Simulation of Northern Rhodes water resources system

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Introduction

The aim of the present study is the simulation of Northern Rhodes water resources system. In Northern Rhodes most of water need is covered by the exploitation of the extended ground water reservoir which develops in the study area (Ydroereyna, 1999). This exploitation is accomplished using a dense network of water drills and in a lesser degree by springs. Last years an attempt to use surface runoff water has been made, expressed by the design and foundation of water dams and other similar infrastructures. Concerning the adequacy of water resources, the situation is satisfactory without important pressures, although in dry seasons reports for water level degradation are made by some of municipality's authorities. However, the increase of the population and especially the increased rate of tourism growth sets a necessity to estimate the efficiency of the water resources system for the future.

Methodology

Firstly, the available hydrological and hydrogeological data from studies that have tooк place in the area have been collected. The processing of the above mentioned data was made at three stages:

- Unification of hydrological basins in seven units, in order to simplify the simulation. Basic criterion for the unification was the hydrolithological character of the units.
- Spatial distribution of rainfall using Thiessen's polygons method (Thiessen, 1911)
- Estimation of potential evapotranspiration using Thornthwaite method (Thornthwaite, 1948)

In the next phase of the study a conceptual basin simulation model has been developed using the available discharge data from Gadouras watershed automatic station. The model was designed in an Excel worksheet environment. Next, using "Castalia" software, synthetic rainfall time series were produced with a 1000 years' time length. Using as entry data the synthetic rainfall timeseries, and the monthly mean values of the PET, the basin model was applied in the unified basins. The application of the model produced runoff and percolation timeseries (1000 years length).

Water demand analysis focused on the next uses: a) water supply of domestic population, b) water supply for tourism, c) water supply for industrial purposes, d) irrigation and e) water supply for farming and aviculture purposes.

Finally, the conceptual basin model produced timeseries and the demand analysis data, were introduced into "Hydrognomon" software, which has been used for water resources system simulation.

Processing of hydrological and Hydrogeological data

Northern Rhodes consists of 28 hydrological basins. For the purposes of the present study these basins were unified to 7 units in order to simplify the water resources system simulation. Basic criterion for the unification of the basins was their respond to percolation, concerning that most of water need is covered by the extended ground water reservoir which develops in the area. The following procedure has been followed for this unification:

- The geological map of the study area was digitized.
- A constant value, representing the percolation coefficient, was given to each geological formation.
- The digitized vector data were transformed to raster data based on the coefficient of percolation.
- The weigted average coefficient value of each unified basin was finally estimated

The results for each basin are the following (table 1):

Table 1

Basin name	Weigted average percolation coefficient
Arxaggelos	14,71
Attavyros	9,98
Kalithea	16,52
Kameiros	16,49
Petaloudes	16,09
Rhodes	13,47

Discussing the above table it is concluded that the unified hydrological basins show a similar character concerning their respond to percolating water. This fact allows us applying the conceptual basin simulation model that will be developed in Gadouras basin to the rest of the basins.

Next, the available data from the meteorological stations were used for the spatial distribution of rainfall using Thiessen's polygons method (Thiessen, 1911). The calculated timeseries were corrected using rainfall gradient value which was estimated as b=0.45.

Also, potential evarotranspiration was estimated using Thornthwaite method (Thornthwaite, 1948). The selection of the method among the other methods was supported by the fact that it demands for the calculations only temperature timeseries, which were available for the majority of the stations. The calculated PET timeseries were corrected using typical temperature gradient values (Dingman, 1994).

Basin simulation model

A. Generally

The basin simulation model that has been developed for the purposes of this study was is based on "Zygos" basin simulation model (Kozanis & Efstratiadis, 2006). It was development in an Excel worksheet environment and its basic difference from "Zygos" is the division of the conceptual soil tank into two zones (upper and lower zone). This modification was made in order to increase the real evaporotranspiration, which was sub estimated by Zygos.

B. Model Parameters

The model consists of 10 parameters:

K: The percentage of rainfall which runoffs directly (dimensionless).

K1, K2: The capacities of the upper and lower soil tanks (L).

Sinit: The initial soil water content as percentage of the potential soil content capacity (dimensionless).

λ: The rate of hypodermic flow from the soil tank (dimensionless).

μ: The rate of soil water content discharge into the conceptual aquifer tank (dimensionless).

Yb: The threshold for the production of basic flow from the aquifer tank (L).

ξ: The rate of basic flow production from the aquifer tank (dimensionless).

φ: The rate of water loss from the aquifer tank (dimensionless).

Yo: The initial water content of the aquifer tank.

C. Model operation

Model uses as entry data the rainfall and PET timeseries. Firstly, it calculates the direct evaporation of the rainfall water and then covers the direct runoff. The remaining amount of water is infiltrated in the upper soil tank were at the first stage the evapotranspirationis satisfied. At the next step hypodermic flow is calculated. The next stage concerns the evapotranspirationof the lower soil tank. The remnant soil content is then percolated to the aquifer tank. Completing the soil tank procedures the model checks for the overflow of the soil tank which produces spill flow.

Part of the water which has percolated in the aquifer tank covers the basic flow. Finally from the remnant water a part represents the water losses (to the sea or to adjacent basins). The computational procedure of the model is represented in the next flow diagram (diagram 1):

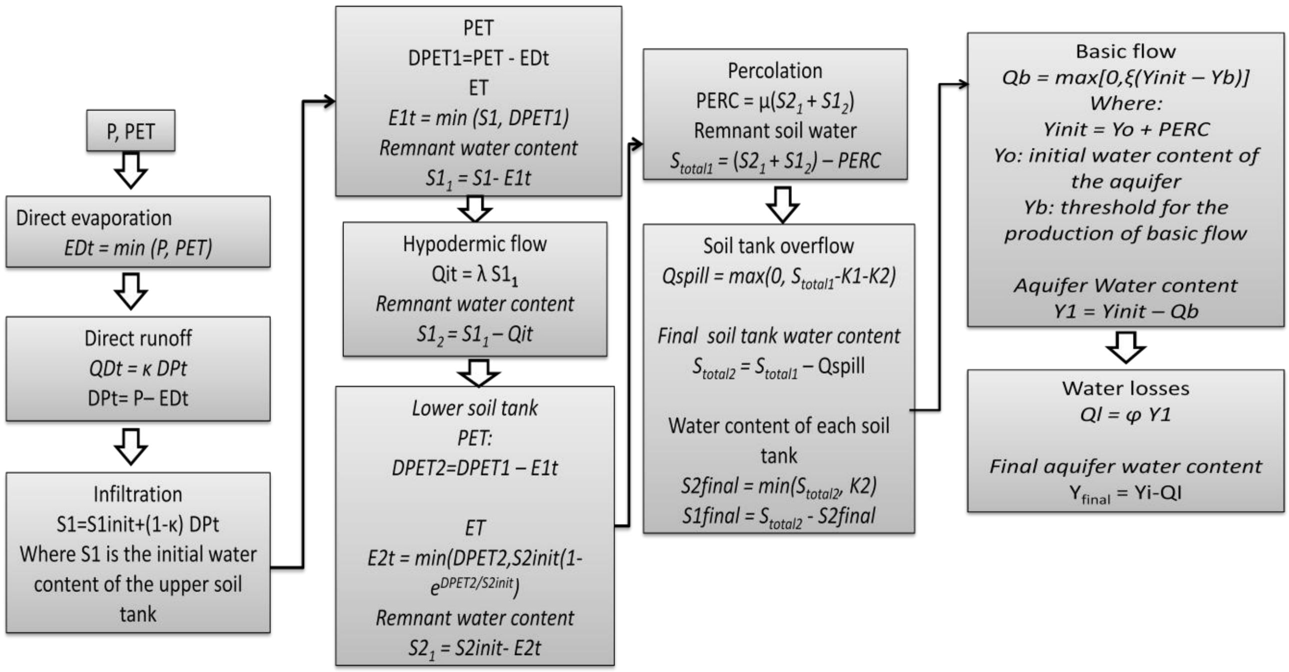

Diagram 1

At the end of the computational procedure the calculated timeseries are surface runoff, real evapotranspirationand percolation to the aquifer tank.

D. Model calibration

For the calibration of the model an error function has to be selected. Usually, for hydrology application Nash and Sutcliffe's coefficient of determination is used. In the present study a multiple error function was developed, based on the coefficient of determination. The form of the error function is the following:

$R' = \alpha R - \beta GPEN - BIAS - NFP - FP$

Where:

R: the coefficient of determination (Nash and Sutcliffe, 1970)

BIAS: bias function

NFP: a penalty function which is applied when the measured flow is zero and the model gives no values >0 (NFP: No flow penalty).

FP: a penalty function which is applied when the measured flow >0 and the model gives zero values (FP : flow penalty).

GPEN: a penalty function which was used in order to bound the trend of percolation timeseries to increase.

α, β: weight coefficients with values 100 and 0.01 respectively.

The objective function for the calibration was the following:

$$\text{Maximize}(R')$$

For the calibration the evolutionary algorithm was selected using Solver add in of Excel.

E. Model results in Gadouras basin

Three tests were run, which differed in the PET timeseries that was used. In the first test the calculated Thornthwaite's PET timeserie was selected, in the second the measured evapotranspiration time series from Gadouras automatic meteorological station, and finally in the third test Thornthwaite's PET timeserie multiplied by a factor with 1.3 value. Concerning model parameters the results are as follows (table 2):

Table 2

Model parameter	Test 1	Test 2	Test 3
κ	0,00	0,00	0,00
K1	400	376	400
K2	100	119	100
sinit	0,27	0,30	0,1
λ	0,063	0,087	0,07
μ	0,175	0,132	0,165
Yb	81	82	81
ξ	0,00	0,00	0,00
φ	0,153	0,16	0,146
Yo	48	49	48
Objective function R'	1,185	2,030	-1,644
Coefficient of determination R	0.798	0,799	0,795

The results for the annual water balance are the following (table 3):

Table 3

	Test 1	Test 2	Test 3
Rainfall (P) (%)	100	100	100
Surface runoff (Q) (%)	12,9	13,0	13,0
Evapotranspiration(ET) (%)	48,5	63,8	52,6
Infiltration and percolation (%)	39,4	26,6	33,1
Basin outflow (%)	2,2	2,2	2,2

From the three tests that have been performed the third test model parameters were selected for the following reasons:

- Thornthwaite PET timeseries can be used (available for all the basins)
- Parameter values correspond to the natural characteristics of the study area
- The initial soil water content at the starting point of the simulation (October) represents better the natural conditions at this time

- The annual water balance which is estimated is near the expected values for teh study area.

F. Application of the model in the unified basins

The application of the model in the unified basins gave values of the water balance slightly different from these estimated in Gadouras Basin:

Evaporotranspiration: *61.1-65.2%*

Surface runoff: *7.6-8.6%.*

Infiltration and percolation: *27.9% έως 30.7%.*

This deviation is caused due to the different time length of the time series. In the unified basins time series have a length of 13 years comprising more hydrological information than Gadouras time series which show a for years length.

Rainfall synthetic time series

For the production of the synthetic rainfall time series Castalia software was used (Eftratiadis et al., 2006). As entry data rainfall timeseries from the meteorological stations of the study area were used, producing 1000 years time length series.

Water demand analysis

A. Generally

According to studies that have been accomplished in the study area, the present conditions of the available water resources are described as satisfactory without important pressures. Analytically, reports from the public authorities show that:

Municipality of Rhodes mainly covers its water demands using water drills from Kallithea basin. Every year an amount of 5 million cubic meters of fresh water is transferred from Kallithea basin to Rhodes Municipality. According to reports from the area there are not important pressures in the available water reserves, fact that is expressed by the stability of water level in the water drills over the years.

Municipality of Kallithea has surplus water reserves which cover, as mentioned before, Rhodes water needs. It is also planned to support in the near future other adjacent municipalities.

Municipalities of Ialysos, Afantou and Arxaggelou, especially in dry seasons, report water resources incomprehensiveness, and many cases of water level degradation.

Municipalities of Kameiros, Petaloudes and Attavyros report that the water resources cover their needs, without lowering the level of water pumps in the water drills.

B. Water demands estimation

Water demand analysis focused in five axes: a) water supply of domestic population, b) water supply for tourism, c) water supply for industrial purposes, d) irrigation and e) water supply for farming and aviculture purposes.

Water supply of domestic population was estimated using a daily water consumption of 150 litres per day per person. This value increased and decreased 20% for the summer and winter season respectively. For non domestic population (tourists) the value of consumption was set at 250 litres per day per person. For farming and aviculture purposes water demand per person was set at 40litres per day for big animals, 5 litres per day for small animals and 0.05litres per day for fowls.

Water resources system simulation

A. Generally

The simulation of Northern Rhodes water resources system was performed using "Hydronomeas" software (Efstratiadis et al., 2005). This software has been designed mainly for surface systems simulation, however in the present study an attempt to include also groundwater systems has been done.

The main components that had been used for the water resources system simulation were the following:

- Reservoirs, representing groundwater systems
- Junctions, representing a demand area for supply or irrigation water
- Aqueducts

B. Components analysis

Hydronomeas uses the following data to perform the reservoir simulation:

- Runoff, rainfall and evaporation timeseries
- The spill level in m that corresponds to the reservoir's storage capacity.
- The Initial level in m that corresponds to the reservoir's Initial volume at the
- beginning of the simulation.
- The Intake level in m that corresponds to the reservoir's Dead volume.

In order to perform the simulation of a ground water aquifer using reservoir components the following assumptions have been made:

- As entry data has been used percolation time series as it was calculated from the conceptual basin simulation model.
- The spill and intake levels had been set at 100 and 0 meters respectively
- Level – volume curve is expressed by a linear equation
- The storage capacity of the aquifer is calculated using the maximum value of percolation time serie.

In order to transform this value (it is given in mm of water column) to cubic meters the following procedure has been followed:

- All the water drills were plotted in a Geographical Information System (Arc Gis 9.1)
- A buffer zone was designed for each water drill according to the following table (table 4):

Table 4

Aquifer materials	**Buffer zone (m)**	
	Free aquifer	Artesian aquifer
Fine and medium grained sands	100-200	250-500
Coarse grained sands	300-500	750 -1500
Aquifers in fractured rocks	500-1000	1000-1500

- The total surface of the buffer zones for each unified basin was calculated and then was multiplied with percolation time series maximum value.

For each aquifer the following storage capacity has been estimated (table 5):

Table 5

Basin	**Attavyros**	**Arxaggelos Upper basin**	**Arxaggelos lower basin**	**Kameiros**	**Kallithea**	**Petaloudes**	**Rhodes**
Όγκος (hm^3)	2,872381	1,144384	2,946913	5,20984	20,63917	8,69397	6,404576

Concerning the water demand junction, monthly time series that have been estimated in the demand analysis chapter were introduced in the model, clustering water supply components (domestic and non domestic population, industrial, farming and aviculture water needs). For the aqueducts, a typical value of $10m^3$/sec had been set, with a leakage coefficient of 0.5 and

0.2 for irrigation and water supply aqueducts respectively. Finally target priorities were set at 1 for water supply and 2 for irrigation.

C. Network design

Network design is shown in figure 1. Groundwater reservoirs are represented with the blue squares connected with demand junction (white circles) by the aqueducts (blue lines).

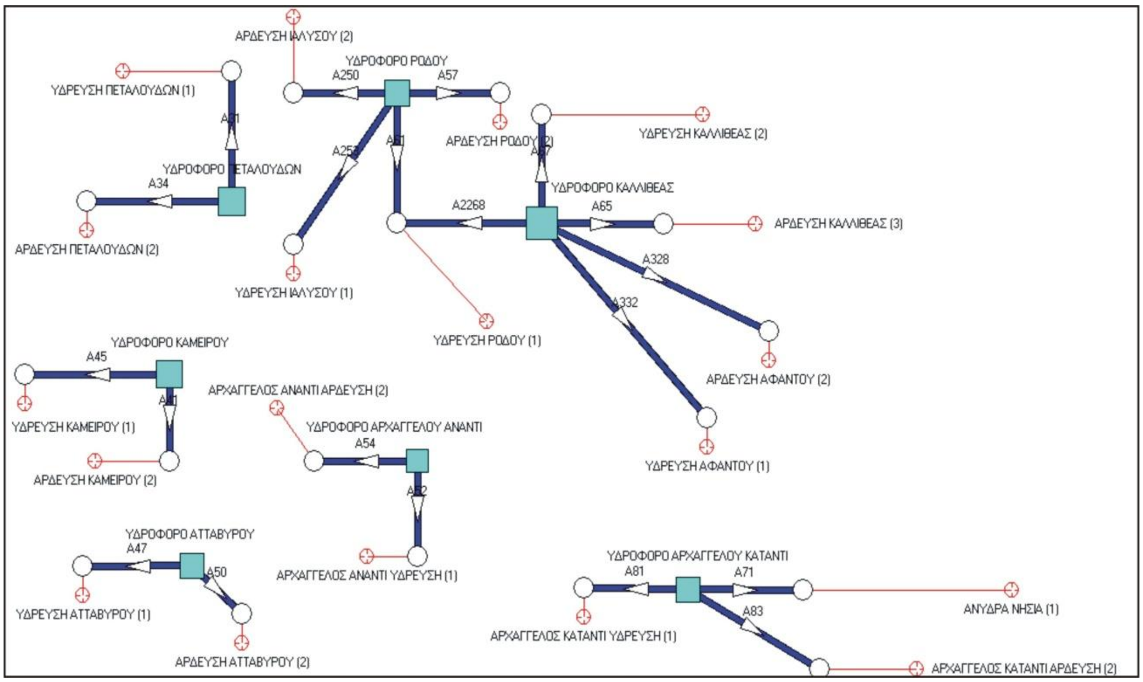

Figure 1

D. Simulation results

Scenario 1 – Present conditions

Simulation results for the present conditions are the following:

- Municipalities of Kallithea, Petaloudes, Afantou and Kameirou show very good water resources efficiency as expressed by the zero mean annual failure probability
- Municipalities of Rhodes and Ialysos show mean annual failure probability for water supply and irrigation of 0.2%. This value represents a satisfactory water resources situation, however the contribution of Kallithea's water resources system for Rhodes water supply should be ignored.
- Municipality of Arxaggelos shows a low water resources efficiency with increased mean annual failure probability (0.8% for water supply of the upper basin and 10.9% and 18.7% for irrigation of the upper and lower basins respectively.

- In Municipality of Attavyros the mean annual failure probability is 0.1% representing satisfactory efficiency of the water resources system.

Scenario 2 – Evaluation of Rhodes water resources system efficiency

In the second scenario Rhodes water resources system efficiency was evaluated, cutting from the network Kallithea aquifer - Rhodes water demand aqueduct. The simulation showed an increased mean annual failure probability for Rhodes and Ialysos Municipalities (5.0% and 7.9% for water supply and 4.4% and 5.1% for irrigation respectively), explaining the necessity for the use of Kallithea's water drills.

Scenario 3 – 30% increase in water demand

At the third scenario a 30% increased water demand for water supply use was introduced, following the network plan of the first scenario. The results were the following:

- Municipalities of Kallithea, Petaloudes, Afantou and Kameirou show very good water resources efficiency as expressed by the zero mean annual failure probability
- Municipalities of Rhodes and Ialysos show mean annual failure probability for water supply of 1.2% and 2.3% respectively. This value shows that even with the use of Kallithea's water drills the expected future increase in water demand will decrease the water resources system efficiency. Irrigation represents a mean annual failure probability of 0.6 and 0.8% respectively.
- Municipality of Arxaggelos shows a low water resources system efficiency with increased mean annual failure probability (0.8% for water supply of the upper basin and 10.9% and 18.7% for irrigation of the upper and lower basins respectively.
- Municipality of Arxaggelos shows a very decreased water resources system efficiency with mean annual failure probability 0.1% and 1.8% for water supply and 20.9% and 12.6% for irrigation for the upper and lower basin respectively.

Scenario 4 – Evaluation of Rhodes water resources system efficiency for a 30% increased water demand.

In this scenario Rhodes water resources system efficiency was evaluated increasing 30% the water demand, cutting from the network Kallithea aquifer - Rhodes water supply aqueduct. The simulation showed an increased mean annual failure probability for Rhodes and Ialysos Municipalities (19.1% and 28.8% for water supply and 15.0% and 16.9% for irrigation respectively), explaining the necessity for the introduction in the system of Gadouras dam.

Scenario 5 – Introduction of Gadouras dam in water resources system

At this final scenario the behaviour of the system was simulated introducing Gadouras dam and using 30% increased water demands. For dam characteristics the proposed values of Koutsoyiannis (1998) were used. The supply of the water transport network was set at $1m^3$/sec. The downstream environmental supply was estimated at $0.1m^3$/sec. Simulation results showed that system efficiency is increasing considerably with Gadouras dam introduction in the system. Mean annual failure probability decreases at 0.1% and 0.5% for Rhodes and Ialysos municipalities respectively. For irrigation mean annual failure probability is estimated at 0.3%. The last scenario points out the necessity for Gadouras dam construction, concerning the increased water demands of the near future.

Conclusions

A. Conceptual basin simulation model

Generally the model expresses the natural characteristics of the study area, expect of the springs absence, which are present although in a small degree in some areas (e.g. Rhodes basin).

B. Water resources system simulation

Simulation results correspond satisfactory to the present days situation. Exception are the results for Afantou Municipality were the model shows very good efficiency, however reports from the area, especially in dry seasons, point out water resources incomprehensiveness, and many cases of water level degradation. This failure of the model resulted due to false network design, were Municipality of Afantou is connected with Kallithea's very efficient groundwater system.

Concerning "Hydronomeas" and its performance in simulating ground water systems, the attempt is satisfactory as long as simulation results correspond in a very good degree to present days situation. However it would be useful a simultaneous run of "Hydronomeas" and conceptual basin simulation model, in order to calibrate the basin simulation model parameters considering also water demands, which affect the response of the system

C. Efficiency of available data

Concerning the available data, it was very important that discharge measurements of Gadouras river existed, considering that in south Agean region Gadouras discharge station is the only one operating.

For water drills the situation is more depressive:

- Municipalities give data in different form or no data at all.
- For private water drills there are no data or the existing data are totally inefficient
- The number of illegal water drills is unknown
- Most of water drills don't have piezometers or water meters

The above described situation leads to the conclusion that as long as honest will for rational water resources management does not exist the majority of the studies, in lack of measurement data, will be based in the assumptions that the researchers make in order to cover this data lack.