Hydrological study for the operation of Aposelemis reservoir – Extended abstract (2001 & 2003)

Scope and contents of the study

The scope of the study was the analytic and systematic approach of the Aposelemis reservoir operation, based on probabilistic/stochastic analysis, which aimed at complementing the previous studies and giving reliable estimations about the reservoir's safe release. The study gave emphasis to the estimation of the contribution of the surface water resources of Lasithi Plateau basin to the reservoir's water potential, which is affected by the hydraulic communication between the basins of Lasithi Plateau and Aposelemis due to their karstic geologic background. For this purpose, extensive collection and processing of historical hydrological records were required, in addition to the development and calibration of a conceptual hydrological model for both watersheds. The estimation of the safe reservoir release was based on a stochastic model for the generation of synthetic inflow series and a simplified simulation-optimisation model of the hydrosystem composed of Lasithi plateau – Aposelemis reservoir – boreholes – urban and rural consumption. By applying the above models, several scenarios were examined, referring to alternative values of the physical hydraulic communication between the two basins and different system's reliability levels.

Hydrological data processing

The hydrological data processing included the following:

- validation and aggregation of daily rainfall records;
- consistency control of annual rainfall values;
- testing of daily discharge measurements;
- filling-in and extension of monthly rainfall and runoff records;
- building of geographical layouts (river network, watersheds, digital terrain model, hydrometeorological stations) and computation of geographical properties of the watersheds (surface, mean elevation, Thiessen polygons);
- calculation of monthly surface rainfall records, based on point rainfall records;
- rainfall-runoff correlation analysis.

Hydrological model of Lasithi Plateau and Aposelemis basins

The hypothesis of hydraulic communication between Lasithi Plateau and Aposelemis basins

Inflows to the Aposelemis reservoir originate from the runoff of the upstream basin as well as the runoff of the Lasithi Plateau basin. The latter, which is now drained through a system of sinkholes, will be conveyed to the reservoir via a diversion tunnel, that is planned to be constructed upstream of the sinkholes. But there is evidence that part of the Lasithi Plateau runoff already supplies the Aposelemis basin, through a groundwater system starting from the sinkholes and ending at the karstic springs of Kastamonitsa, which are located along the SW branch of the Aposelemis stream. According to habitants' witnesses, which is consistent with the behaviour of the runoff time series, these springs operate temporarily and only during intensive storm events, having then very high discharge.

One of the main purposes of the study was to investigate the impacts of the possible hydraulic communication between the two basins to the hydrological performance of the Aposelemis reservoir. The investigation was based on hypothetical scenarios, assuming arbitrary values of the mean contribution of Lasithi Plateau's water potential to the Aposelemis runoff, equal to 0%, 30% and 50%. Given that this contribution cannot be uniform in time, a conceptual model was developed, which estimates the Kastamonitsa springs discharge by simulating the hydrological processes of the study area, for a specific mean communication percentage between the two basins. According to the model results, statistical relationships were developed for each one of the communication scenarios (30% and 50%), in order to correlate the Kastamonitsa springs monthly outflow with the Lasithi monthly runoff (Eqs. 3.5 and 3.6).

The hydrological model of Lasithi Plateau and Aposelemis basins

The mathematical model comprised two independent components. The first one represents the hydrological processes of the Aposelemis watershed and computes its surface runoff, whereas the second one represents the draining process of the Lasithi Plateau watershed through the sinkholes and computes the Kastamonitsa springs outflow. The total runoff of Aposelemis river, upstream of the Potamies discharge gauge, is obtained by adding up the output of the two model components. A schematic representation of the model is shown in Figure 1.

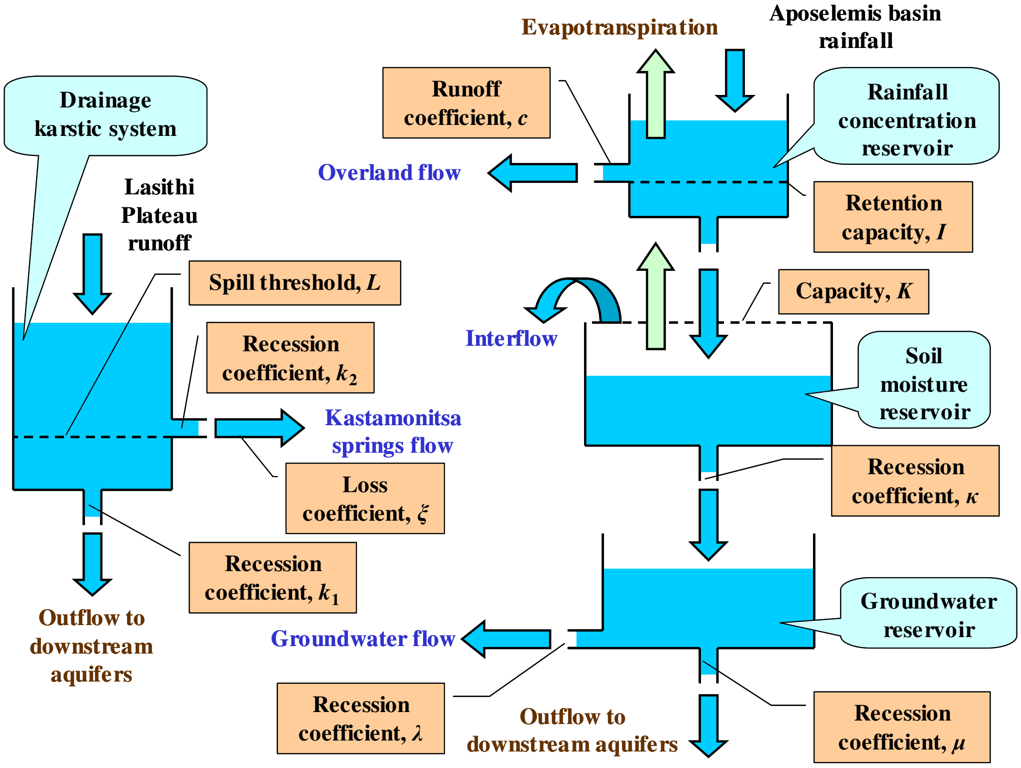


Figure 1: Schematic representation of the Lasithi Plateau – Aposelemis water balance model.

The transformation of rainfall to runoff at the Aposelemis basin outlet is implemented by successive transformations of the rain through a system of three interconnected reservoirs, representing hydrological processes. The first one simulates the overland flow and retention processes, the second one simulates the soil moisture zone processes (interflow, percolation, evaporation) and the third one simulates the groundwater processes. On the other hand, for the simulation of the draining processes of Lasithi Plateau through the sinkholes, an infinite capacity reservoir was assumed, which is fed by the Plateau runoff and discharges to the Kastamonitsa springs. Input of the model was the daily rainfall and potential evapotranspiration of the Aposelemis basin and the daily runoff of the Lasithi Plateau basin, while its output was the total runoff of the Aposelemis river, decomposed as surface and spring runoff. The total number of model parameters was 10.

The model calibration period was 5844 days or 16 hydrological years, from 1/10/73 to 30/9/89. The calibration was based on historical records of daily discharge, taken from the Potamies gauge. Four indices of goodness of fit were used, which were coupled in a weighted objective function, particularly:

- the typical monthly runoff error;
- the typical daily runoff error;
- the typical error of zero flow periods;
- the square difference between the standard deviations of the historical and the computed runoff samples.

Moreover, in order to define a specific hydraulic communication percentage between the two basins, an appropriate penalty term was incorporated to the objective function, ensuring that the ratio of the mean discharge of Kastamonitsa springs to the total Aposelemis discharge takes this specific value.

Three hydraulic communication scenarios were examined, assuming a ratio of 0%, 30% and 50%. For all scenarios, the fitting of the model to the historical runoff series was satisfactory. However, the fact that the fitting of the model became better as this ratio increased is evidence that the hydraulic communication assumption is true.

Estimation of Aposelemis basin spring runoff

To correct the runoff series at the Potamies site, historical as well as synthetic, an approximate statistical relationship was developed, which estimates the runoff due to the outflow through the Kastamonitsa springs as a function of the Lasithi Plateau runoff, on a monthly basis. For this purpose, the simulated spring discharge values were correlated with the corresponding runoff values of Lasithi Plateau basin, for each of the two hydraulic communication scenarios (30% and 50%).

Reservoir operation study

The simulation-optimisation model of system's operation

Figure 2 illustrates the water resources system composed of the Aposelemis reservoir and the rest of water supply projects of Lasithi Plateau and the areas of Heraclion and Agios Nicolaos. A monthly simulation model was developed for the above system, based on parametric reservoir operation rules. These rules determine the boreholes' target release as a function of the actual reservoir storage. More specifically, five storage fluctuation zones are assumed, and for each one of them the desired release from the boreholes is determined as a ratio λ_k of the actual water supply demand target. By definition, if the reservoir's actual storage is less than 20% of its capacity the ratio λ_1 is set equal to 100% (i.e., the demand is fulfilled only by groundwater resources), while if the storage is more than 80% of its capacity λ_5 is set equal to 0% (i.e., the demand is fulfilled only by surface water resources). For intermediate reservoir storage values, the supply is made partly from the reservoir and partly from the boreholes, according to the ratios λ_2, λ_3 and λ_4. The operation rules are distinguished for the refill (December to April) and the drawdown (May to November) period.

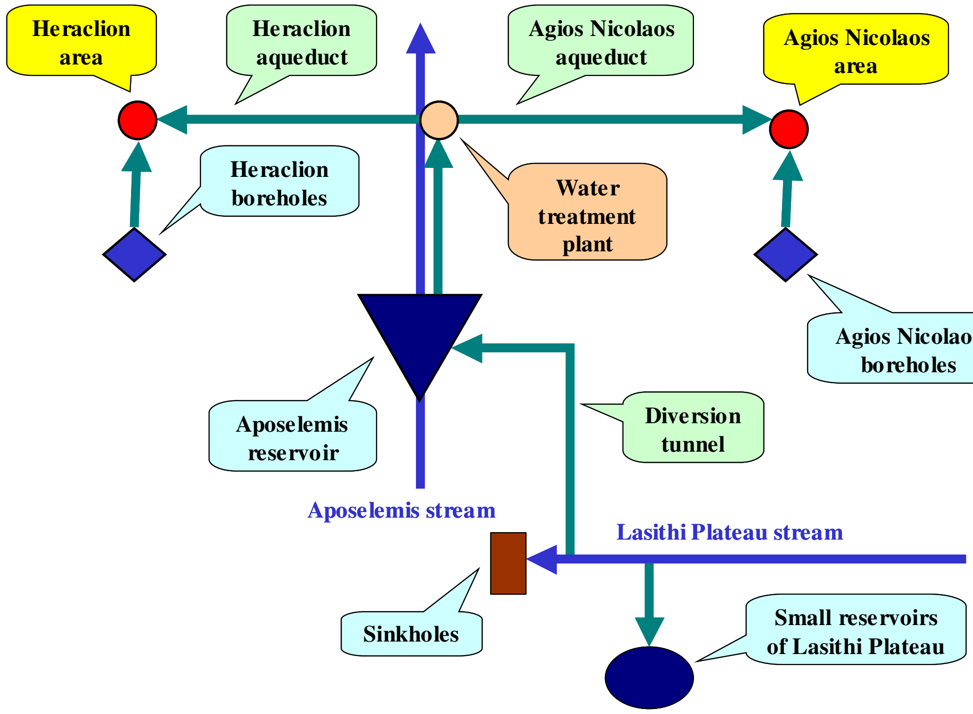


Figure 2: Schematic layout of the hydrosystem.

System's performance is evaluated by running the simulation model for a given set of parameters λ_k and given annual water supply target, *D*. In order to maximise the system's safe yield, an optimisation model was built, demanding to maximise the annual water supply target for a given reliability level. The reliability is computed as the ratio of total successful periods to total simulated periods. A period is assumed successful if and only if the total withdrawal from surface and ground resources equals the annual water supply target.

Generation of synthetic inflow series

Inflows to Aposelemis reservoir originate from the runoff of the upstream watershed, the rainfall on the reservoir's surface and the runoff from Lasithi Plateau, which will be conveyed to the reservoir via the diversion tunnel. To generate synthetic series for the above variables, a two-level multivariate stochastic model was used. In the higher level, the model enables preservation of important features on an annual timescale, such as hydrologic persistence, whereas in the lower level it enables reproduction of features on a monthly or sub-monthly timescale, such as periodicity.

To implement the model, historical records were used from the corresponding hydrometeorological stations. After generating the synthetic series, the runoff record of the Aposelemis watershed was corrected by subtracting the springs' contribution, originating from the surface resources of the Lasithi Plateau basin. For this purpose, the two statistical relationships referring to the corresponding hydraulic communication scenarios (30% and 50%) were applied.

Stochastic simulation of the hydrosystem

Several stochastic simulation scenarios of system's operation were examined, by modifying the hydraulic communication percentage, the system's desired reliability level and the annual decrease of Lasithi Plateau runoff that is due to irrigation withdrawals. The main results are presented in Table 1. The scenarios are written in the form A_{ij}, B_{ij} and Γ_{ij}. Scenarios A, B, Γ refer to 0%, 30%, 50% hydraulic communication percentage, repectively. Index *i* refers to the reliability level, whereas index *j* refers to the annual decrease of Lasithi Plateau runoff resulting from water storage upstream at the plateau for fulfilling its water needs. For *i* = 1, 2 and 3 a 98%, 95% and 90% reliability level is set, respectively. On the other hand, for *j* = 1 and 2 the annual decrease of Lasithi Plateau runoff that is assumed equal to 3.0 and 1.5 hm^3, respectively.

Table 1: Results of stochastic simulation scenarios (in hm^3).

Scenario	Hydraulic Commu-nication (%)	Relia-bility level (%)	Decrease of Lasithi runoff for Lasithi water needs	**Mean annual reservoir release for water supply**	Mean annual groundwater release	Annual water supply target	Mean annual water supply release
A_{11}	0	98	3.0	16.732	17.925	34.801	34.657
A_{21}	0	95	3.0	17.372	18.762	36.383	36.135
A_{31}	0	90	3.0	18.074	19.814	38.374	37.888
A_{12}	0	98	1.5	17.666	18.108	35.912	35.774
A_{22}	0	95	1.5	18.483	19.143	37.883	37.625
A_{32}	0	90	1.5	19.313	19.843	39.644	39.156
B_{11}	30	98	3.0	16.021	18.366	34.531	34.387
B_{21}	30	95	3.0	16.633	19.154	36.032	35.787
B_{31}	30	90	3.0	17.204	20.393	38.115	37.597
B_{12}	30	98	1.5	17.255	18.190	35.584	35.445
B_{22}	30	95	1.5	17.871	19.197	37.319	37.068
B_{32}	30	90	1.5	18.590	20.016	39.106	38.606
Γ_{11}	50	98	3.0	15.486	18.517	34.147	34.003
Γ_{21}	50	95	3.0	15.967	19.141	35.352	35.107
Γ_{31}	50	90	3.0	16.429	20.438	37.358	36.867
	50	98	1.5	16.618	18.662	35.420	35.279
Γ_{22}	50	95	1.5	17.215	19.292	36.746	36.507
Γ_{32}	50	90	1.5	17.747	20.543	38.787	38.291

To all scenarios a 0.5 hm3, allocated for ecologic discharge, should be added to estimate the total reservoir release.

Table 2: Synoptic results of optimization scenarios based on the historic time series and withdraw for Lasithi 3.0 hm^3/yr at the diversion tunnel entrance (29 simulation yrs 1968-1997).

	Scenario I_{A1}	Scenario I_{B1}	Scenario $I_{\Gamma1}$
Mean annual reservoir release (hm^3)	16.025	15.917	15.160
Mean annual groundwater release (hm^3)	18.887	18.855	19.530
Annual water supply target (hm^3)	35.349	35.348	35.348
Mean annual water supply release (hm^3)	34.912	34.772	34.690
Mean annual inflow to the reservoir from Lasithi Plateau (hm^3)	14.279	14.279	14.279
Aposelemis basin runoff (hm^3)	9.115	6.099	4.632
Mean annual spill (hm^3)	5.988	3.113	2.416

The main conclusions of the stochastic simulation analysis were the following:

- The mean annual water supply from the system ranges from 34.0 to 39.1 hm^3, according to the assumptions made for the hydraulic communication, the reliability level and the annual decrease of Lasithi Plateau runoff because of water storage at the plataeu. If a 95% reliability level is assumed, the mean annual water supply release ranges from 35.1 to 37.6 hm^3.
- If from the above quantity we subtract the contribution of groundwater resources, the safe release from Aposelemis ranges from 16.0 to 18.5 hm^3, for the same reliability level (95%).
- Even if a considerable (up to 50%) decrease of the water resources of Aposelemis is assumed, because of its hydraulic communication with the Lasithi Plateau watershed, the impact to the system's safe yield is limited. The reason is that, because of the relatively small reservoir capacity, the entire surplus amount cannot be stored. Thus, the assumption of zero hydraulic communication (scenarios A) leads to a considerable increase of spills, whereas the increase of reservoir's safe release is less significant. Indeed, the mean annual spill reaches 5.1, 3.2 and 2.5 hm^3, for scenarios A_{11}, B_{11} and Γ_{11}. We note that spills occur almost only during the period January-March, and even for the 50% hydraulic communication scenarios they continue to be important.
- Because of the hydrological regime of the study area, the operation rules impose an intensive use of groundwater resources during winter, given that even November is very dry. Indeed, during autumn, the mean reservoir storage remains less than the 1/3 of its capacity, and this percentage increases up to 50% only in January. Moreover, the fact that the mean storage fluctuation remains almost constant for all scenarios indicates that, generally, the reservoir operation is not affected by various uncertainties that characterise the whole system. The monthly variation of Aposelemis reservoir storage for 95% reliability is shown in Fig. 4.13.

Conclusions

The main conclusions of the study were the following:

1. The watersheds of Aposelemis and Lasithi Plateau have an adequate infrastructure for hydro-meteorological measurements. The available data is satisfactory both in quality and quantity and provides a sufficient basis for the hydrological design of the Aposelemis projects.
2. According to the available discharge measurements of the period 1964-65 to 1996-97, the mean annual surface runoff of the Lasithi Plateau basin upstream of the Kato Metohi (A=127.1 Km^2) discharge gauge is 16.7 hm^3, and the corresponding value of the Aposelemis basin upstream of the Potamies (A=76.6 Km^2) discharge gauge is 11.5 hm^3. For use in the model adjustments for the basin area difference between the measurements site and the outflow location were made and the period 1964-1968 where discharge measurements were missing were excluded for the determination of the statistical characteristics. However, it is conjectured that inflows to Aposelemis reservoir do not necessarily correspond to the sum of these two magnitudes, as it is suspected that part of surface runoff of the Aposelemis basin already originates from Lasithi Plateau. According to the hydraulic communication assumption, during intensive storm events (and only then) the karstic system starting from the sinkholes of the Plateau discharges through the karstic springs of Kastamonitsa (it is anticipated that the springs are part of the same karstic system), which are located into the Aposelemis watershed.
3. In order to quantify the extent of hydraulic communication tracer measurements and discharge measurements were performed. The recent measurements confirmed the hydraulical communication, but are do not give sufficient information for reliable quantitative estimation of the extent of the communication.

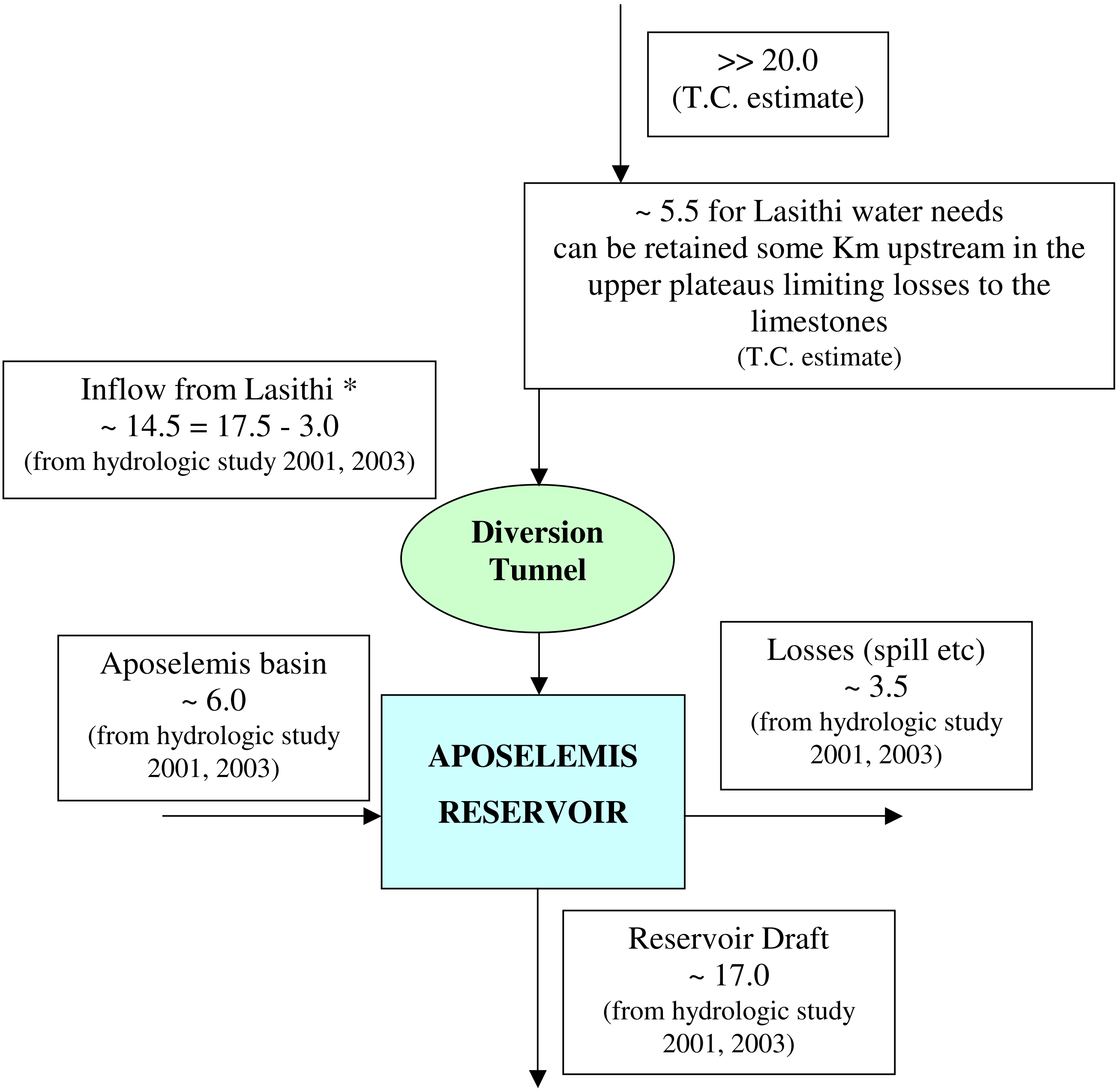
4. Meanwhile, in order to overcome the existing uncertainty regarding the extent of hydraulic communication, a scenario approach was used. To estimate the contribution of Kastamonitsa outflows to Aposelemis runoff, a daily conceptual rainfall-runoff model was developed, representing the hydrological processes of the two basins. Three scenarios with mean contribution of Lasithi Plateau's water potential to the Aposelemis runoff, equal to 0%, 30% and 50%, were examined. The second scenario is compatible with the rough estimate of equal runoff coefficients of the two basins, while the third one is the outcome of the optimisation of a conceptual model of the two basins on a daily basis.
5. According to the above assumptions, the water potential of the two basins, transferred to the site of the Aposelemis dam, is 26.6, 23.5 and 22.0 hm^3/year, for the 0%, 30% and 50% scenarios, respectively.
6. By subtracting 1.5-3.0 hm^3/year from the Lasithi Plateau runoff, as impact of fulfilling the Plateau water demand, the mean annual inflow to the Aposelemis reservoir becomes 19.0-25.1 hm^3.
7. By taking into account water losses due to spill and evaporation, the water potential of Aposelemis reservoir becomes **17.9, 17.1 and 16.5** hm^3/year, in which a 0.5 hm^3 for the discharge allocated for environmental preservation is included, assuming a 95% reliability level and a 3.0 hm^3/year decrease of the Lasithi Plateau runoff to fulfill water demand at Lasithi plateau, for the **0%, 30% and 50%** hydraulic communication scenarios, respectively.
8. If the decrease of Lasithi Plateau runoff due to water storage at the plateau is limited to 1.5 hm^3/year, the corresponding yield becomes 19.0, 18.4 and 17.7 hm^3/year. The above amounts could be available after combined management of surface and groundwater resources, which currently supply the areas of Heraclion and Agios Nicolaos.
9. From the above we conclude that the final impact of the hydraulic communication of the two basins does not exceed 1.4 hm^3/year, proving that it is not critical for the system's operation. The small differences between the three hydraulic communication scenarios are due to the fact that most of the strormwater originating from the Lasithi Plateau basin will be spilled. These spills cannot be avoided because of the relatively small storage capacity of Aposelemis reservoir versus the particular hydrological regime of inflows, which is characterised by high coefficient of variation.
10. Through the combined management of surface and groundwater resources, the total amount of available water resources for drinking water supply (in the surrounding areas of Heraclion and Agios Nicolaos) is estimated to be 35.1 - 37.6 hm^3/year for 95% reliability.

For Aposelemis J.V.
the representative

L.S. Lazaridis

<u>**Accepted probable scenario of reservoir operation**</u>

Hydraulic communication between Lasithi Plateau and Aposelemis basins ~30-50%
(percentage of Aposelemis discharge originating from Lasithi Plateau)
reliability 95%



Schematic Average Water Balance (in hm3/yr) for Aposelemis Reservoir

* 17.5 is based on measurements of the 1968-1997 period and adjusted for the basin difference between the measurement location (127.1 Km2) and the tunnel entrance (130.1 Km2).