources and Mineral - SEMARH of the Paraíba state supplied the data of annual rainfall, monthly and daily of 23 gauges, spread in the river basin studied, from 1973 to 1990 period. In the SEMARH were still obtained the evaporation data, estimated by the program of Soil Humidity Control. This task was performed by the partnership of the Paraiba state Government and Space Research's National Institute - INPE.

The streamflows data were obtained in the National Agency of Water (ANA) and in the Civil Engineering Department, Federal University of Campina Grande - UFCG, from 1973 to 1990 period. Those data are natural streamflows, free of changes provoked by hydraulic systems such as bridges and dams. The ANA did do consistence analysis in them.

2.3 Methodology

The main steps to developing this work were: treatment for the terrain elevation data; to get the physics characteristics of the river basin, based on terrain elevation data with resolutions of 1.0 kilometer and 90 meters; vegetal cover fraction, using satellite image; development and application of the water balance model for to estimate the superficial runoff for inside the Epitácio Pessoa dam.

2.3.1 Vegetal cover

For to characterize the vegetation, Geographical Information Systems tools were used. This characterization is estimated by the NDVI and by the vegetal cover fraction of the river basin in study, based on images of the satellite Landsat - TM 5. According to (Gutman and Ignatov, 1998) can be written as:

$$Vfrac = (NDVI - NDVI_0)/\left(NDVI_\infty - NDVI_0\right) \quad (1)$$

where $NDVI_0$, $NDVI$ and $NDVI_\infty$ are the minimum value, the maximum value, and the average of the vegetal index, respectively, in each grid point.

Water balance model for the Caraúbas sub-basins and Poço de Pedras

To estimate the superficial runoff for the Caraúbas sub-basins and Poço de Pedras, the model was developed based on identification and in the hydrology processes quantification. The form of the model is similar to the proposed by (Jothityangkoon et al., 2001, 2003; Galvíncio and Sousa, 2005, 2006, 2007). The Caraúbas control points, and Poço de Pedras were chosen because of streamflows time series recent. Besides of this, the drainage areas represent great part of the areas of the Paraíba sub-basins and Taperoá, upstream of those control points.

The information obtained by terrain elevation data such as: subbasin terrain inclination, stream length and substream, areas, and the vegetal cover fraction were used in the adjustment of the water balance model. The Fig. 2 displays the stream gauge locations of Caraúbas, Poço de Pedras and Boqueirão de Cabaceiras.

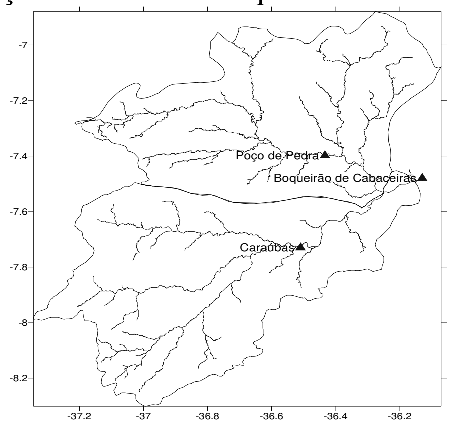

Figure 2. Stream gauge locations

The superficial runoff is influenced by several causes that can facilitate or not its happening. Those causes can be of climatic nature, related to rainfall and the evaporation or related to the physical characteristic of the river basin. The model developed in Galvíncio and Sousa (2006) was based on the mass conservation principles. Initially, was considered the rainfall variation, because is the more important climatic variable for the superficial runoff. Soon after, the runoff was separated in two fundamental parts: superficial runoff and subsuperficial. The potential evapotranspiration was divided in surface evaporation and in plants transpiration. All methodology used in the water balance procedure can be seen in Galvíncio (2005).

2.3.2 Water balance equations

The Eq. (1) was proposed to estimate the physical processes on river basin:

$$ds(t)/dt = p(t) - q_{ss}(t) - q_{se}(t) - e_b(t) - e_v(t) \tag{1}$$

where $p(t)$ is the intensity of the rain (mm), $q_{se}(t)$ is the superficial runoff rate or water excess after soil saturation, $\frac{ds(t)}{dt}$ is the water volume variation stored in the soil, q_{ss} is the subsuperficial drainage, $e_b(t)$ is the evaporation rate in the soil without vegetation, and $e_v(t)$ is the rate of vegetal transpiration. The subsuperficial runoff in the Eq. (1) is described as function of the soil storage water:

$$q_{ss} = (s - s_f)/t_c \quad se \quad s > s_f \tag{2}$$

$$q_{ss} = 0 \qquad se \qquad s < s_f \tag{3}$$

where S_f is the soil water storage, for given field capacity. It is assumed that $S_f = f_c D$, where f_c is the field capacity of the river basin and D is the soil average depth. The argument for using field capacity is that, often, when the soil humidity content is smaller than the field capacity, the capillarity force is larger than the gravity force, therefore the runoff is delayed. The time of response of the subsuperficial runoff t_c is based on Darcy's law and represents the underground aquifer in triangular way for tilted surface. In the t_c estimate is assumed that the hydraulic gradient is an approach of the soil surface angle, so:

$$t_c = L\phi / 2K_s \tan\beta \tag{5}$$

where L is the lateral runoff average length, $\tan\beta$ is the surface average slope, and K_s is the saturated mean hydraulic conductivity.

The soil evaporation estimate without vegetation is given as:

$$e_b = S / t_e \tag{6}$$

$$t_e = S_b / (1 - M) e_p \tag{7}$$

where t_e is the time, associated to the soil evaporation without vegetation and given by the equation (14), $S_b = D\phi$ is the soil humidity storage capacity, D is the soil average depth (mm), ϕ is the average porosity (mm), M is the fraction of vegetal covering of the river basin, and vary from zero to one.

The plants transpiration estimate is given by the Eqs. (8) and (9):

$$e_v = M k_v e_p \qquad se \qquad s > s_f \tag{8}$$

$$e_v = S / t_g \qquad se \qquad s < s_f \tag{9}$$

and

$$t_g = s_f / M k_v e_p \tag{10}$$

where t_g is the time, associated to transpiration and k_v is plants transpiration efficiency, according to (Eagleson, 1978) k_v is usually equal to one. The parameter M is used to divide the total evaporation in soil evaporation without vegetation and in transpiration of plants. The soil evaporation without vegetation e_p depends on relation of s and S_b. When s is larger than S_f the transpiration is maximum and equivalent to e_p. When s is smaller than S_f the transpiration is given by a fraction of e_p.

2.4 Model parameters

The parameters of the monthly model are classified in the categories that follow: topographical D, ϕ, f_c, L, K_s and vegetal M, k_v. Here, the results will be presented as time series with intraannual variability of the superficial runoff.

2.5 **Criteria to evaluate the model**

In this study were used two criteria to select the best estimative to model. The first criteria adopted was to evaluate the response of the model using the Nash-Sutcliffe coefficient. The second consists to obtain the accounted for variance using the determination coefficient (R2). The Nash-Sutcliffe (NS) coefficient efficiency is given as (Nash and Sutcliffe, 1990):

$$NS = \left[\sum (Q_i - \overline{Q})^2 - \sum (Q_i - \hat{Q}_i)^2\right] / \sum (Q_i - \overline{Q})^2 \tag{11}$$

where Q_i and $\hat{Q}_i$ are observed and estimated streamflows, respectively, $\overline{Q}$ is mean streamflow observed. The determination coefficient (R2) is given as the square correlation coefficient. It estimates the critical variation common between variables.

2.6 Scenarios climate change

Based on the hypothetical scenarios (combining temperature increase or decrease of 1, 2 and 3^0C with precipitation changes of -100, -50, -25, 0, 25, 50, 100%), the sensitivity of hydrological and water resource systems variables to global warming are investigated in the Epitácio Pessoa watershed. The water balance model was used to simulate monthly runoff and soil moisture for these sub-basins or basins under different climatic conditions.

3. Results

3.1 The runoff distributed in Epitácio Pessoa watershed

The Epitácio Pessoa watershed is divided into 2 sub-basins. In the Caraúbas and Taperoá sub-basins. Figs. 3 and 4 show the distribution of runoff in the watershed Epitácio Pessoa dam.

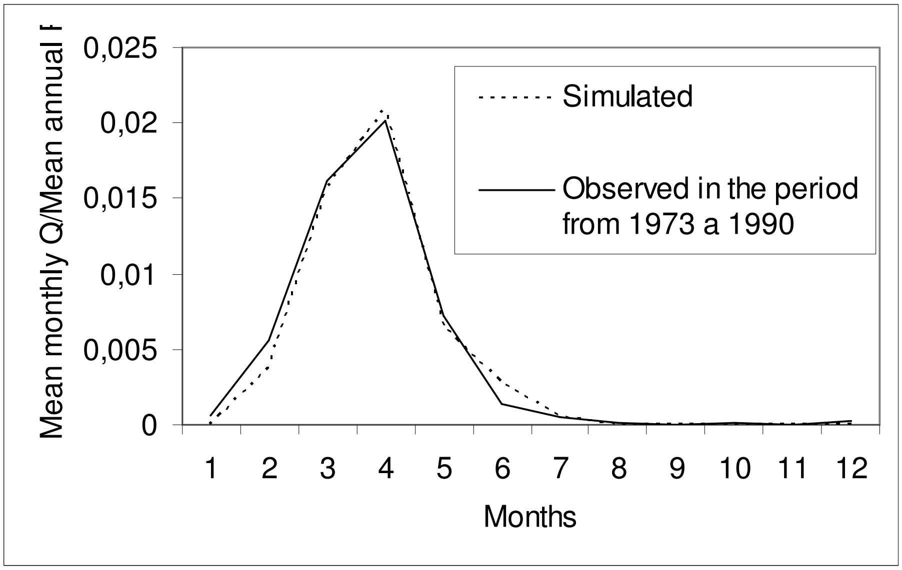

Figure 3 - Simulated (dash line) and observed (solid line) runoff in the watershed Epitácio Pessoa dam

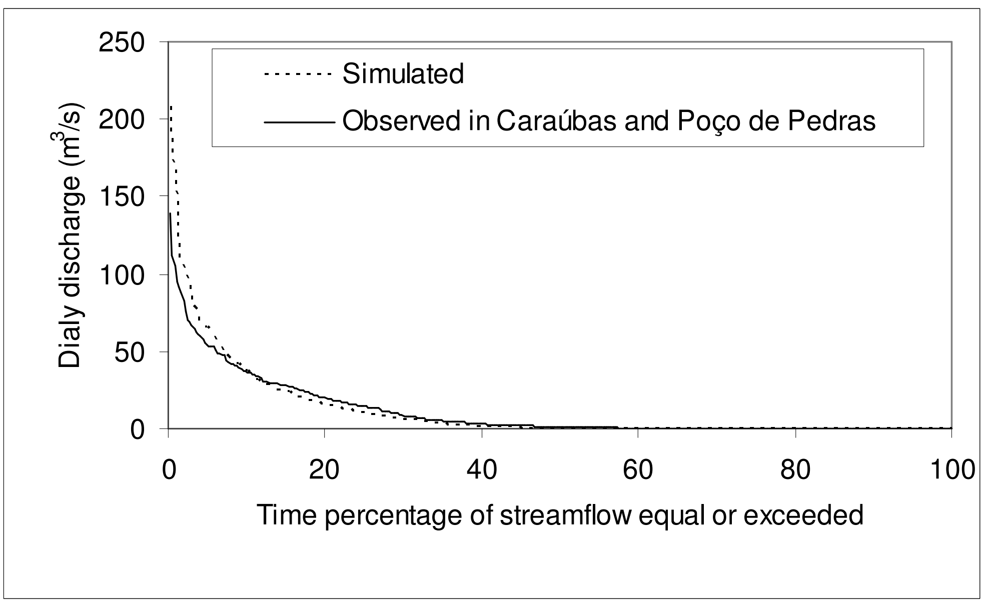

Figure 4 – Simulated (dash line) and observed (solid line) runoff in the watershed Epitácio Pessoa dam

3.2 Sensitivity of runoff to climate change

Based on the hypothetical scenarios the sensitivity of hydrological and water resource systems variables to global warming are investigated in the Epitácio Pessoa watershed.

Table 1 shows that temperature increases of 1^0C combined with 25% change in the expected precipitation is likely to result in runoff change from 0,66 to -0,3. If the precipitation is unchanged and temperature increases from 1 to 3^0C, the runoff change will decrease from 0,978 to 0,92 the criterion NASH. From Table 3 it is show that the runoff is more sensitive to precipitation variation than to temperature increase. As a matter of fact, IPCC report (WMO and UNEP, 2001) has found the projected changes in precipitation.

Table 1 – The sensitivity of runoff to temperature change (∂T) and precipitation change (∂P)

	(∂P)				
(∂T)	**-50**	**-25**	**0**	**25**	**50**
-3	-0,06	0,74	0,973	-0,59	-5,4
-2	-0,08	0,71	0,974	-0,51	-5,23
-1	-0,1	0,69	0,976	-0,42	-5,02
0	**-0,127**	**0,66**	**0,979**	**-0,3**	**-4,75**
1	-0,15	0,62	0,95	-0,18	-4,4
2	-0,17	0,58	0,94	-0,05	-4,11
3	-0,19	0,54	0,92	0,09	-3,7

The Figure 5 shows the runoff change in relation the percentage of precipitation change. When the precipitation increases 50% of the value of the runoff almost 600% increase. When the precipitation decreases 50% the runoff will be zero. Figure 6 shows that the decrease of 50% of the precipitation E basta a precipitação diminuir 50% a runoff será zero. The Figure 6 show que a diminuição de 50% da precipitation the runoff change increased em torno de 40%. Se a temperatura aumentar 1, 2 and 3^0C a vazão diminuirá em tonro de 2, 3 and 5%, respectivamente.

When precipitation increases 50% of the value of the flow reaches almost 600% increase. When the precipitation decrease 50% to runoff will be zero. Figure 6 shows that the decrease of 25% of the precipitation the runoff will decrease 40%. If the temperature increase 1, 2 and 3^0C the runoff decrease 2, 3 and 5%, respectively.

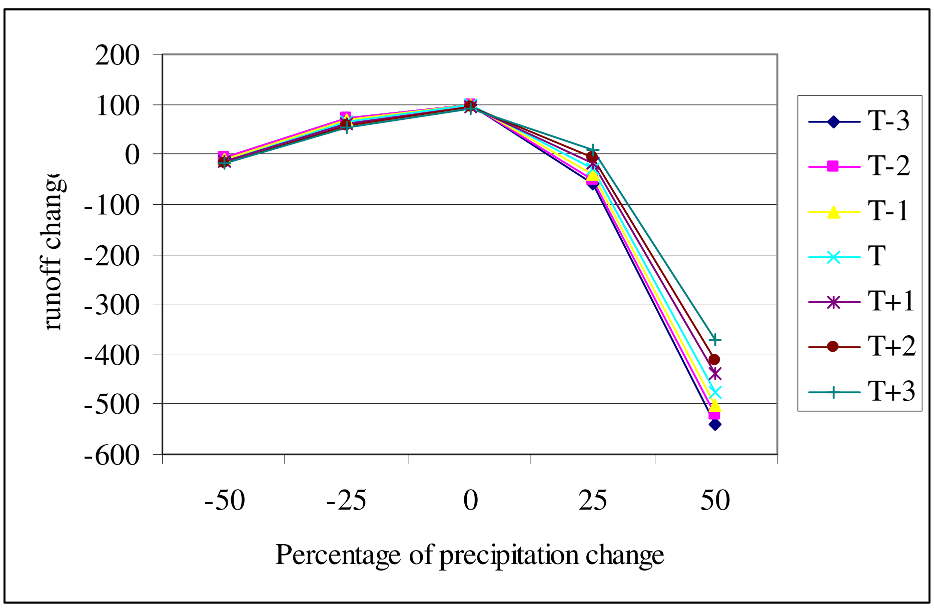

Figure 5 – Relation percentage of precipitation change and runoff change

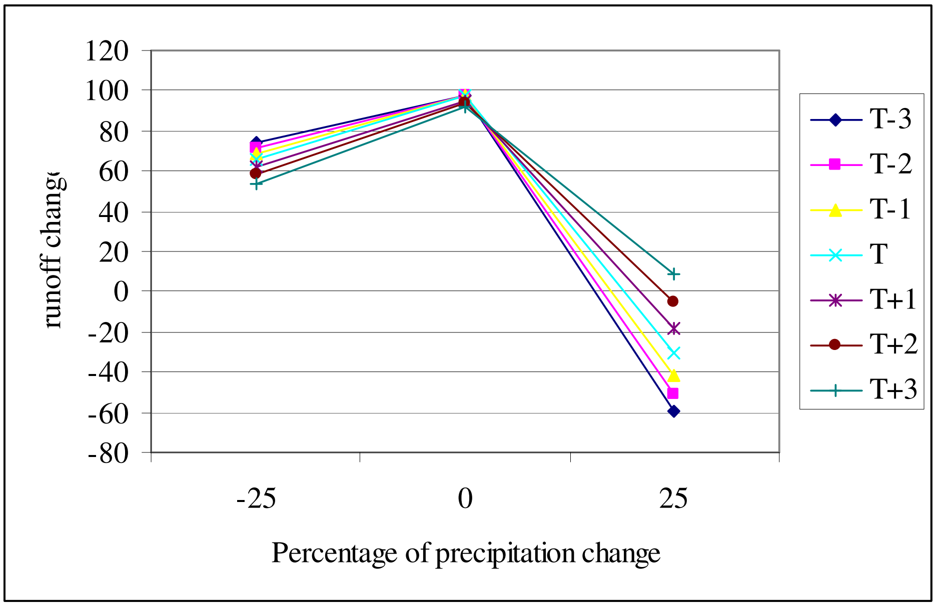

Figure 6 – Relation percentage of precipitation change and runoff change

4. Conclusion

The runoff is more sensitive to variation in precipitation than to increase in temperature. Climate change challenges existing water resources management practices by additional uncertainty. Integrated water resources management will enhance the potential for adaptation to change.

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