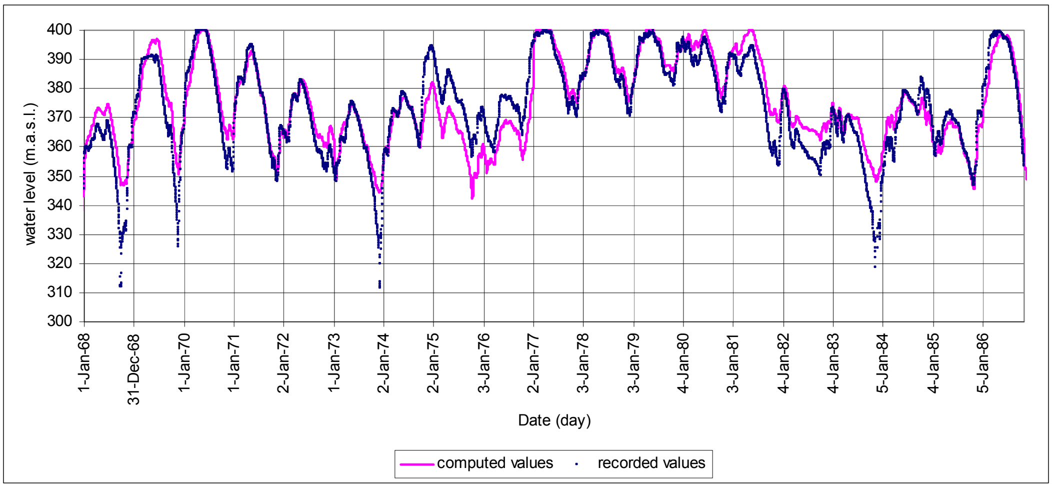


Figure 61. Headwater stage diagram of Bileća reservoir

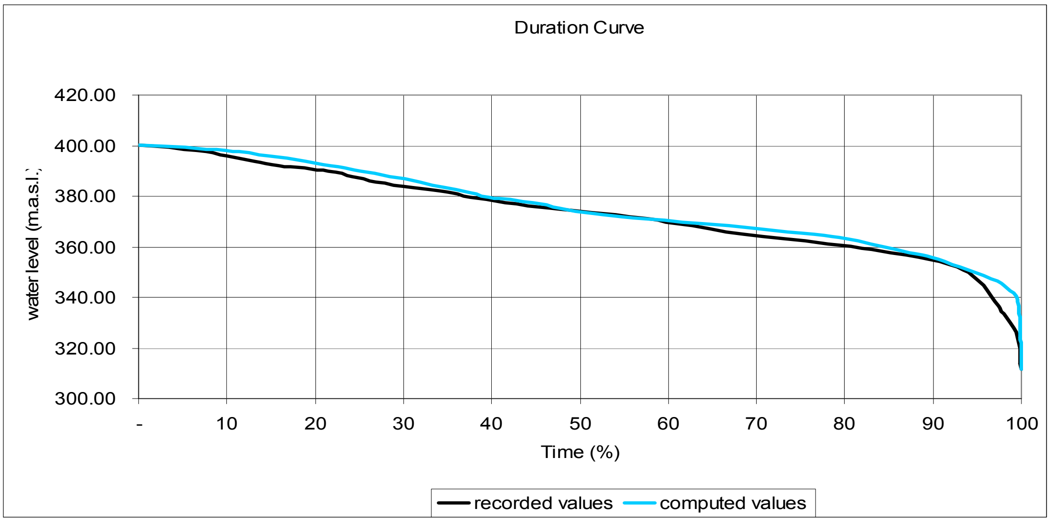


Figure 62. Headwater stage duration curve for Bileća reservoir

The best match between computed and registered headwater stages of Bileća reservoir is achieved during the period of model parameter identification, both in terms of the dynamics and absolute water stages, i.e. multi-annual average values. These values are:

- Computed 375.95 m asl and
- Registered 373.87 m asl

and they indicate an absolute difference of 2.08 m is, which is a relatively small quantity. There is a very good match between computed and registered headwater duration curves for the Bileća reservoir in the entire range of water stage variation.

It may be concluded that there is a **good match between computed and recorded values** in all key points of the model, and that there is a specially good match between computed and registered values for system output profiles (Do and Bileća), which is an indication that the discharge formation process in the drainage area during the period of simulation model parameter identification was assessed and modeled at an exceptionally high level, regardless of the complexity, lack of investigation and incomplete hydro-meteorological study of the drainage area. The results obtained may be applied in practice with an adequate degree of reliability.

Model validation was based on parameter values obtained in the calibration process, for conditions reflecting operation of the tunnel between Dabarsko Polje and Fatničko Polje. The team that prepared this part of the Study was not familiar with the exact operating mode of the tunnel between Dabarsko Polje and Fatničko Polje, and it was therefore assumed that the tunnel operated in full compliance with the rating curves shown in Figure 7.

The validation period was from 1 November 1986 to 31 December 2003. During this period the availability of hydro-meteorological data varied, as evidenced by Figure 52 - Figure 54. The period from 1961 to 1990 is relatively well supported by weather data, or rather precipitation data. There was combat in this area from 1991 to 1993 and, as a consequence, practically no measurement and recording by the stations. After 1994 measurement and recording was resumed at a limited number of these stations. Therefore, in order to apply the simulation model, weather data series were entered as shown in Section 2 of the Study. The entered daily values for this period have a lower degree of accuracy and their role is only to allow the running of the simulation model.

The results of simulation are also graphically represented in the form of parallel diagrams of computed values and values recorded by selected key data stations of the system. In the specific case, analogous to the model parameter identification period, computed results are graphically represented in the form of:

- The Bregava River hydrograph of the Do gauging station (Figure 63);
- The Bregava River discharge duration curve for the Do gauging station (Figure 64);
- The water stage diagram of the Dabarsko Polje plain (Figure 65);
- The water stage duration curve for the Dabarsko Polje plain (Figure 66);
- The water stage diagram of the Fatničko Polje plain (Figure 67);
- The water stage duration curve for the Fatničko Polje plain (Figure 68);
- The headwater stage diagram of the Bileća reservoir (Figure 69);
- The headwater stage duration curve for the Bileća reservoir (Figure 70).

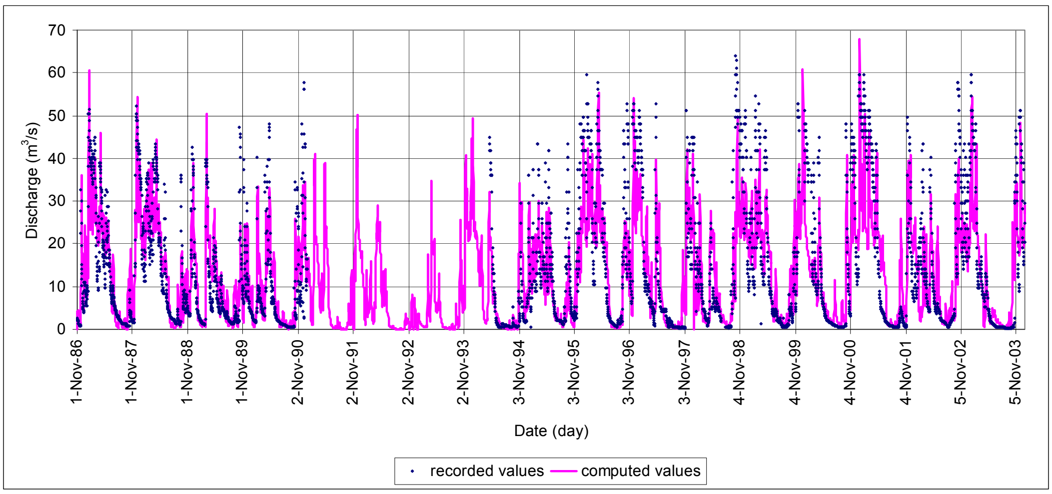


Figure 63. The Bregava River hydrograph of Do gauging station

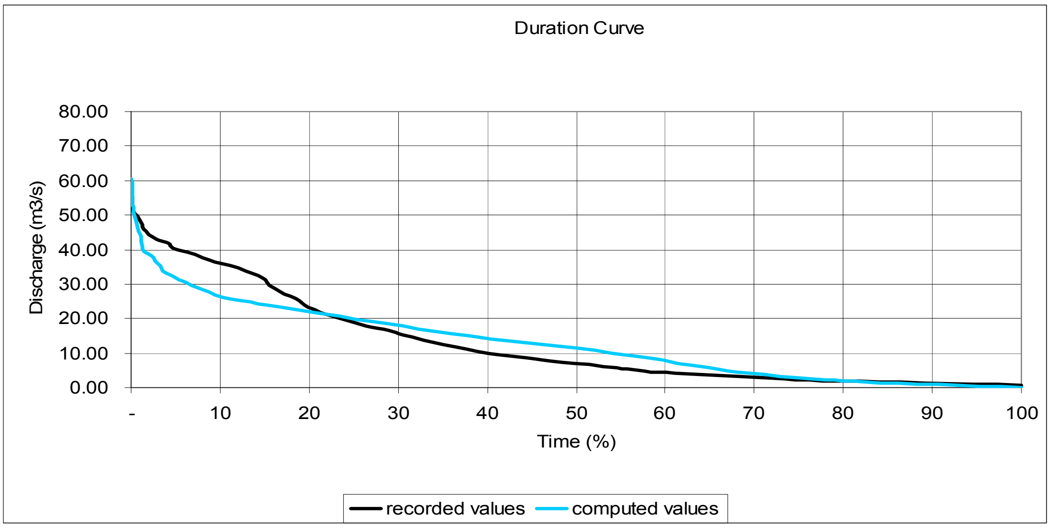


Figure 64. The Bregava River discharge duration curve for Do gauging station

The discharge simulation results obtained for the Bregava at the Do gauging station profile in the model validation stage, presented by means of parallel diagrams showing computed and registered values (Figure 63) and corresponding discharge curves (Figure 64), indicate a relatively good match between the said values. The significant differences during the periods of high flow result from the assumption that the tunnel between Dabarsko Polje and Fatničko Polje operated at full capacity, i.e. that water from Dabarsko Polje generally flowed in the direction of Fatničko Polje, which likely led to the reduction of computed high flows of the Bregava at the Do gauging station profile.

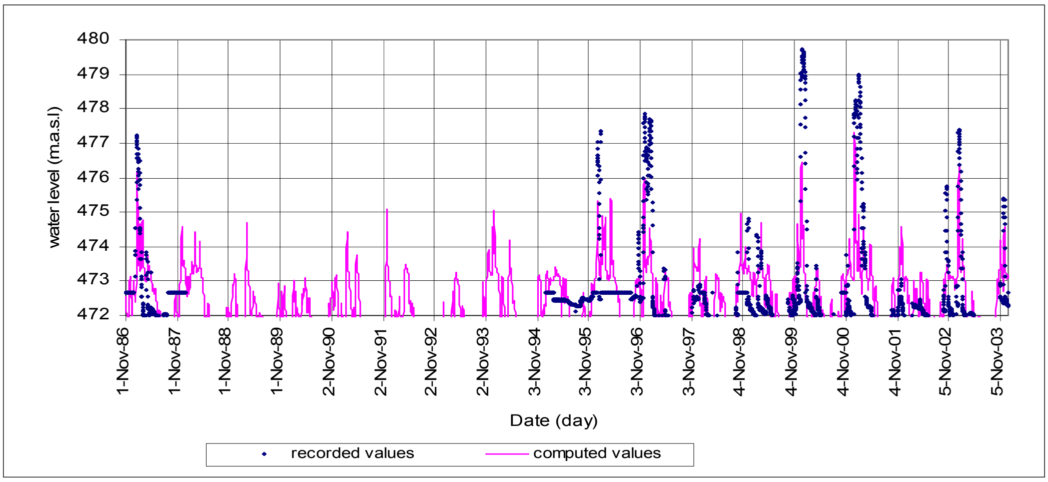


Figure 65. Water stage diagram of Dabarsko Polje plain.

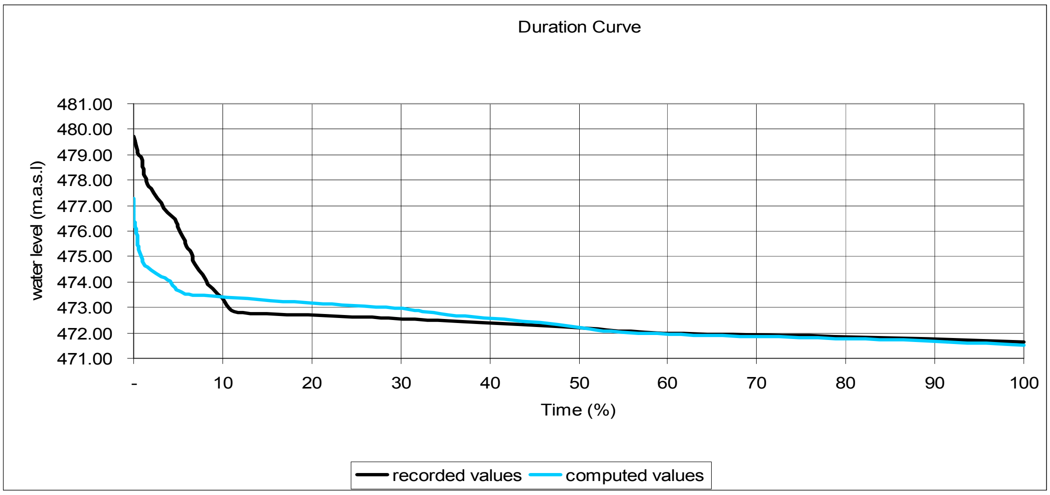


Figure 66. Water stage duration curve for Dabarsko Polje

The computed water stages during the model validation period are shown by means of parallel diagrams of computed and registered water stages in the Dabarsko Polje (Figure 65) and corresponding water stage duration curves (Figure 66). Water stage measurement discontinuities during this period are evident, while the form of the water stage duration curve is very similar to the discharge duration curve of the Bregava at the Do gauging station profile.

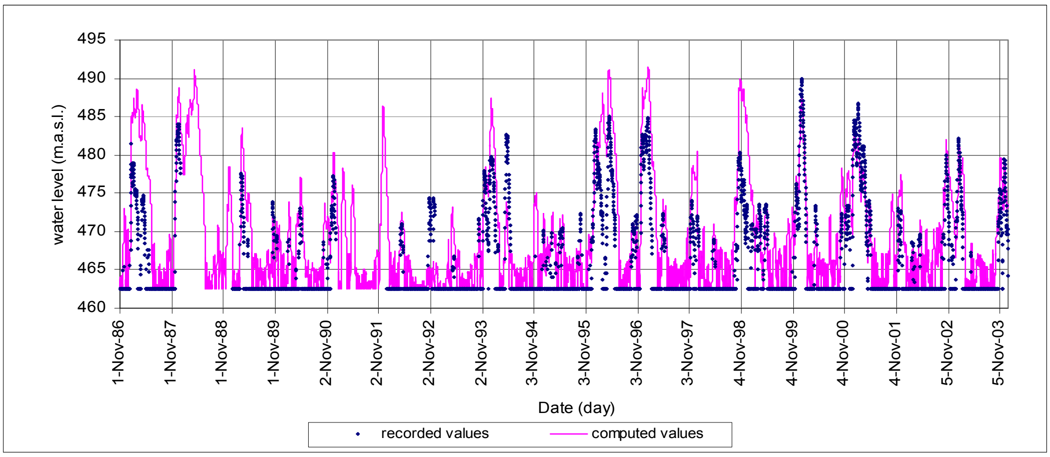


Figure 67. Water stage diagram of Fatničko Polje

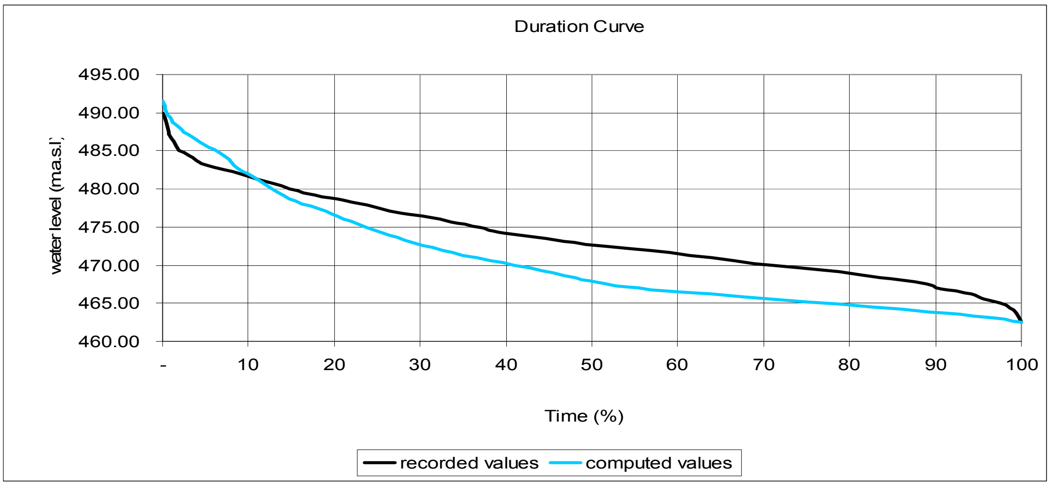


Figure 68. Water stage duration curve for Fatničko Polje

Computed and registered water stage diagrams for Fatničko Polje are shown in Figure 67 and the corresponding water stage duration curves in Figure 68. It may be concluded from these figures that there are significant differences between computed and registered values. The water stage duration curves were not based on the same number of input data, in view of significant discontinuities in Fatničko Polje during and after the war. However, the applied simulation model runs continuously and also computes Fatničko Polje water stages during the periods when they were not registered.

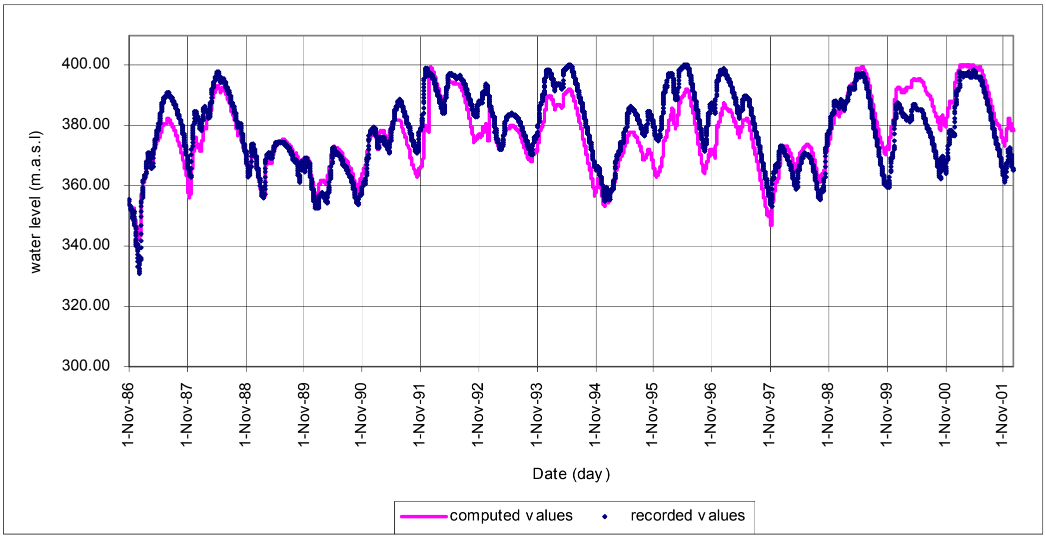


Figure 69. Headwater stage diagram of Bileća reservoir

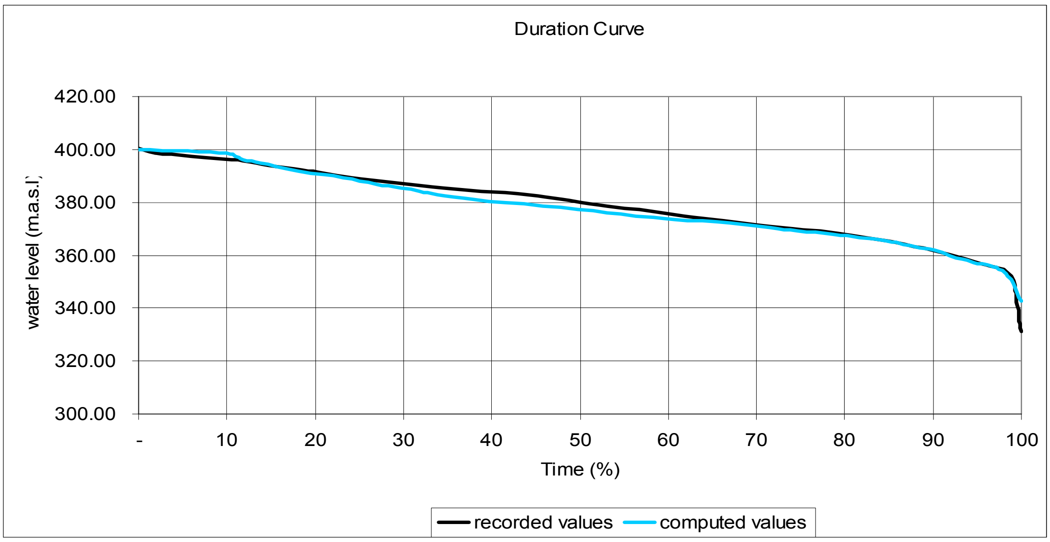


Figure 70. Headwater stage duration curve for Bileća

The best match between computed and registered values was obtained for Bileća reservoir. Figure 69 shows parallel chronological water stage diagrams with computed and registered headwater stages of the reservoir, and Figure 70 shows the duration curves for the same stages. A minimal difference between the two figures is evident, attesting once again that the applied simulation model may successfully be used in practice to monitor the discharge processes in the considered portion of the Trebišnjica River drainage area.

The study team assessed that the input data for the selected period of model validation had varying degrees of accuracy. This is reflected in the accuracy of the simulations. The assessments made for the period from 1986 to 1990 have the highest accuracy, followed by the period of the war where no significant monitoring took place in the drainage area until 1994. Very modest monitoring was resumed in 1994, and thus a number of assumptions were made for that period in order to run the model. Obviously this had an impact on output data accuracy for the said period.

5.1.6. Scenarios and uncertainty analysis

The following two scenarios were selected to assess the impact of the transfer of water from Dabarsko Polje to Fatničko Polje, and from there to the Bileća reservoir, on the flow regime of the Bregava River at the Do station profile:

1. **Natural conditions:** no water transfer occurs, and
2. **Managed conditions:** water is transferred from Dabarsko Polje to Fatničko Polje to the Bileća reservoir

Both scenarios were simulated for the period from 1 January 1961 to 31 December 2003. The spatial parameters of the model, which were not relevant to the design of the two tunnels, remained constant. Tunnel parameters (flow conveyance curves, and Regulation of outflow from Dabarsko Polje) were obtained from the project coordinator. A graphic interpretation of these curves is shown in Figure 7 and Figure 9.

It is the general assessment of the study team that the input data for the selected period of model application had varying degrees of accuracy. This is reflected on the accuracy of the simulations.

The presented results show that the applied simulation model developed for the system in question provides a relatively good agreement between the computed and the observed hydrographs in relation to the dynamics of the flood wave formation and its occurrence, as well as to the total quantity of water.

The deviations between the computed and the observed discharge (levels) at the control zones are the function of:

- basic hydro-meteorological input data accuracy (attributed to the different data sources)
- data flow continuity (the collapse of the monitoring system during the war and its slow recovery),
- complex flow conditions through the karst medium and
- assumptions on the Dabarsko Polje- Fatničko Polje Tunnel operation in the previous period

The best agreement between the computed and the observed water level and discharge values was obtained for the period 1972-1986, with a possible extension of the confidence up to 1990, due to the quality and number of datasets (discussed earlier in this chapter). Very modest monitoring resumed in 1994, and thus a number of assumptions were made based on expert judgement for that period in order to run the model.

This had an impact on output data accuracy for the said period although it can be concluded that the runoff process formation within the watershed, despite of the system complexity, insufficient field data and inadequate study of the catchment, was well conceived and adequately modelled for the purposes of this work.

5.1.7. Results and discussion

A specific assessment of river flow simulation results for the considered reach of the Trebišnjica and Bregava drainage area was made for both of the above system scenarios. The same inputs and outputs were used for the period from 1 January 1961 to 31 December 2003, including the same identified spatial parameters of the model. The results of simulation are shown in the form of discharge duration curves for Bregava River at Do station profile. A graphic interpretation of the results is given in Figure 71 - Figure 74.

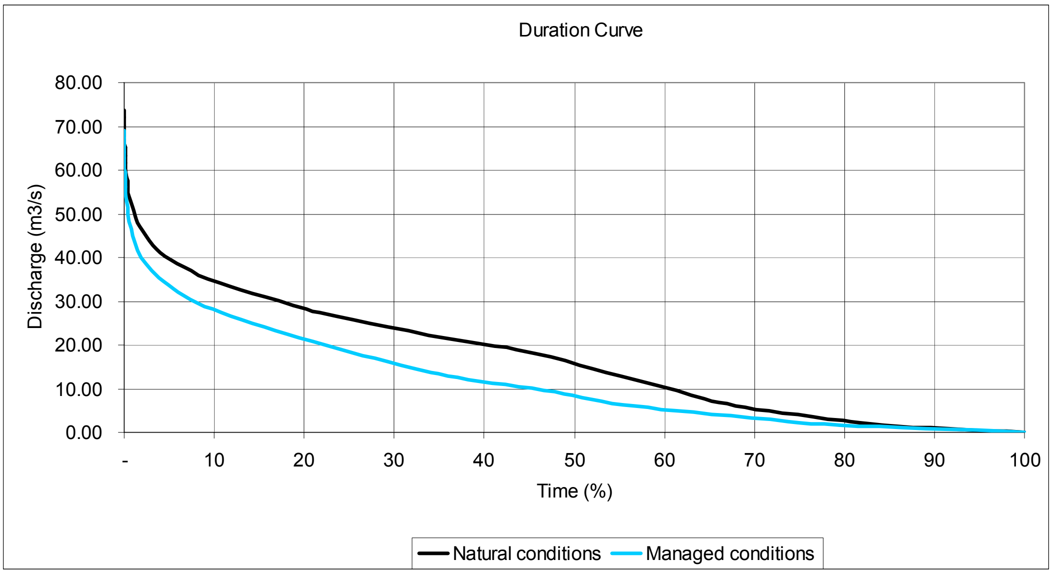


Figure 71. The discharge duration curves for Bregava River under natural and managed conditions

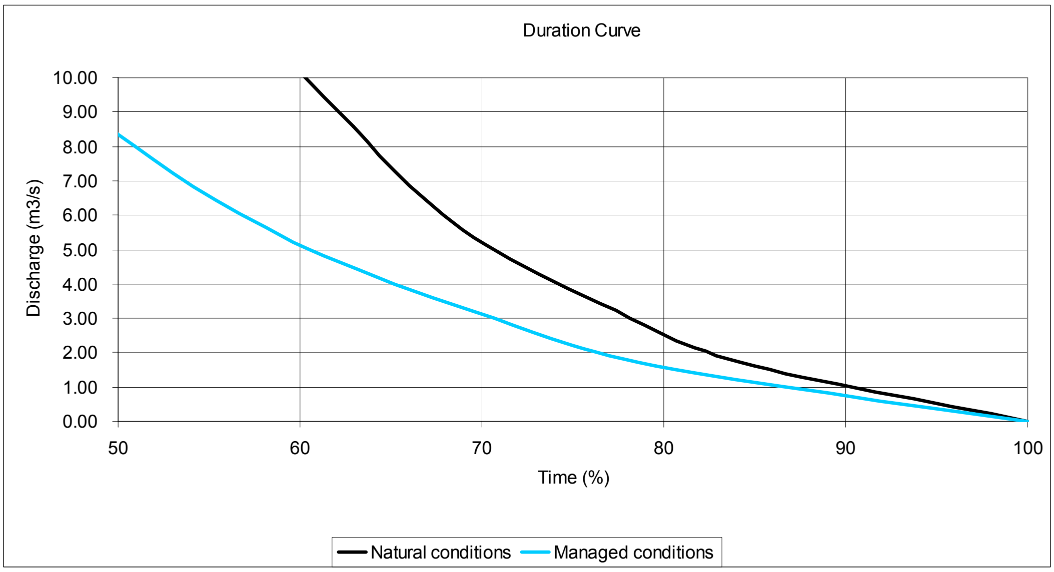


Figure 72. The discharge duration curves for Bregava River under natural and managed condition s- flow under 5 m3/s

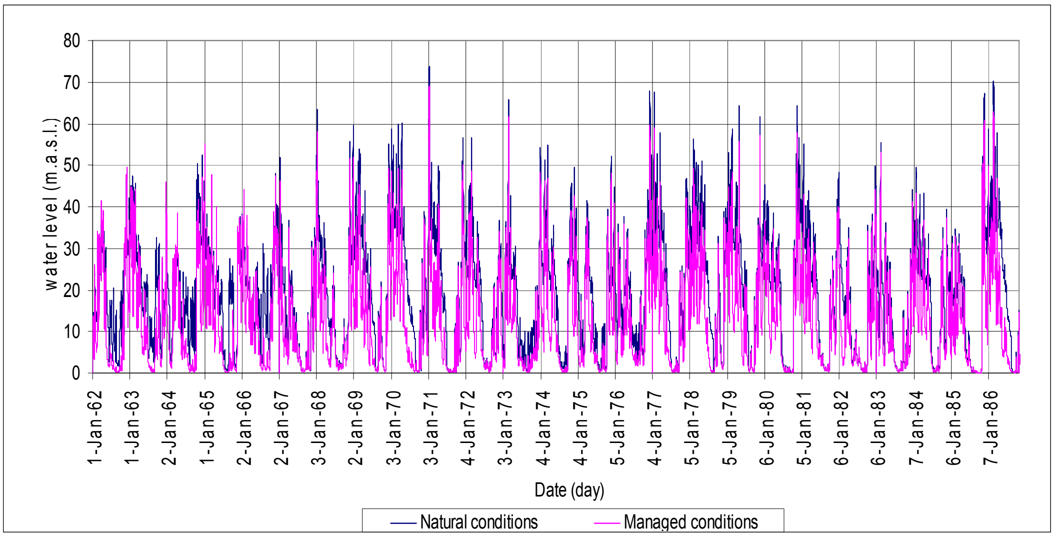


Figure 73. The hydrograph of Bregava River for Do gauging station under natural and managed conditions, for the period 1962-1986

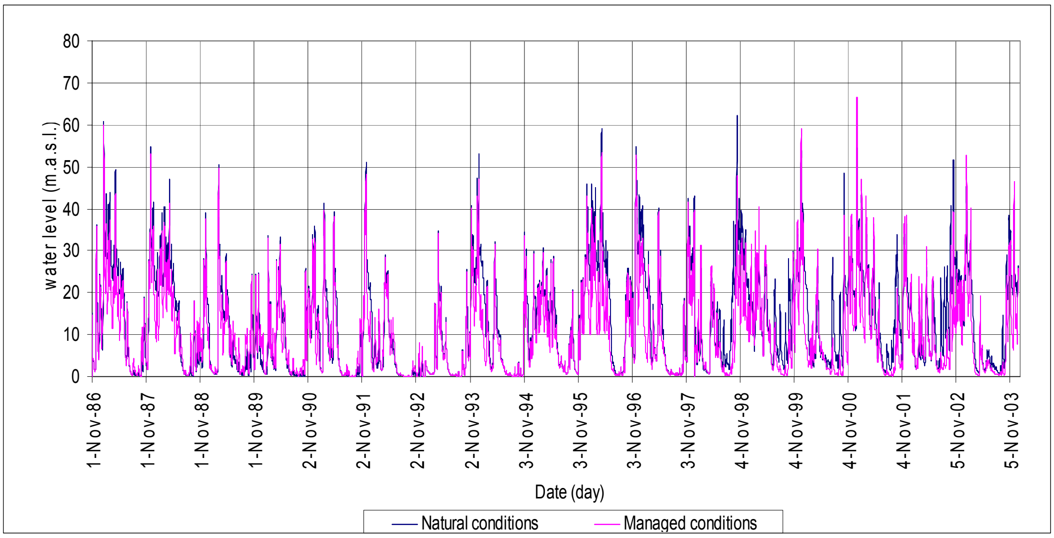


Figure 74. The Bregava River hydrograph of the Do gauging station for natural and managed conditions, for the period 1986-2003

For the sake of comparison in Figure 71 and Figure 72, the following discharge duration curves are shown for the Bregava at the Do station profile:

- Discharge duration curve under natural conditions, QN (T), and
- Discharge duration curve under managed conditions, QM (T).

The total difference between the two discharge duration curves is defined by the integral

$$Q^{P} = \int_{0}^{T} Q^{N}(T) - Q^{M}(T)\,dt$$

and it is the total amount of water Q^P transferred from the natural drainage area of the Bregava into the Bileća reservoir as a multi-annual average. In the specific case, the total amount of water is

$$Q^P = 153.05 \ 10^6 \ m^3$$

In terms of the multi-annual average value of mean annual discharges, it follows that about 30% of the discharge from the natural drainage area of the Bregava is transferred to the Bileća reservoir.

Based on the above, it follows that primarily it is the high flows in Bregava that are affected by the water transfer, while the low flow regime will not be affected significantly.

It is considered possible to further improve the low flow regime of the Bregava at the Do station profile by engineering measures, such as the ones proposed in other projects of the Upper Horizons system.

5.1.8. Conclusions

Based on the above, it follows that primarily it is the **high flows in Bregava that are affected by the water transfer**, **while the low flow regime will not be affected significantly**.

Furthermore, it is considered possible to further improve the low flow regime of the Bregava at the Do station profile by engineering measures, such as the ones proposed in other projects of the Upper Horizons system.

5.2. The K Sim^2 Hydrologic Model

5.2.1. Model Description

This model was built with the deliberate intent to be as simple as possible. A first option to build a simple model is to develop statistical relationships among the involved processes on the basis of the available time series. However this black box approach may be not appropriate for the target of the study, since such a model will be hardly adaptable to future conditions that depart from natural ones. Thus, a black box approach will not be very useful to assess the impacts of a specific management policy. A second option, which was finally followed, is to simplify the system, grouping together several of its components and simultaneously using simplified conceptual dynamics of the system. Thus, this model could be characterized as a lumped conceptual model, in which the features represented are kept to a minimum. The main objectives of the model are: (a) to investigate whether simple mechanisms can describe in a satisfactory manner the system behaviour; (b) to identify essentials and discard details in the system dynamics, and (c) to identify sets of parameters for which the system behaviour is described well. If the model, after its calibration, turns out to give sufficient approximation of the system behaviour, then it can be used for a first assessment of the impacts of certain future management conditions. This can be done by incorporating the management rules into the model operation, in addition to the natural system dynamics.

The resulting model will be referred to as the K Sim2 model which stands for Karst Simulation Simplified Model. Instead of being a general purpose model, it was built especially for the particular case study based on the specific structure and peculiarities of the hydrosystem studied. Simultaneously, however, it was based on a general experience of the behaviour of karstic systems, especially from Greece (Koutsogiannis *et al* (2001); Rozos *et al.* (in press)).

A schematic cross section of the hydrosystem with the natural hypothetical connections in karstic fields (poljes) and the artificial tunnels constructed (DP-FP) or under construction (FP-BR) is shown in Figure 75. A general layout of the same is shown in Figure 76.

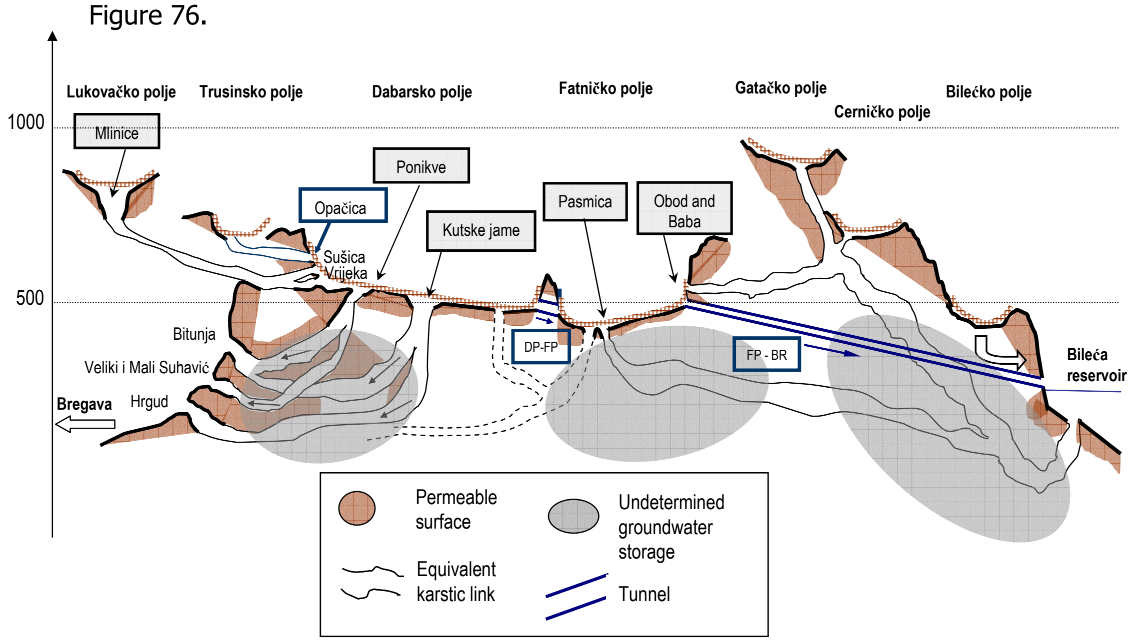


Figure 75. Schematic of the hydrosystem of Trebišnjica and Bregava river catchments with the karstic fields (poljes), the natural hypothetical karstic connections and the artificial tunnels constructed (DP-FP) or under construction (FP-BR).

Figure 76. General layout of the hydrosystem of Trebišnjica and Bregava river catchments with the karstic fields, the natural hypothetical connections, the artificial tunnels and the locations of meteorological and hydrometrical stations.

The model of the hydrosystem is shown in Figure 77. The model includes the following water storage components:

a. A **soil moisture reservoir** that represents all soil-water processes in the Trebišnjica and Bregava river catchments.
b. A single hypothetical **polje** which merges the Dabarsko and Fatničko polje system, which are connected directly to each other and to the Trebišnjica and Bregava rivers. All other poljes of the wider area (Gatačko, Bilećko, Lukovačko), which are not directly linked to the Bregava river, are not modelled explicitly.
c. A **groundwater reservoir** near the springs discharging to the Bregava River.

The hydrological processes taken into account by the model, apart from those related to water storage in the above reservoirs, are the following:

i. **Precipitation**: This is the input from the atmospheric system and is regarded as known.
ii. **Land evapotranspiration**: This is an output of the hydrosystem to the atmospheric system. It is unknown and is estimated during simulation of the soil moisture reservoir so that it does not exceed the potential evapotranspiration, which is assumed to be known.
iii. **Evaporation from poljes**: This is again is an output of the hydrosystem to the atmospheric system. Its value at a certain time step in depth units is assumed known, but its value in volumetric units depends on the area of the poljes, which is estimated during simulation of the polje reservoir.
iv. **Runoff**: This includes both surface and subsurface runoff, whose distinction in this karstic system is very difficult as water may move within the catchment area alternating between surface and subsurface paths. In the model, a distinction is made based on the rate of movement and assuming three rates, direct, quick and slow (as explained in the following paragraphs), rather than on the specific paths it follows.
v. **River flow**: Only the Bregava river discharge is modelled. According to the target of this study, the Bregava river flow is the most important system output.
vi. **Artificial diversion**: This is the diversion of water from the polje system to Trebišnjica river and is taken into account when the system operation under future regulated conditions is studied.

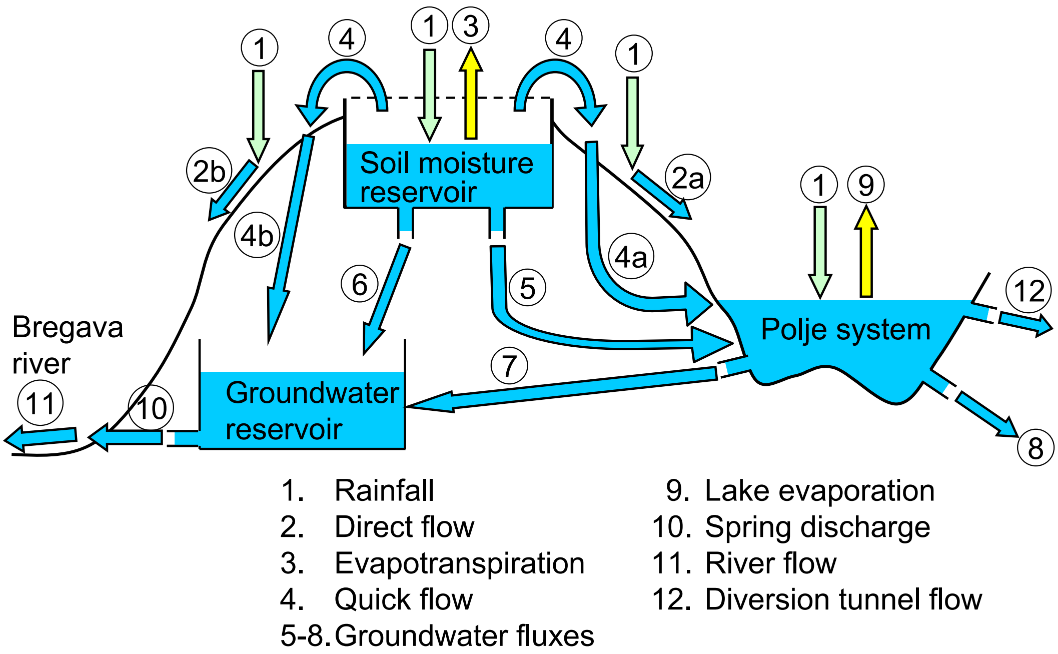


Figure 77. Schematic of the K Sim^2 model.

Based on the above described storage components the following transformations of water quantities are assumed, which are also depicted in Figure 77 with the numbering shown in the relevant paragraphs:

1. **Rainfall**: In the absence of separate data for liquid and solid precipitation, it is assumed that all precipitation falls as rainfall. Three types of surfaces are assumed: Impervious areas, pervious areas with soil cover and water areas (poljes); the first two areas are assumed constant in time whereas the third is

assumed to vary in time and is determined in terms of the water level of the polje via the elevation-area-volume curve.

2. **Direct flow**: Rainfall falling on impervious areas is directed towards either the polje system (2a) or the Bregava River (2b). The amount of this flow is determined by the relevant areas F_{2a} and F_{2b}, which are assumed constant but unknown (model parameters).
3. **Evapotranspiration**: Rain falling onto pervious areas (covered by soil) is evaporated or transpired in a rate that does not exceed the rate of potential evapotranspiration. If rainfall is smaller than potential evapotranspiration, then water from the soil moisture store is abstracted until either potential evapotranspiration is satisfied, or the soil moisture reservoir emptied.
4. **Quick flow**: If rainfall is higher than potential evapotranspiration, then the excess water is stored in the soil moisture reservoir, until this reservoir reaches its capacity K (in units of volume per unit area, i.e. depth), which is assumed constant and unknown (model parameter). Rainfall higher than the amount that can be stored is transformed to quick flow. This is directed towards either the polje system (4a) or the Bregava River (4b). The amount of this flow is determined by the relevant areas F_{4a} and F_{4b}, which are assumed constant but unknown (model parameters).
5. **Slow flow to polje system**: When the soil moisture reservoir is not empty, an amount proportional to the stored water S (expressed as volume per unit area) is leaked from it and directed to the polje system following groundwater paths. The amount of leakage, expressed in units of volume per unit area, is $k\,S\,\Delta t$, where Δt is the time step (chosen to be one day for all simulations) and k a constant parameter. Thus, the total volume directed to the polje system is determined by the relevant area F_5 which does not necessarily coincide with F_{4a}; F_5 is assumed constant and unknown (additional parameter).
6. **Slow flow to Bregava River**: As in the previous case, an additional amount of leaked water is directed to Bregava. It is determined by the relevant area F_6 which does not necessarily coincide with F_{4b}. In addition, the sum of areas F_5 + F_6 does not necessarily equal the sum F_{4a} + F_{4b} as some of the leaked water may be directed to other neighbouring catchments. F_6 is assumed constant and unknown (additional parameter).
7. **Leakage of polje system to Bregava**: From both the Dabarsko and Fatničko poljes, water can leak and is directed towards the Bregava River (e.g. through Ponikve hole, Kutske jame, and a few smaller sinkhloles in Dabarsko as well other sinkholes in Fatničko). All these paths are modelled as a single "conduit" which conveys water from the polje system to Bregava. The water leaked from the polje to this conduit is assumed to depend on the storage in the polje system. Specifically, the amount of this water is assumed to be $f_7(V)\,\Delta t$, where V is the volume of water stored in the polje system and $f_7(\ )$ is a function whose mathematical form and parameters will be discussed in the next subsection.
8. **Leakage of polje system to Bregava**: Another amount of water stored in the polje system leaks towards the Trebišnjica River via sinkholes mainly in Fatničko polje. These sinkholes are modelled as a single hole. Again, the water leaked from the polje to this hole is assumed to depend on the storage in the polje system. Specifically, the amount of this water is assumed to be $f_8(V)\,\Delta t$, where $f_8(\ )$ is a function with mathematical form similar to that of $f_8(\ )$ (see next subsection).
9. **Evaporation from polje**: For simplicity, the lake evaporation, expressed in volume per unit area, is assumed equal to the potential evapotranspiration. Thus, the total volume of evaporation is determined directly in each simulation step, given the storage V, which also determines the area A, through the elevation-area-volume curves.

10. **Spring discharge**: The karstic springs discharging to the Bregava River are modelled as an outlet from the groundwater storage. The volume of water depends on the groundwater reservoir storage *G* and is given as $f_{10}(G)\ \Delta t$, where $f_{10}(\ )$ is a function with mathematical form similar to that of $f_7(\ )$ (see next subsection).
11. **River flow**: The Bregava river flow is the sum of the spring discharge (10) and the direct flow (2b).
12. **Diversion tunnel flow**: When the model is run for the future regulated conditions, a regulated discharge is assumed through the FP-BR tunnel. The discharge in this reservoir is determined by the tunnel discharge capacity and the regulation rules followed. Both these depend on the water level at the polje. Assuming that the water in the polje system corresponds to the Dabarsko polje water level and according to the agreed regulation rules, it will be assumed that the tunnel is kept open only when the water level in polje is higher than +472 m asl.

Both direct flow and quick flow are assumed to arrive either to the polje system (2a, 4a) or to Bregava River (2b, 4b) without any time lag. In contrast, for each of the groundwater fluxes (5, 6, 7), in addition to the lag time due to the residence in the relevant reservoir, which is indirectly determined in simulation, another constant lag of one day is assumed to account for the time it takes water move along the relevant groundwater path.

The system dynamics are described by the continuity equations at all nodes of the hydrosystem schematisation, shown in Figure 77, and all functions and rules described analytically in the above points.

5.2.2. Model parameters and main assumptions

The model parameters have been already discussed in the previous subsection and can be classified in three categories. The first category includes portions of the catchment areas: F_{2a}, F_{2b}, F_{4a}, F_{4b}, F_5, and F_6. In a typical catchment, these areas are supposed to be known. However, in the examined case, even the total catchment area is uncertain. The area of the catchment around the Dabarsko polje, shown in Figure 76, is 396 km^2. However, as far as the discharge of the Bregava River at Do is concerned, the water of only a portion of this area is directed there, since water is also conveyed, via the natural underground paths depicted in Figure 75 and Figure 76, to the Trebišnjica River. At the same time, additional areas from neighbouring catchments are drained towards the Bregava river, as is also shown in Figure 75 and Figure 76. Therefore all the above listed and described portions of catchment areas are regarded as unknown parameters to be estimated in the model calibration phase. Generally, it is expected that the sum $F_{2a} + F_{2b} + F_{4a} + F_{4b}$ is greater than 396 km^2 whereas the sum $F_5 + F_6$ is smaller than the sum $F_{4a} + F_{4b}$.

The second category contains parameters related to the soil moisture reservoir, namely the storage capacity (K) and the leak coefficient (k).

The third category contains the parameters of the functions $f_7(V)$, $f_8(V)$ and $f_{10}(G)$, which determine groundwater fluxes. A single mathematical expression was assumed for all three. In an initial attempt this expression was assumed to be a power law, but this was not able to describe sufficiently the low flows at Do. Therefore, eventually a three-parameter logistic curve was used, which is S-shaped and has the mathematical expression:

$$f(x) = \frac{p\,(1 - e^{-nt})}{1 + m e^{-nx}}$$

where p is a saturation value (i.e., $f(x) \to p$ as $x \to \infty$) and m and n are additional parameters. The existence of a saturation value is an approximation of the slow rate of increase of discharge vs. the increase of volume for large volumes; in any case it is an imperfection of the model but it gave rather satisfactory results as will be demonstrated later. In conclusion, the third category contains nine parameters in total, namely the triplets (p_7, m_7, n_7), (p_8, m_8, n_8) and (p_{10}, m_{10}, n_{10}).

Thus, the total number of parameters is 6 + 2 + 9 = 17; a list is given in Table 7. In addition to these, three initial values of storages, namely S_0, V_0, and G_0, are also unknown and can be estimated in the calibration process.

The elevation-area-volume relationships of the polje system can be approximated mathematically by power law relationships such as

$$A(z) = \kappa(z - z_0)^{\lambda}, \quad V(z) = \kappa\,(z - z_0)^{\lambda + 1} / (\lambda + 1)$$

where z, A and V are respectively the elevation, area and volume, z_0 is the datum (i.e., the elevation for which A = 0) and κ and λ are parameters. In initial model runs, the parameters κ and λ were not fixed but rather unknown additional parameters, so that the hypothetical polje system can take the optimal shape between the single Dabarsko polje and the aggregate of Dabarsko and Fatničko poljes. Thus, in the optimization procedure (see subsection 5.2.4) the constraint that $V(z)$ of the hypothetical system is between $V(z)$ of the Dabarsko polje and the aggregate $V(z)$ of Dabarsko and Fatničko poljes was set. Eventually, however, the optimization resulted in $V(z)$ of the hypothetical system virtually equal to the aggregate $V(z)$, so finally κ and λ were determined directly from the curves of the two polje and were not regarded as model parameters.

Table 7. List of K Sim^2 model parameters.

Description	Symbol	Units
Impervious area with direct flow directed to the polje system	F_{2a}	km^2
Impervious area with direct flow directed to Bregava	F_{2b}	km^2
Pervious area whose spill (quick flow) is directed to the polje system	F_{4a}	km^2
Pervious area whose spill (quick flow) is directed to Bregava	F_{4b}	km^2
Pervious area whose leak (slow flow) is directed to the polje system	F_5	km^2
Pervious area whose leak (slow flow) is directed to Bregava	F_6	km^2
Soil reservoir storage capacity	K	mm
Leak coefficient of soil moisture reservoir	k	d^{-1}
Saturation discharge of polje system leak directed to Bregava	p_7	m^3/s
Parameter m of the storage-leak relationship corresponding to polje outflow 7	m_7	-
Parameter n of the storage- leak relationship corresponding to polje outflow 7	n_7	hm^{-3}
Saturation discharge of polje system leak directed to Trebišnjica	p_8	m^3/s
Parameter m of the storage- leak relationship corresponding to polje outflow 8	m_8	-
Parameter n of the storage- leak relationship corresponding to polje outflow 8	n_7	hm^{-3}
Saturation discharge of groundwater discharge to Bregava	p_{10}	m^3/s
Parameter m of the storage- discharge relationship corresponding to groundwater outflow 10	m_{10}	-
Parameter n of the storage- leak relationship corresponding to polje outflow 10	n_{10}	hm^{-3}

5.2.3. Use of Data

After an extended investigation of the large collection of data series of the area, a small number was chosen which are the most relevant to the target of the study, the longest and the more reliable. These data series are listed in

Figure 78, where also the data availability over the years of station operation is shown. The station locations are shown in Figure 76. The total time span covered by the data series has been divided into two periods, where the first (1/1/1961-31/10/1986), referred to as period A, corresponds to completely natural conditions of the hydrosystem, whereas the second (1/11/1986-31/12/2003), referred to as period B, corresponds to partly regulated conditions as the DP-FP tunnel was operated during that period. Due to complete or significant absence of data during period B, some years were excluded, so finally period B consists of the sub-periods 1/11/1986-1/12/1990 and 1/5/1994-31/12/2000.

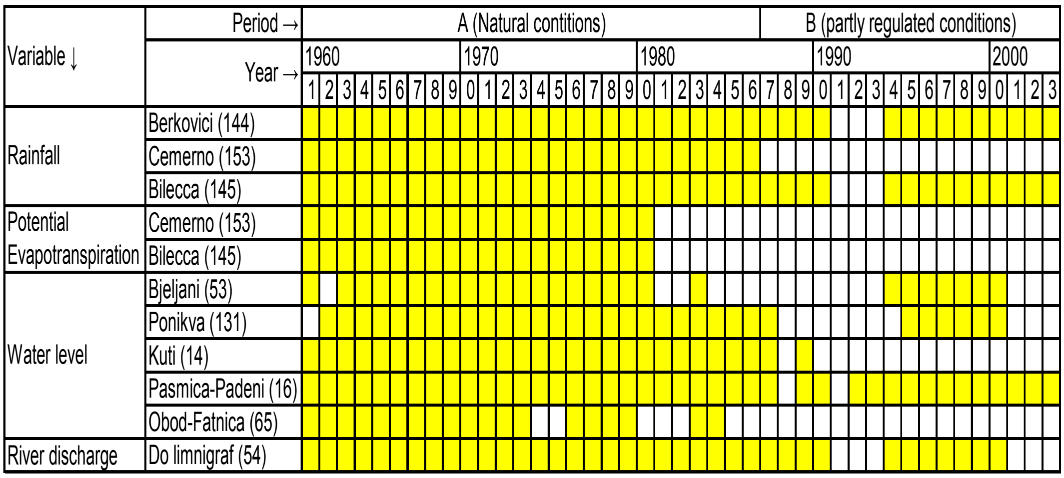


Figure 78. Used data series and data availability: the white boxes correspond to years with complete absence of measurements whereas the remaining boxes correspond to years with complete or incomplete series of measurements.

The rainfall data series chosen are those of stations Berkovići, Čemerno and Bileća. These are the longest available and their locations span the wider area of the Trebišnjica and Bregava river catchments. The mean annual rainfall depths for the three stations are respectively 1505.1, 1822.7, and 1569.9 mm (the larger value for Cemerno must be attributed to the higher elevation). The daily values are well correlated to each other: the correlation coefficients for the couples Berkovići-Čemerno, Berkovici-Bileća and Cemerno-Bileća are respectively 0.787, 0.775, and 0.796. No in-fill of the gaps in measurements was performed. An average series for the entire area was formed by taking the average of the three daily measurements in each day. In the absence of values for a particular station the average was estimated from the remaining values. Obviously, this creates a non-homogeneity of the resulting series but this is not regarded as a major problem for the purposes of the simplified model studied. The resulting mean annual average rainfall depth for the whole period is 1559.7 mm and the corresponding values for periods A and B are 1693.7 and 1309.4 mm, which indicates a reduction of rainfall in the more recent years.

For two of the above stations, namely Čemerno and Bileća, there exist series of estimated potential evaporation. These were used in the model, after extension to cover all required periods, which was done simply by taking the average of the same date for all available years. The mean annual potential evapotranspiration depths for the two stations are respectively 895.4 and 1055.1 mm (the larger value for Cemerno is explained by the higher elevation). The daily values are well correlated to each other, with correlation coefficient equal to 0.901. Again, an average series for the entire area was formed by taking the average of the two daily measurements in each day.

For the water level of the Dabarsko polje, three stations were used, namely Bjeljani, Ponikva and Kuti; the Vrijeka station was also studied but it does not have good correlations with the other stations. In contrast, the three chosen stations are well correlated to each other as shown in Figure 79 (Kuti-Bjeljani), Figure 80 (Ponikva-Kuti) and Figure 81 (Ponikva-Bjeljani). A problem is apparent in Figure 81, where the points of simultaneous measurements corresponding to period B depart from the equality line having an average distance of 2.9 m. This problem appears in fact in the sub-period 1995-2000, in which the two stations have common measurements. Unfortunately, there do not exist measurements at Kuti for the same period, so it is difficult to identify the reasons of this difference (e.g., if it was caused by the partly regulated conditions or by shift in the datum of the staff gauge of one of the stations which has been not recorded) and correct the measurements. The final series of water level in Dabarsko polje, which was used for the model, was formed by taking the average of the three daily measurements in each day.

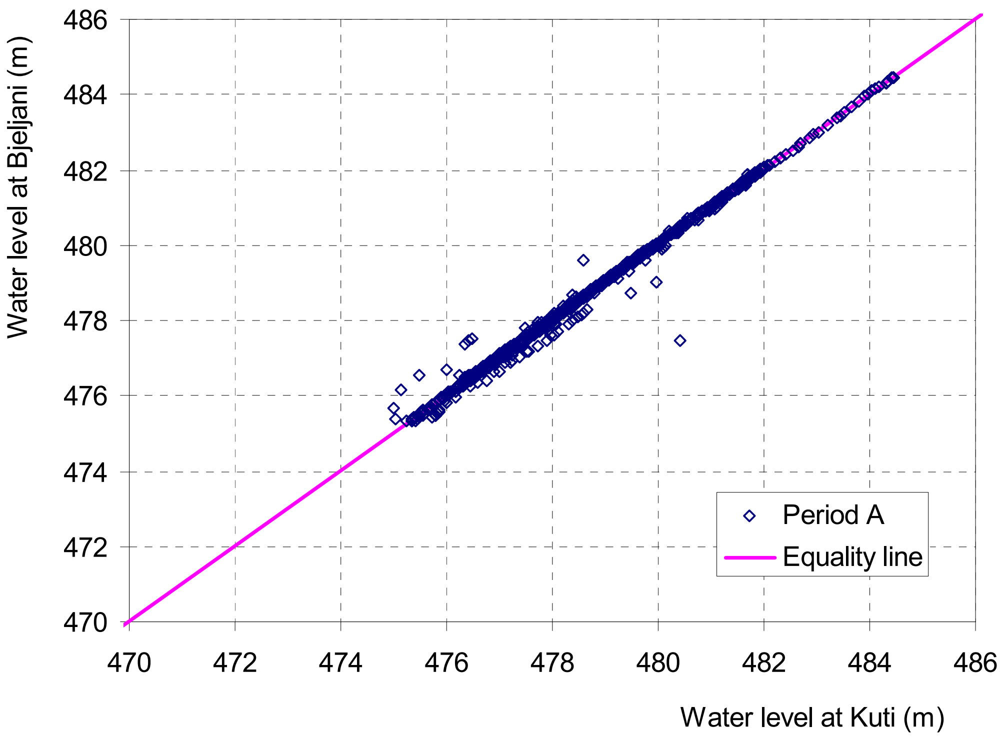


Figure 79 Comparison of simultaneous daily water level measurements at Kuti and Bjeljani in Dabarsko polje.

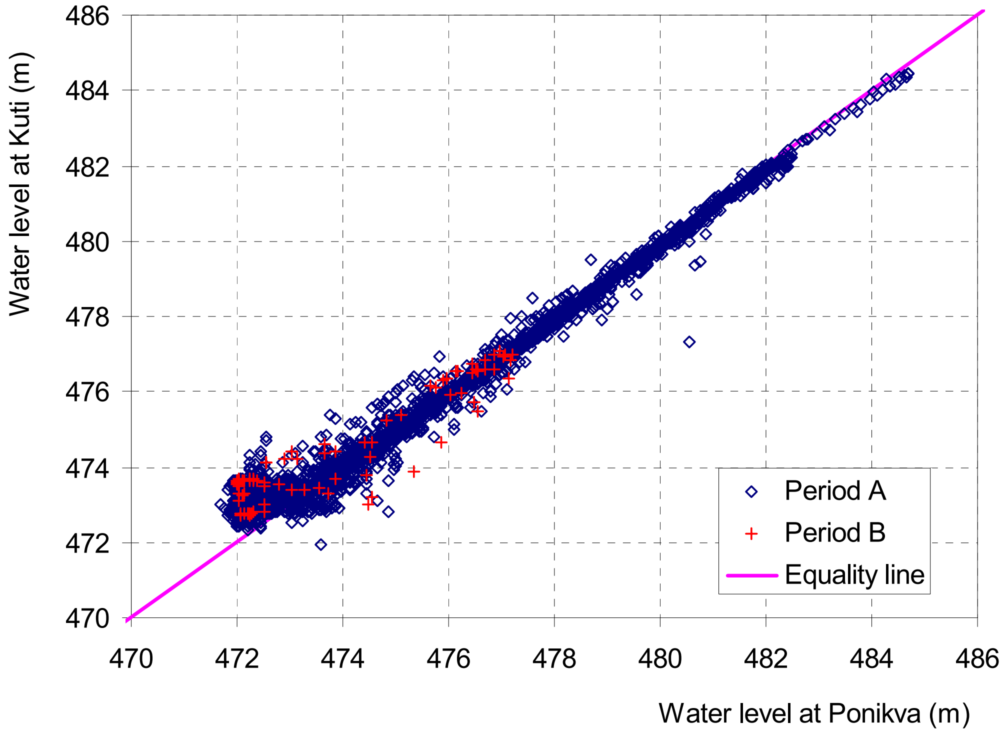


Figure 80. Comparison of simultaneous daily water level measurements at Ponikva and Kuti in Dabarsko polje.

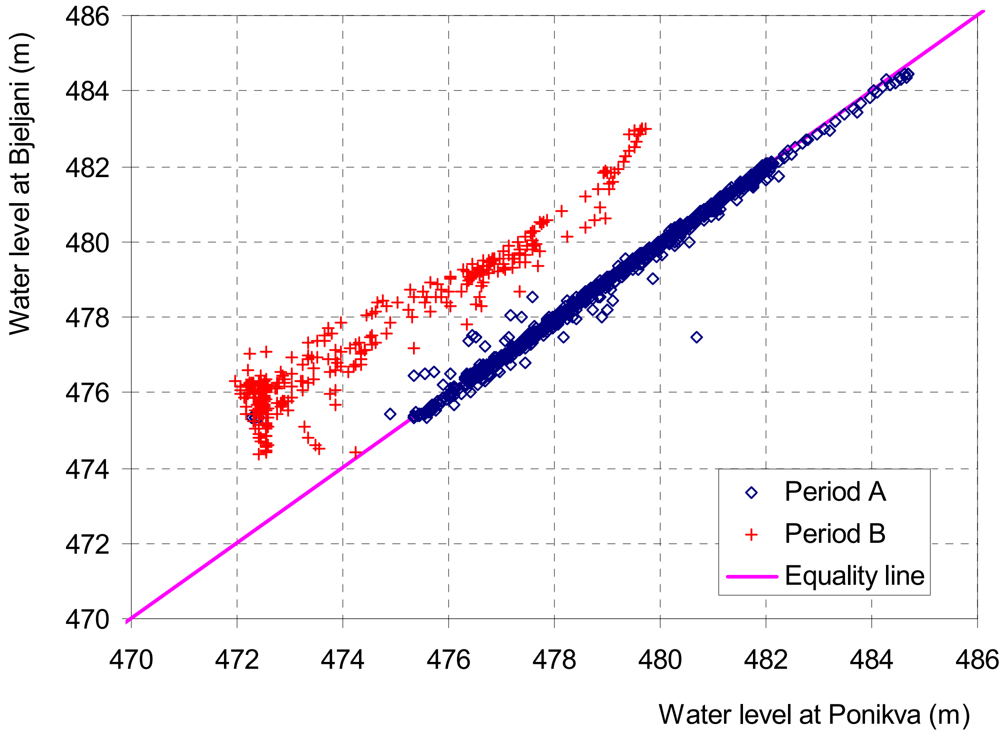


Figure 81. Comparison of simultaneous daily water level measurements at Ponikva and Bjeljani in Dabarsko polje.

For the water level of the Fatničko polje two stations were used, namely Pasmica-Padeni and Obod-Fatnica; the Obod-Preliv station was also studied but it does not have good correlations with the other stations. The two chosen stations are well correlated to each other as shown in Figure 82. A problem appears for the Pasmica-Padeni station, for which some measurements seem to be unrealistically constant, equal to 480.60 m, where at the same time the water level at Obod-Fatnica is higher and varying. Inspection of original measurements shows that this problem has been caused by a set of measurements constantly equal to 1000 cm, which are obviously erroneous; thus, they were deleted from the record. The final series of water level in Fatničko polje was formed by taking the average of the two daily measurements in each day. A comparison of the daily water levels at the two poljes for the days in which the water level in both poljes exceeds 471.50 m (this value is the minimum elevation in Dabarsko) is show in Figure 83. This figure shows a fair correlation between the two water levels (the correlation coefficient is 0.737) and simultaneously a higher dispersion of the water level in Fatničko, whose difference from the simultaneous water level in Dabarsko may reach 15 m. This indicates that there may be several ways of defining the water level in the hypothetical polje system that was considered in K Sim2 (since the two poljes do not have a common water level). The assumption chosen was to consider the water level of the hypothetical polje system equal to that of the Dabarsko polje, as this is more closely related to the discharge of Bregava at Do. The relation of the daily discharge of Bregava at Do with the daily water elevation in Dabarsko is depicted in Figure 84. The correlation coefficient is as high as 0.767, but this value is not very informative as the arrangement of points is not linear but tends to be stabilized in a saturation value for large levels at Bregava. The correlation between the daily discharge of Bregava and the daily precipitation is rather poor (correlation coefficient 0.233) as depicted in Figure 85.

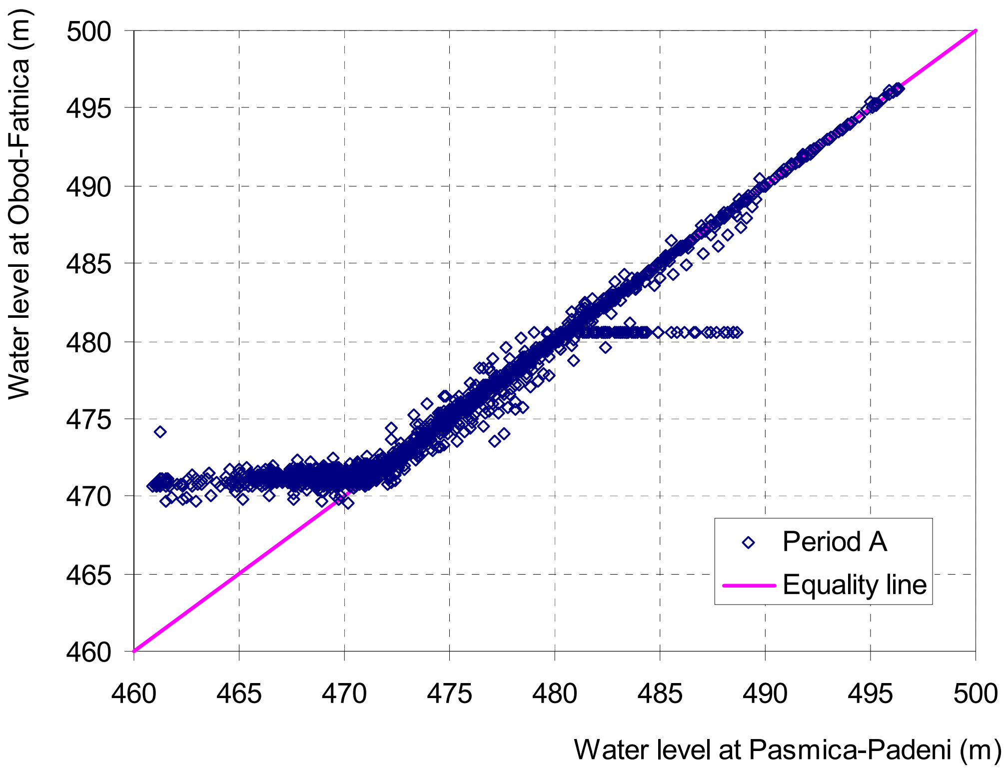


Figure 82. Comparison of simultaneous daily water level measurements at Pasmica-Padeni and Obod-Fatnica in Fatničko polje.

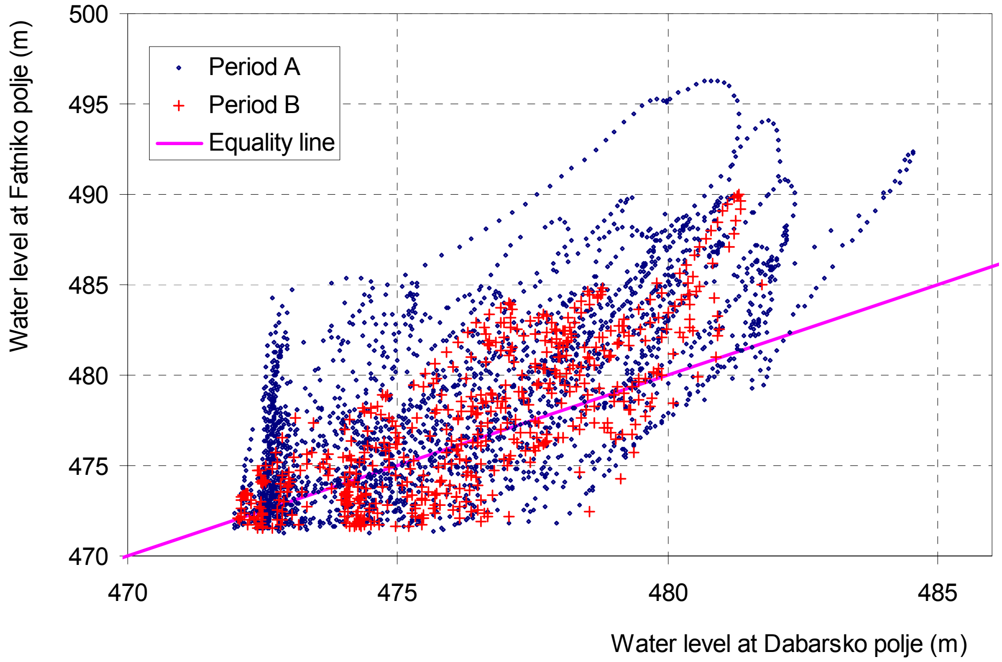


Figure 83. Daily water level in Fatničko polje vs. simultaneous water level at Dabarsko polje.

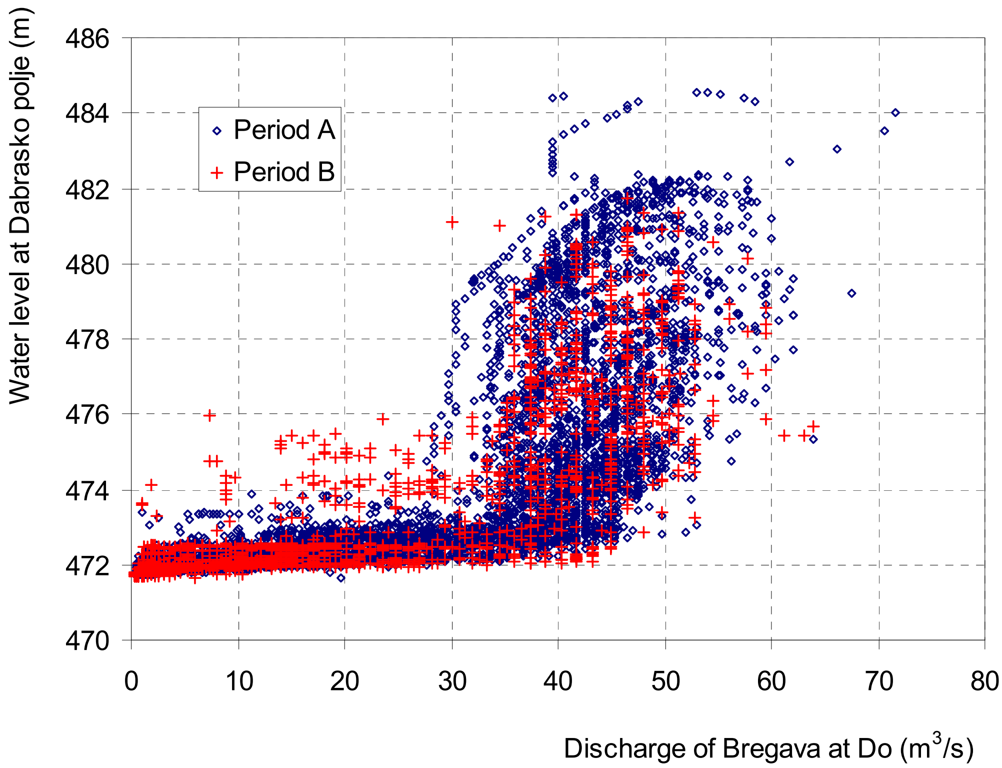


Figure 84. Daily discharge of Bregava river at Do vs. simultaneous daily water level at Dabarsko polje.

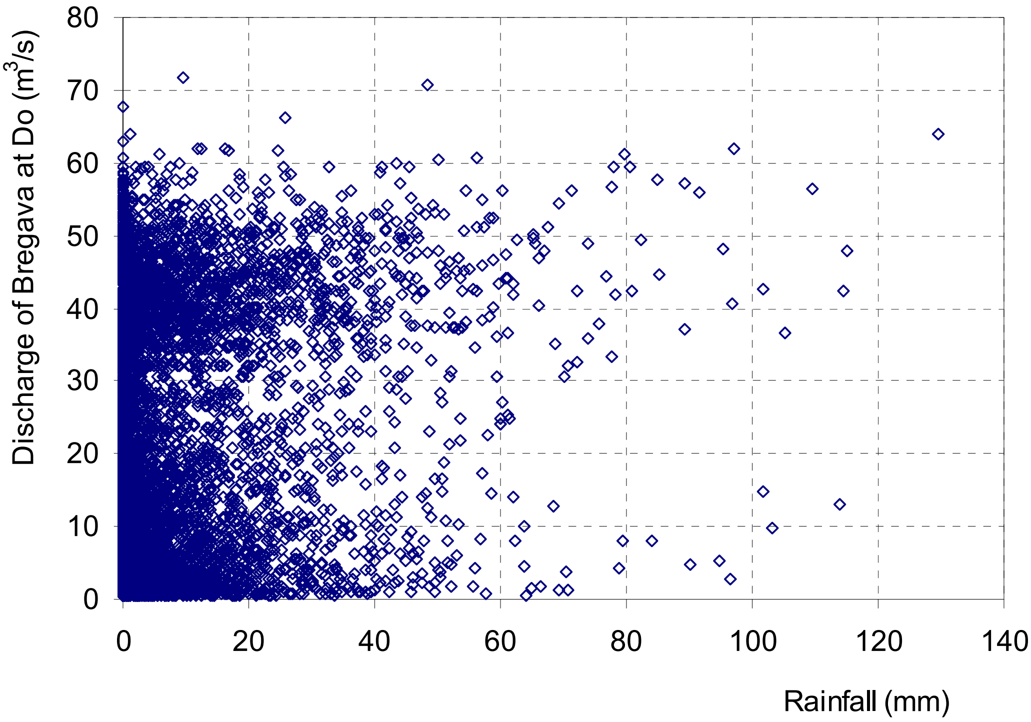


Figure 85. Daily discharge of Bregava River at Do vs. simultaneous average daily rainfall at wider area.

5.2.4. Calibration and Validation

A model calibration problem is a typical nonlinear nonconvex optimisation problem, in which the objective function to be optimised is an expression of the goodness of fit, and the control variables are the model parameters and the initial conditions. In the case studied, the objective function can be based on two observable variables, namely the discharge of Bregava at Do and the water level at the polje system (hypothesized to be represented by the water level of the Dabarsko polje).

The objective function was assumed to be the weighted sum of squares of differences between:

- the daily measured and simulated water levels of the polje system;
- the logarithms of the measured and simulated daily discharges of Bregava at Do (where the logarithmic transformation was used to give more emphasis to the low flows);
- the measured and simulated averages over the calibration period of daily discharges of Bregava at Do (included in the objective function to minimize the bias of the model);
- the measured and simulated standard deviation over the calibration period of daily discharges of Bregava at Do (included in the objective function to assure good reproduction of the duration curve of Bregava flows);

Table 8. Fitted values of K Sim^2 model parameters.

Description	Symbol	Units	Value
Impervious area with direct flow directed to the polje system	F_{2a}	km^2	68.9
Impervious area with direct flow directed to Bregava	F_{2b}	km^2	5.2
Pervious area whose spill (quick flow) is directed to the polje system	F_{4a}	km^2	184.7
Pervious area whose spill (quick flow) is directed to Bregava	F_{4b}	km^2	389.3
Pervious area whose leak (slow flow) is directed to the polje system	F_5	km^2	174.0
Pervious area whose leak (slow flow) is directed to Bregava	F_6	km^2	345.2
Soil reservoir storage capacity	K	mm	58.8
Leak coefficient of soil moisture reservoir	k	d^{-1}	0.024
Saturation discharge of polje leak directed to Bregava	p_7	m^3/s	15.9
Parameter m of the storage-leak relationship corresponding to polje outflow 7	m_7	-	0.54
Parameter n of the storage- leak relationship corresponding to polje outflow 7	n_7	hm^{-3}	0.15
Saturation discharge of polje leak directed to Trebišnjica	p_8	m^3/s	4.9
Parameter m of the storage- leak relationship corresponding to polje outflow 8	m_8	-	0.52
Parameter n of the storage- leak relationship corresponding to polje outflow 8	n_7	hm^{-3}	0.13
Saturation discharge of groundwater discharge to Bregava	p_{10}	m^3/s	49.7
Parameter m of the storage-discharge relationship corresponding to groundwater outflow 10	m_{10}	-	6.2
Parameter n of the storage- leak relationship corresponding to polje outflow 10	n_{10}	hm^{-3}	0.10

The control variables are the model parameters listed in Table 7 and the three initial values of storage components. In order for the parameters to have some physical meaning, their values are generally assumed to lie within certain limits. However, in this case no limits were imposed a priori, and the parameter values were tested *a posteriori* and found to be physically consistent.

The tools used for optimisation are a collection of powerful algorithms that have been developed and become commercially available by Frontline Systems (http://www.solver.com). These include components of classical optimisation techniques, evolutionary techniques and combinations thereof. The classical techniques implement the so called Generalized Reduced Gradient Method (GRG) (Lasdon et al., 1978, 1992), which has been proven in use over many years as one of the most robust and reliable approaches to solving difficult NLP problems. The code also includes multistart methods for global optimisation that use the GRG method on sub-problems to find locally optimal solutions. It also uses sparse matrix storage methods, advanced methods for selecting a basis and dealing with degeneracy, "crashing" methods for finding a feasible solution quickly, and other algorithmic methods adapted for large problems. Another algorithm uses an interior point nonlinear method, also known as a barrier method, which is highly effective on smooth nonlinear problems, even with many degrees of freedom. This method solves a series of barrier sub-problems. It performs one or more minimization steps on each barrier sub-problem, then decreases a barrier parameter, and repeats the process until the original problem has been solved to desired accuracy. The techniques include also a hybrid evolutionary method to solve non-smooth optimisation problems. This hybrid algorithm uses a combination of methods from genetic, evolutionary and classical methods. Genetic algorithm methods in this algorithm use four types of mutation operators, two of which are specific for permutations, and four types of crossover operators, two of which are specific for permutations. Tournament selection is used for crossover candidates, and an algorithm that assigns greater probability of elimination to the least fit members is used to update the population. Classical methods in this algorithm use a gradient-free direct search, a gradient-based quasi-Newton method, and a linearised local gradient method. Several methods are used to satisfy constraints, including both stochastic constraint repair methods and deterministic linear and nonlinear constraint solving methods. All the above algorithms have been used alternatively and in combination for the optimisation of model parameters.

The model was calibrated and verified in period A, in which the system operates in natural conditions. The period was split into two sub-periods, the calibration sub-period (1/1/1961-31/12/1980) and the verification sub-period (1/1/1981-31/10/1986).

Table 9. Indices of K Sim^2 model performance (model fit 1).

	Calibration period	Verification period	Total period A	Period B (2nd verification)
Start date	1/1/1961	1/1/1981	1/1/1961	1/11/1986
End date	31/12/1980	31/10/1986	31/10/1986	31/12/2000
Number of days	7305	2130	9435	5175
Number of months	240	70	310	170
Days with missing water level data	0	0	0	2244
Days with missing discharge data	0	0	0	1309
Months with no discharge data	0	0	0	41
Performance in terms of reproduction of daily polje level				
Historical mean	473.28	472.87	473.19	472.89
Simulated mean	473.65	473.23	473.55	472.83
Bias (%)	0.08	0.08	0.08	-0.01
Historical standard deviation	2.57	2.10	2.48	2.15
Simulated standard deviation	2.45	2.10	2.38	1.63
Difference (%)	-4.59	-0.15	-3.83	-23.93
Coefficient of correlation	0.90	0.78	0.88	0.79
Coefficient of determination	0.79	0.54	0.75	0.63
Performance in terms of reproduction of daily discharge of Bregava				
Historical mean	18.87	16.44	18.32	14.20
Simulated mean	19.11	15.67	18.33	13.13
Bias (%)	1.28	-4.71	0.07	-7.54
Historical standard deviation	17.24	16.16	17.03	15.09
Simulated standard deviation	17.50	16.04	17.24	14.10
Difference (%)	1.53	-0.72	1.25	-6.60
Coefficient of correlation	0.89	0.85	0.89	0.83
Coefficient of determination	0.79	0.71	0.77	0.70
Performance in terms of reproduction of monthly discharge of Bregava				
Historical mean	18.93	16.50	18.38	14.37
Simulated mean	19.18	15.71	18.40	13.05
Bias (%)	1.29	-4.75	0.06	-9.18
Historical standard deviation	15.13	14.25	14.95	12.80
Simulated standard deviation	16.05	14.85	15.83	12.38
Difference (%)	6.13	4.23	5.94	-3.32
Coefficient of correlation	0.93	0.89	0.92	0.89
Coefficient of determination	0.85	0.76	0.83	0.83

The obtained parameters are listed in

Table 8 and the attained performance indices are shown in Table 9. It is observed that the coefficients of determination (also known in hydrologic literature as the Nash-Sutcliffe efficiency) approach the value 0.80 for both the water level and the discharge at the daily time scale in the calibration period; this figure becomes even higher (0.85) if the discharge time series is aggregated at the monthly time scale. These values indicate a satisfactory model performance. This is further demonstrated in Figure 86, which compares historical and simulated series of both the water level in polje (up) and the discharge of Bregava River at Do (down) for one hydrological year 1964-65.)

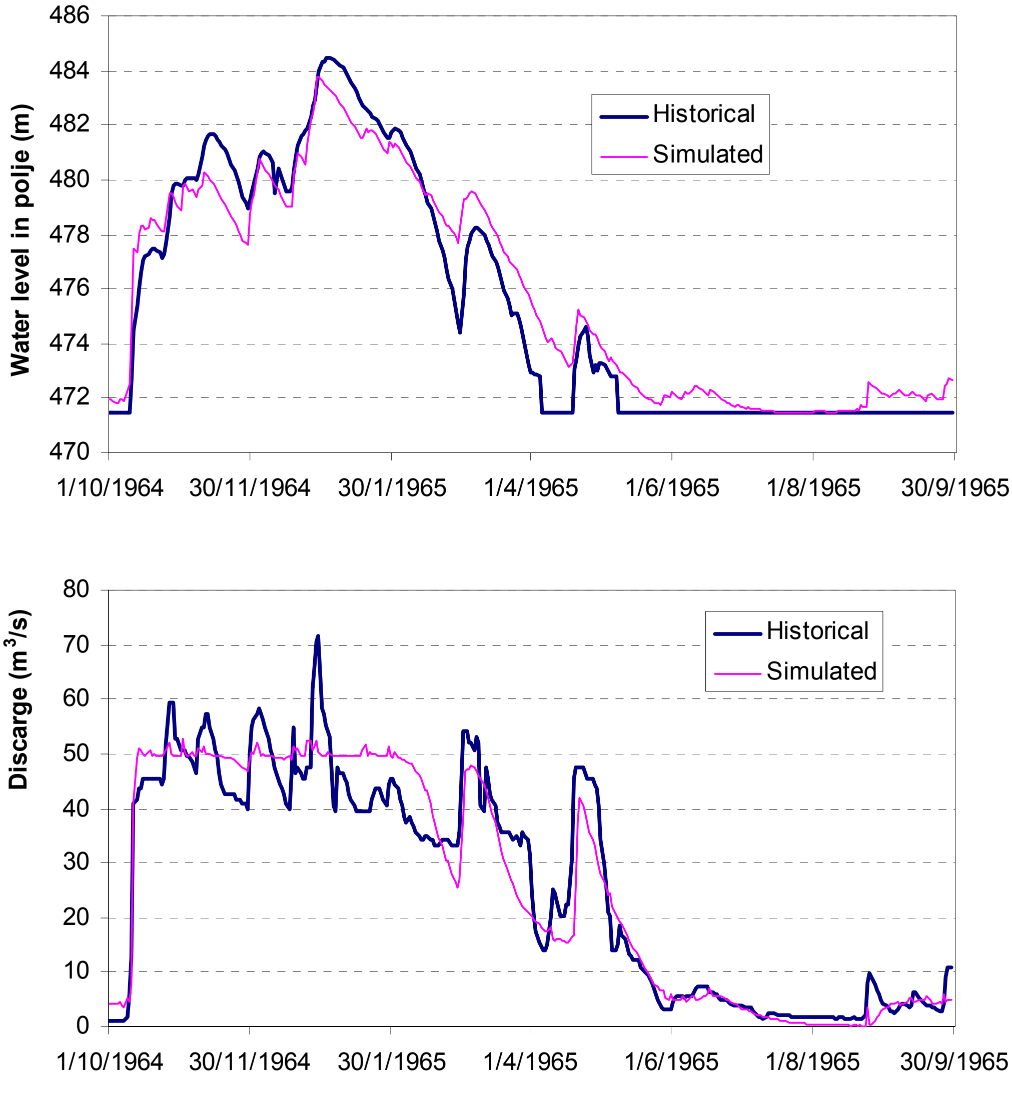
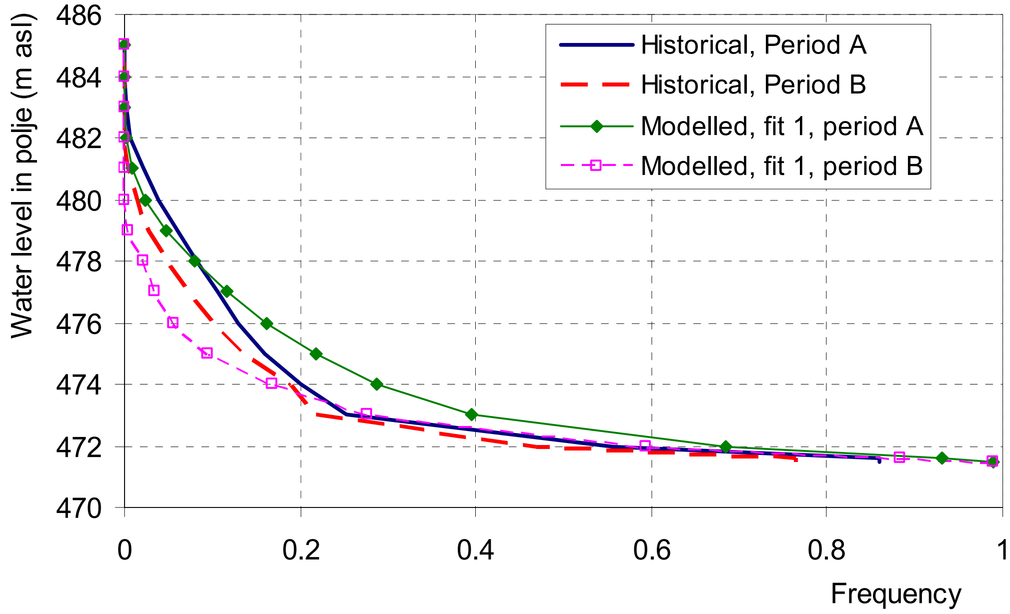


Figure 86. Comparison of historical and simulated series for hydrological year 1964-65: (up) water level in polje; (down) discharge of Bregava River at Do.

As shown in Table 9, the performance indices for the verification sub-period are lower. The performance indices for the entire period A are satisfactory (coefficients of determination 0.75 or more at the daily scale and 0.83 at the monthly scale). In period B, the model cannot describe the partly regulated conditions, as it aggregates both polje in a hypothetical one and thus the flow via the DP-FP tunnel cannot be taken into account. However, the same model with same parameter values was also applied for period B to assess whether the partly regulation condition caused significant changes in the flow regime or not. The performance indices for period B are also shown in Table 9, where it can be observed that they are comparable to those of period A. The good agreement between historical and simulated series shows that the decrease of discharges in period B is explained by the decrease of rainfall (already discussed in above), whereas regulation caused negligible effects.



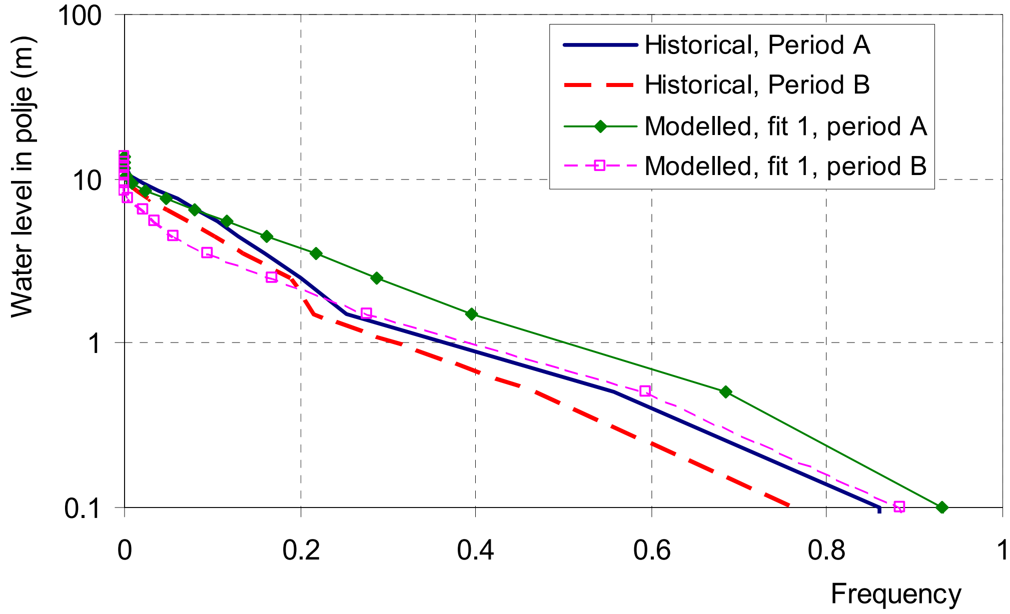
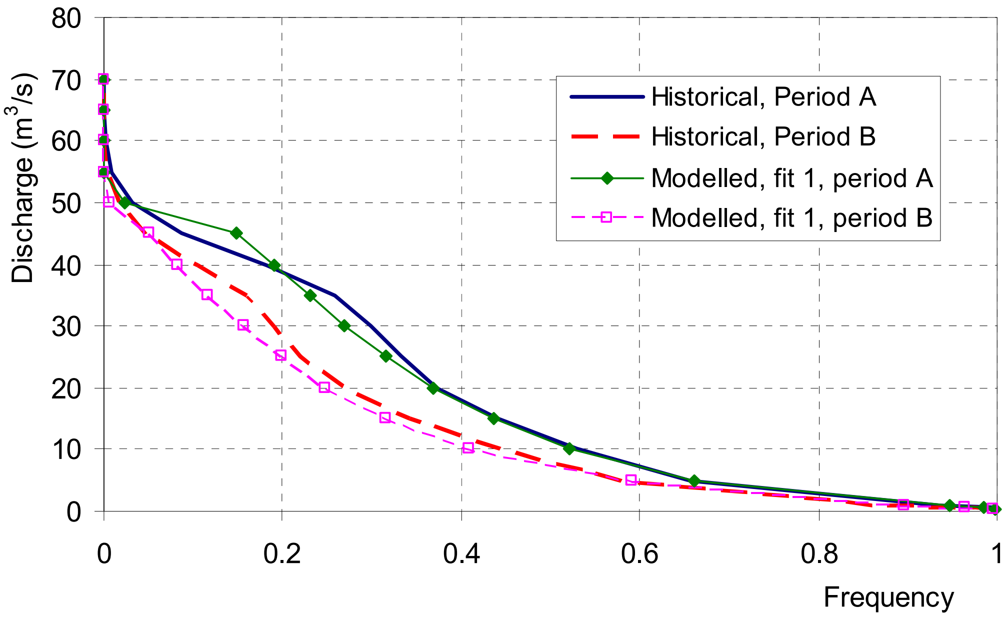


Figure 87. Comparison of historical and simulated duration curves of the daily water level at Dabarsko polje for periods A (1/1/1961-31/10/1986) and B (1/11/1986-31/12/2000): (up) Cartesian plot with water level expressed in meters above sea level; (down) semi-logarithmic plot with water level expressed in meters above a datum equal to 471.5 meters above sea level.

Additional comparison of simulated versus historical time series, in terms of duration curves for both periods A and B, are provided in Figure 87 (daily water level at Dabarsko polje), Figure 88 (daily discharge of Bregava River at Do) and Figure 89 (mean monthly discharge of Bregava River at Do). All figures show a satisfactory behaviour of the model in reproducing duration curves for both periods.



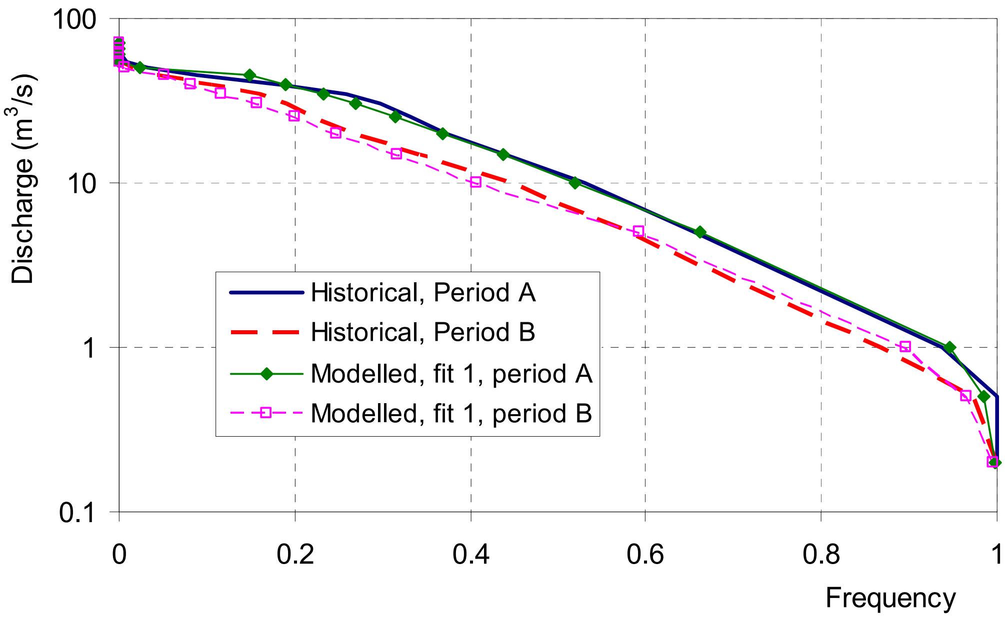


Figure 88. Comparison of historical and simulated duration curves of the daily discharge of Bregava River at Do for periods A (1/1/1961-31/10/1986) and B (1/11/1986-31/12/2000): (up) Cartesian plot; (down) semi-logarithmic plot.

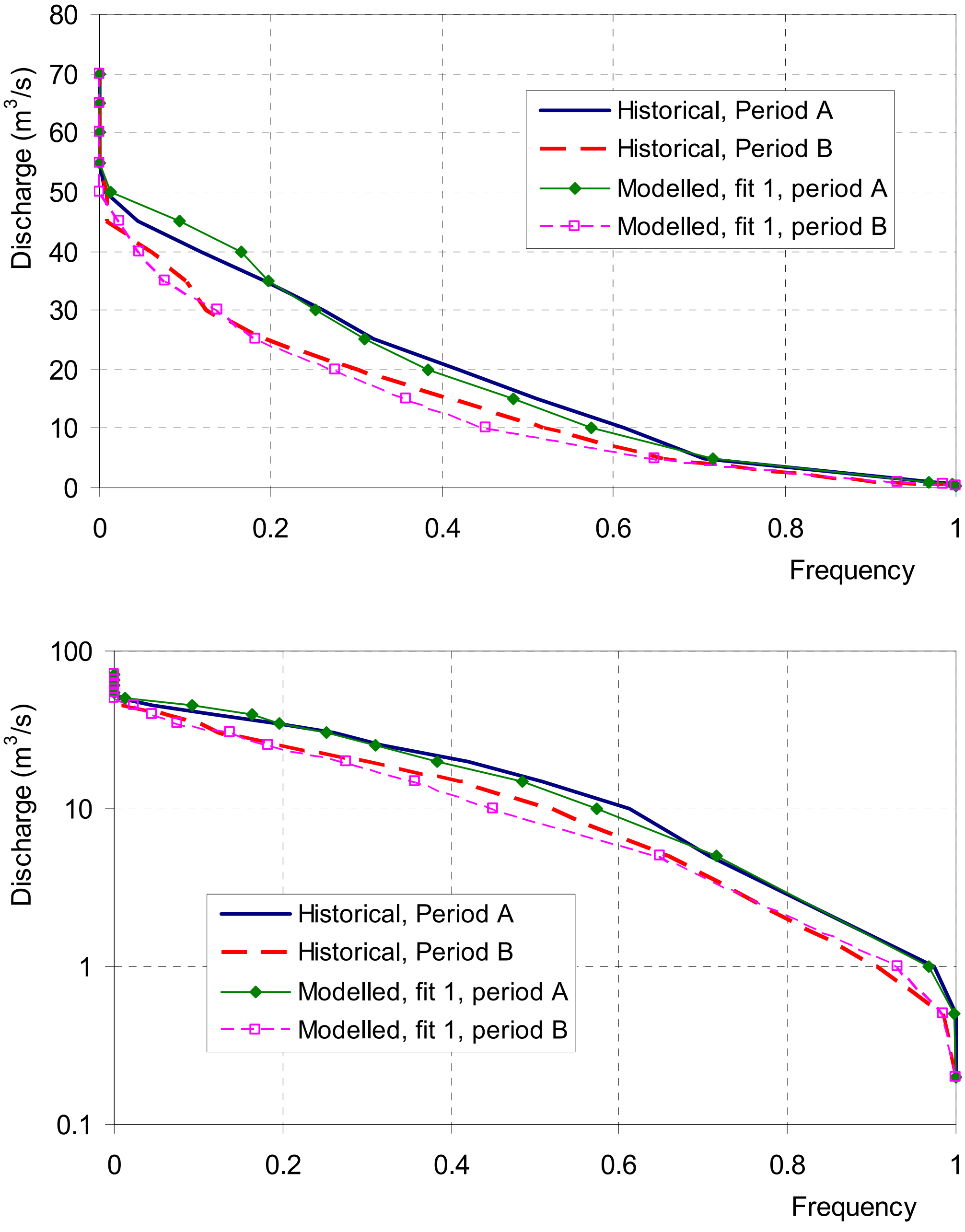


Figure 89 Comparison of historical and simulated duration curves of the mean monthly discharge of Bregava River at Do for periods A (1/1/1961-31/10/1986) and B (1/11/1986-31/12/2000): (up) Cartesian plot; (down) semi-logarithmic plot.

5.2.5. Scenarios and uncertainty analysis

The K Sim^2 model, in addition to the output time series that were discussed in the previous subsection, can break down the total water balance of each hydrosystem component into separate portions related to the origin of water amounts. As far as the discharge of Bregava is concerned, the most important indicator of the impact of the future polje regulation is the percent of total water discharged at Bregava that originates from polje under natural conditions (Flux from poljes (7)). The higher this percentage is the higher the impacts. This however has significant uncertainty, related to the uncertainty of parameters. To demonstrate this uncertainty, two additional different scenarios were constructed by performing alternative model fits on the basis of local minima of the objective function. The performance indices of the additional model fits are shown in Table 10 (model fit 2) and Table 11 (model fit 3). The resulting breakdown of the water balance by origin of water discharged at Do during period A for the three scenarios (model fits) is depicted in Figure 90.

Table 10. Performance indices for K Sim^2 model fit 2.

	Calibration period	**Verification period**	**Total period A**	**Period B (2nd verification)**
Start date	1/1/1961	1/1/1981	1/1/1961	1/11/1986
End date	31/12/1980	31/10/1986	31/10/1986	31/12/2000
Number of days	7305	2130	9435	5175
Number of months	240	70	310	170
Days with missing water level data	0	0	0	2244
Days with missing discharge data	0	0	0	1309
Months with no discharge data	0	0	0	41
Performance in terms of reproduction of daily polje level				
Historical mean	473.28	472.87	473.19	472.89
Simulated mean	473.52	473.11	473.43	472.76
Bias (%)	0.05	0.05	0.05	-0.03
Historical standard deviation	2.57	2.10	2.48	2.15
Simulated standard deviation	2.40	2.01	2.32	1.61
Difference (%)	-6.65	-4.29	-6.23	-25.24
Coefficient of correlation	0.90	0.74	0.87	0.79
Coefficient of determination	0.80	0.49	0.75	0.62
Performance in terms of reproduction of daily discharge of Bregava				
Historical mean	18.87	16.44	18.32	14.20
Simulated mean	17.63	14.39	16.90	12.40
Bias (%)	-6.54	-12.47	-7.75	-12.68
Historical standard deviation	17.24	16.16	17.03	15.09
Simulated standard deviation	16.12	14.47	15.82	12.83
Difference (%)	-6.46	-10.43	-7.08	-14.99
Coefficient of correlation	0.89	0.86	0.88	0.83
Coefficient of determination	0.79	0.71	0.77	0.71
Performance in terms of reproduction of monthly discharge of Bregava				
Historical mean	18.93	16.50	18.38	14.37
Simulated mean	17.69	14.44	16.96	12.34
Bias (%)	-6.57	-12.49	-7.77	-14.13
Historical standard deviation	15.13	14.25	14.95	12.80
Simulated standard deviation	14.51	13.03	14.23	11.08
Difference (%)	-4.12	-8.53	-4.78	-13.48
Coefficient of correlation	0.92	0.89	0.92	0.90
Coefficient of determination	0.84	0.77	0.83	0.83

Table 11. Performance indices for K Sim^2 model fit 3.

	Calibration period	Verification period	Total period A	Period B (2nd verification)
Start date	1/1/1961	1/1/1981	1/1/1961	1/11/1986
End date	31/12/1980	31/10/1986	31/10/1986	31/12/2000
Number of days	7305	2130	9435	5175
Number of months	240	70	310	170
Days with missing water level data	0	0	0	2244
Days with missing discharge data	0	0	0	1309
Months with no discharge data	0	0	0	41
Performance in terms of reproduction of daily polje level				
Historical mean	473.28	472.87	473.19	472.89
Simulated mean	472.70	472.48	472.65	472.35
Bias (%)	-0.12	-0.08	-0.11	-0.12
Historical standard deviation	2.57	2.10	2.48	2.15
Simulated standard deviation	1.51	1.35	1.47	1.19
Difference (%)	-41.36	-36.00	-40.48	-44.60
Coefficient of correlation	0.72	0.56	0.70	0.70
Coefficient of determination	0.45	0.28	0.43	0.41
Performance in terms of reproduction of daily discharge of Bregava				
Historical mean	18.87	16.44	18.32	14.20
Simulated mean	16.55	13.49	15.86	12.02
Bias (%)	-12.27	-17.99	-13.43	-15.36
Historical standard deviation	17.24	16.16	17.03	15.09
Simulated standard deviation	15.26	13.33	14.90	12.02
Difference (%)	-11.45	-17.53	-12.49	-20.35
Coefficient of correlation	0.85	0.82	0.84	0.80
Coefficient of determination	0.70	0.64	0.69	0.67
Performance in terms of reproduction of monthly discharge of Bregava				
Historical mean	18.93	16.50	18.38	14.37
Simulated mean	16.60	13.51	15.90	12.04
Bias (%)	-12.32	-18.13	-13.49	-16.27
Historical standard deviation	15.13	14.25	14.95	12.80
Simulated standard deviation	13.57	11.63	13.20	10.29
Difference (%)	-10.32	-18.34	-11.67	-19.61
Coefficient of correlation	0.89	0.87	0.89	0.89
Coefficient of determination	0.77	0.70	0.76	0.81

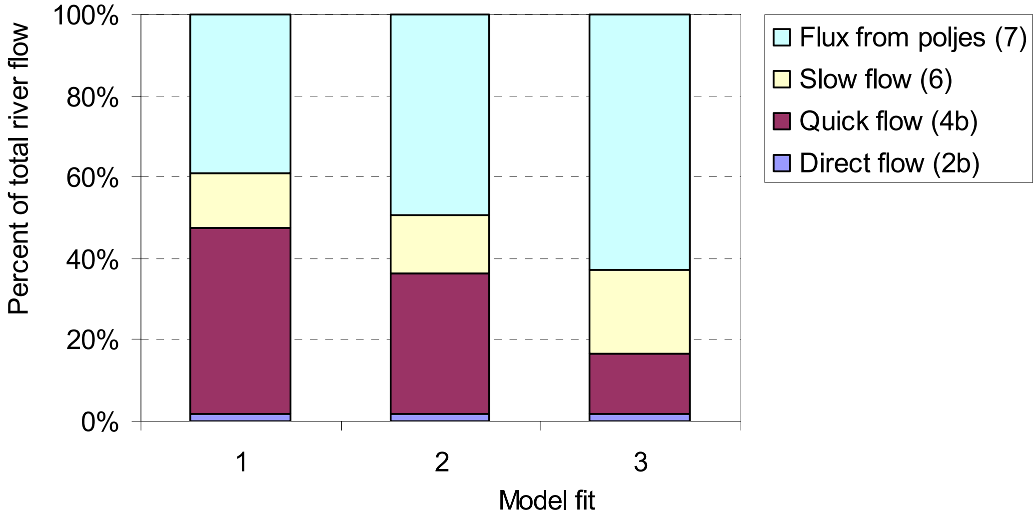


Figure 90. Breakdown of the water balance by origin of water discharged at Bregava River at Do during period A (1/1/1961-31/10/1986) as predicted by the three alternative model fits.

5.2.6. Results

The three scenarios (model fits) were eventually applied to assess the impacts of future regulated conditions. In this case, tunnel 12 was activated and kept open unless the water level in the polje system is 472 m or less. The results are shown in graphical form in terms of duration curves under regulated conditions, in comparison with historical and modelled duration curves under natural conditions. The comparisons have been done using the data of period A and are shown in Figure 91 (daily water level at the polje system), Figure 92 (daily discharge of Bregava River at Do) and Figure 93 (mean monthly discharge of Bregava River at Do).

The results show a small impact of regulation at low flows, which becomes higher for intermediate and high flows. The slight decrease of low flows must be attributed to the general loss of water from the groundwater storage component after the completion of the project and implementation of regulation. Besides, it is observed that the magnitude of the highest flows does not change, but the highest flows become less frequent. This is explained by the form of the storage-discharge curve adopted, which is characterized by a saturation value. Thus, even though the storage will be in general lower after regulation, some periods of time it will be high enough so that the spring discharge will tend to reach the saturation value.

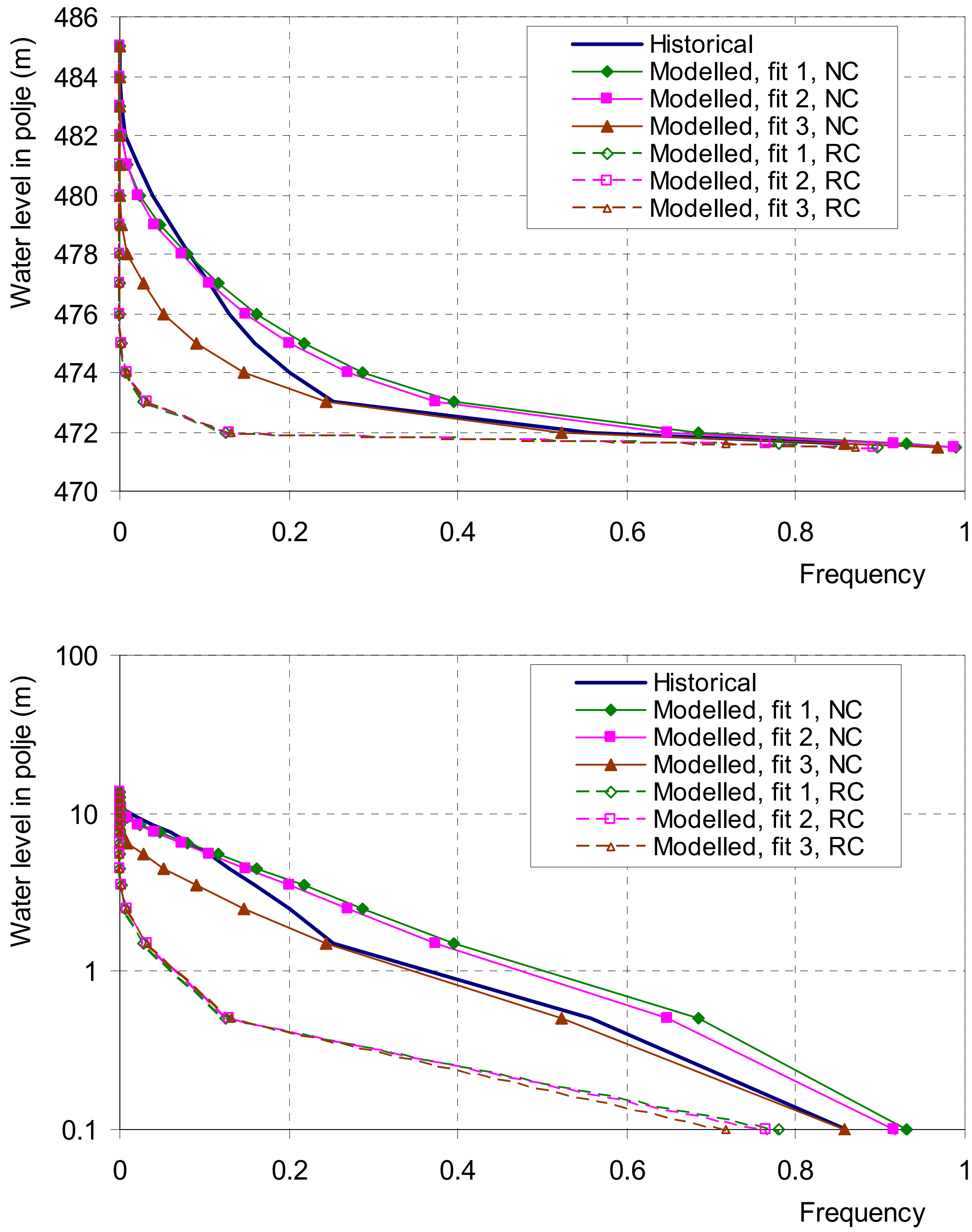
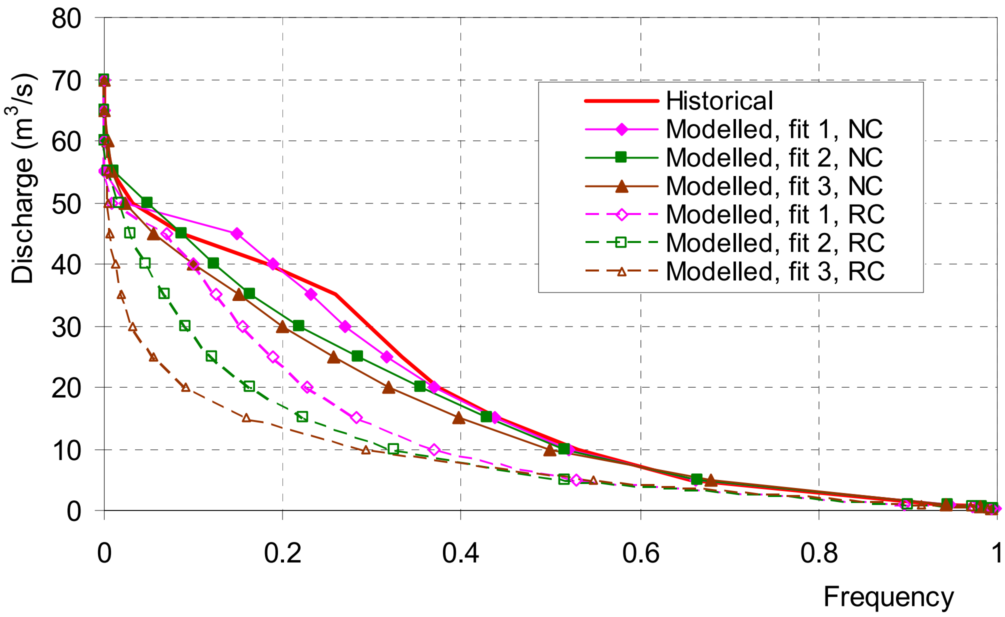


Figure 91. Estimated duration curves of the daily water level at Dabarsko polje under regulated conditions (RC), in comparison with historical and modelled duration curves under natural conditions (NC) (data for period A; 1/1/1961-31/10/1986): (up) Cartesian plot with water level expressed in meters asl; (down) semi-logarithmic plot with water level expressed in meters above a datum equal to 471.5 meters asl.



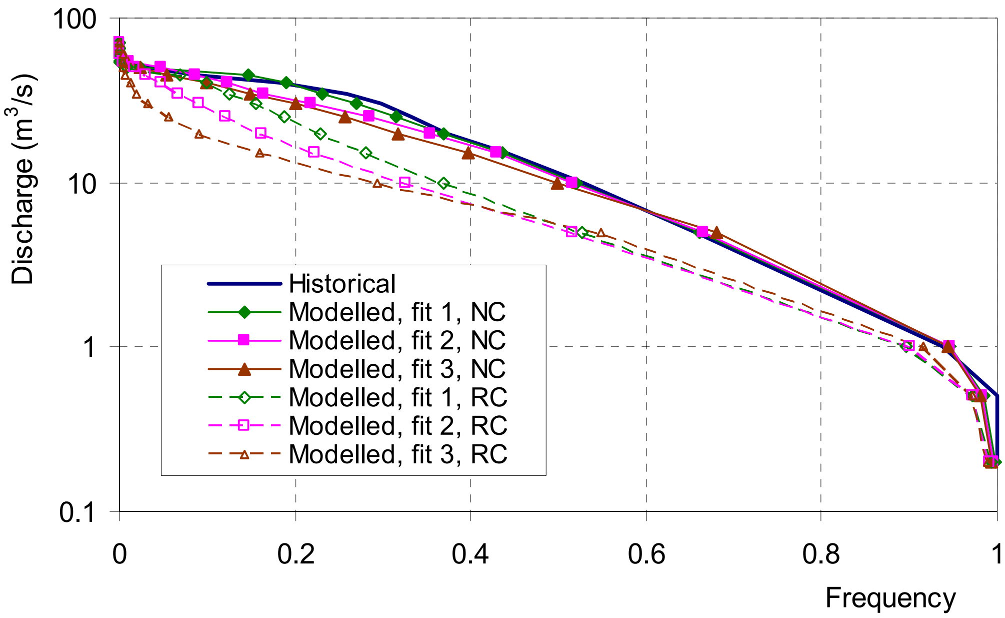
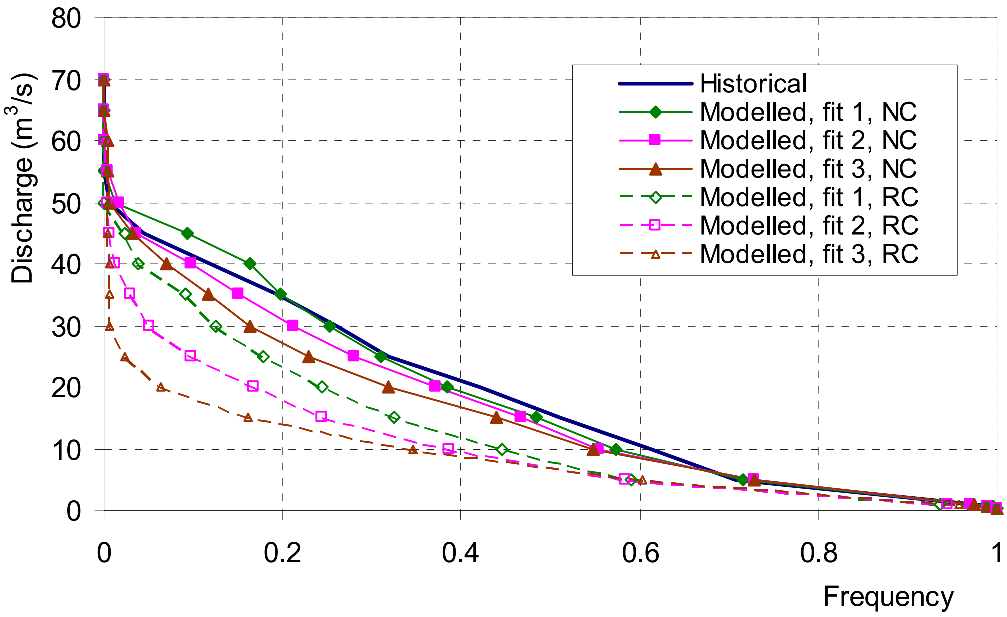


Figure 92. Estimated duration curves of the daily discharge of Bregava River at Do under regulated conditions (RC), in comparison with historical and modelled duration curves under natural conditions (NC) (data for period A; 1/1/1961-31/10/1986): (up) Cartesian plot; (down) semi-logarithmic plot.



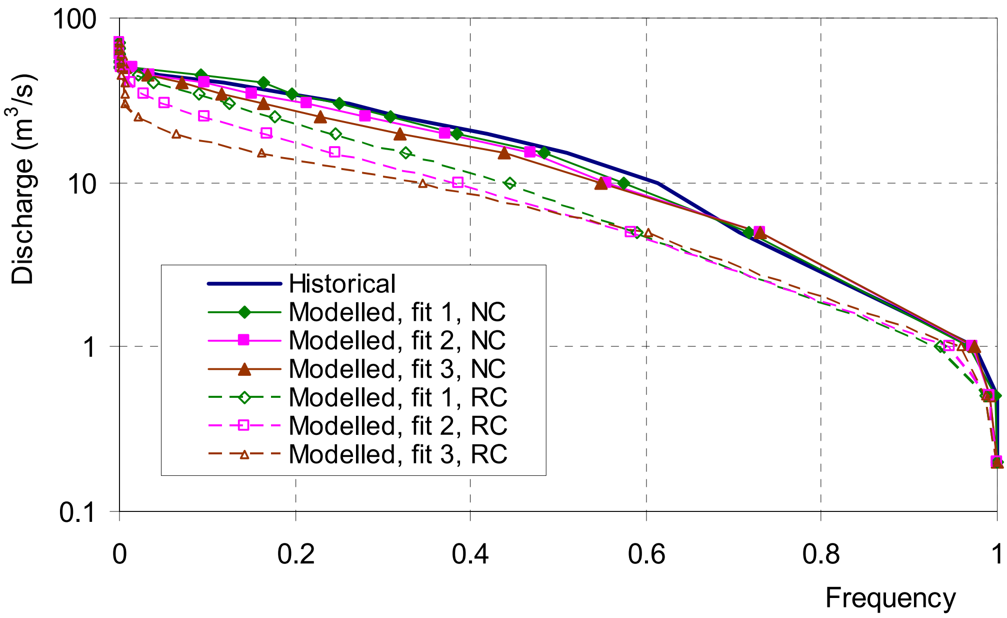


Figure 93. Estimated duration curves of the mean monthly discharge of Bregava River at Do under regulated conditions (RC), in comparison with historical and modelled duration curves under natural conditions (NC) (data for period A; 1/1/1961-31/10/1986): (up) Cartesian plot; (down) semi-logarithmic plot.

5.2.7. Discussion

In general, the fitting of the K Sim^2 model in historical conditions is satisfactory and the results obtained for future regulated conditions seem to be reasonable.

The results show a small impact of regulation at low flows, which becomes higher for intermediate and high flows. The slight decrease of low flows must be attributed to the general loss of water from the groundwater storage component after the completion of the project and implementation of regulation. The intermediate and high flows are more significantly altered because of the amounts of water that will be directed to the Trebišnjica River rather than to Bregava.

However, several sources of uncertainty exist, which are related, among others, to data problems and model simplification and imperfection, as discussed above. In an attempt to improve the model in the future, the following points should be considered:

- The model structure could become more detailed, e.g. modelling separately the two poljes rather than aggregating them into a polje system.
- Snowfall should be taken into account, also incorporating into the model a snow accumulation/melt component.
- All data series need to be more carefully examined and processed. Particularly, the inconsistency of water level measurements of stations Ponikva-Bjeljani in the period 1995-2000 should be resolved.

The most reliable test of the model results can be performed only after the completion of the project and implementation of the management rules in the future.

The management rules should themselves be reassessed in the future, after collection of sufficient data in the new conditions. Obviously, the system operation should not be regarded as a rigid practice but rather as a flexible set of options that can be adapted (in a control-optimisation framework) to take account of the new information gathered, as well as to harmonize to the changing human and environmental needs.

5.3. Physically-Based Modelling

5.3.1. Introduction

In this physically-based approach water balance in the horizontal plane is modelled as a system of links and reservoirs. Two models were developed at two distinct scales:

- A simple model based on quasy-steady state hydraulic simulation treating the problem as a system of reservoirs
- A detailed model based on full-dynamic simulation of flow in the network.

Flow in the unsaturated zone that is primarily vertical is modelled separately with the UNSAT model. Results of the unsaturated zone simulation were used as **input hydrograph** in both models mentioned above.

5.3.2. Description of models

A. UNSAT - Model for simulating vertical water movement and leakage from the unsaturated zone

To model water movement in the aquitard, a series of tests showed that the solution of the Richards equation is very fast compared to other parts of the system. Since Richards' equation treats soil water movement more rigorously than standard two-reservoir models, this approach was adopted for implementation in the physically based model. A brief description of the soil water movement model is presented next:

Net precipitation is calculated as

$$P_{eff} = P(1.-C_{sr}) - P_{int}$$

where P is precipitation, C_{sr} is the surface runoff coefficient and P_{int} is the interception + lateral flow.

Vertical water balance in soil is modelled using Richards' equation:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}(k(h)(\frac{\partial h}{\partial z} - 1))$$

where: h = capillary potential of the soil (cm), k = filtration coefficient as a function of soil moisture content or capillary potential (cm/day), z = vertical coordinate oriented downwards (cm), t = time (day) and C = soil water capacity = $C(h) = d\theta/dh$ (day^{-1}).

To solve the basic partial differential equation which describes the soil water movement in unsaturated conditions, it is necessary to define the soil characteristics (soil moisture curve: $\theta(h)$ and filtration coefficient as a function of moisture content $k(\theta)$). Figure 94 shows a typical shape of these curves for the topsoil.

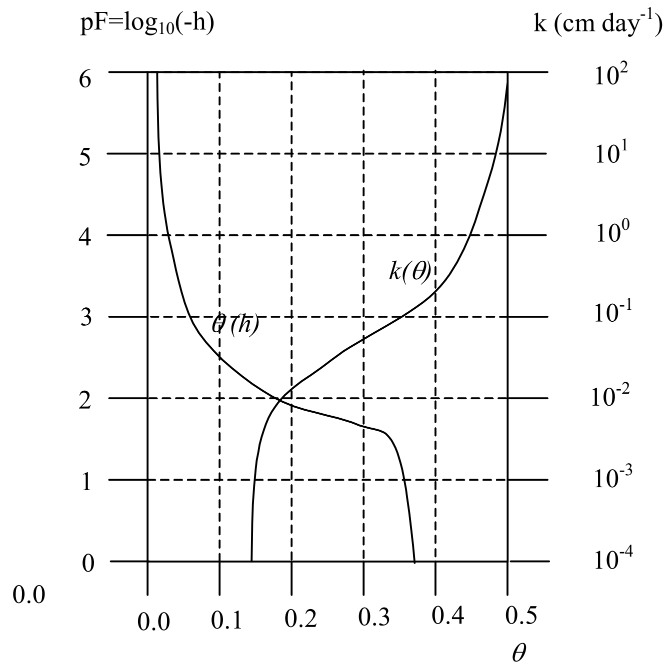


Figure 94. Typical shape of soil characteristics

These curves can be approximated using the following equations: (Van Genuchten; 1980)

$$S_e = \left(1 + (\alpha\,|\,h\,|)^n\right)^{-m} \quad h < 0\,,$$

$$S_e = 1 \quad h > 0\,,$$

$$\frac{k}{K_s} = S_e^{\,1/2}\left[1 - \left(1 - S_e^{\,1/m}\right)^m\right]^2,$$

where α,.and n are soil parameters and m=1-1/n.
In both equations, k is the hydraulic conductivity of the unsaturated soil, K_s is the hydraulic conductivity of the saturated soil and S_e is the relative saturation:

$$S_e = \frac{\theta - \theta_r}{\theta_{\max} - \theta_r}\,,$$

where θ_r is the residual water content and θ_{max} is maximum water content, approximately equal to porosity.

Richards' equation is solved for a series of vertical columns of soil. For each column the following is defined: initial conditions, boundary conditions, soil parameters and computational grid, as shown schematically in Figure 95.

Boundary conditions are defined in the form of flux $q_I(t)$ for the upper boundary (soil surface) and free drainage for the bottom boundary condition. Potential flux on the upper boundary (q^*_I(t)) is calculated, as the difference between precipitation and potential evaporation and it can be either positive or negative. The flux that is calculated in this way is only a potential value that depends on atmospheric conditions. Actual flux through the upper boundary depends on the soil conditions, that is, the ability of a soil to allow infiltration or to release a specified amount of water. In the case of excess rainfall only a part of the precipitation infiltrates and the rest creates runoff. Similarly, evaporation losses are limited by the ability of the soil to transport water from deeper soil layers. This shows that the upper boundary conditions are not known in advance and have to be determined during simulation.

Soil potential (h_Γ) on the upper boundary has to be limited. When rainfall intensity is higher than infiltration capacity of the soil, soil potential is limited to the maximum depth of the water layer that could be created above the soil surface (h_p). In the case of a negative value of potential flux (evaporation is dominant factor) the lower limit of soil potential (h_l) is calculated from the assumption of thermodynamic balance between soil and atmosphere.

The following equations describe the upper boundary condition:

$$\| q^{*}{}_{\Gamma} | \leq | q_{\Gamma} | = | -k(h)(\frac{\partial h}{\partial z} - 1) |$$

$$h_l \leq h \leq h_p$$

$$h_l = \frac{RT}{Mg} \ln(\frac{RH}{100})$$

where R – universal gas constant $Jmol^{-1}K^{-1}$, T – air temperature [K], M – molecular weight of water [kg mol^{-1}] and RH - relative moisture (%).

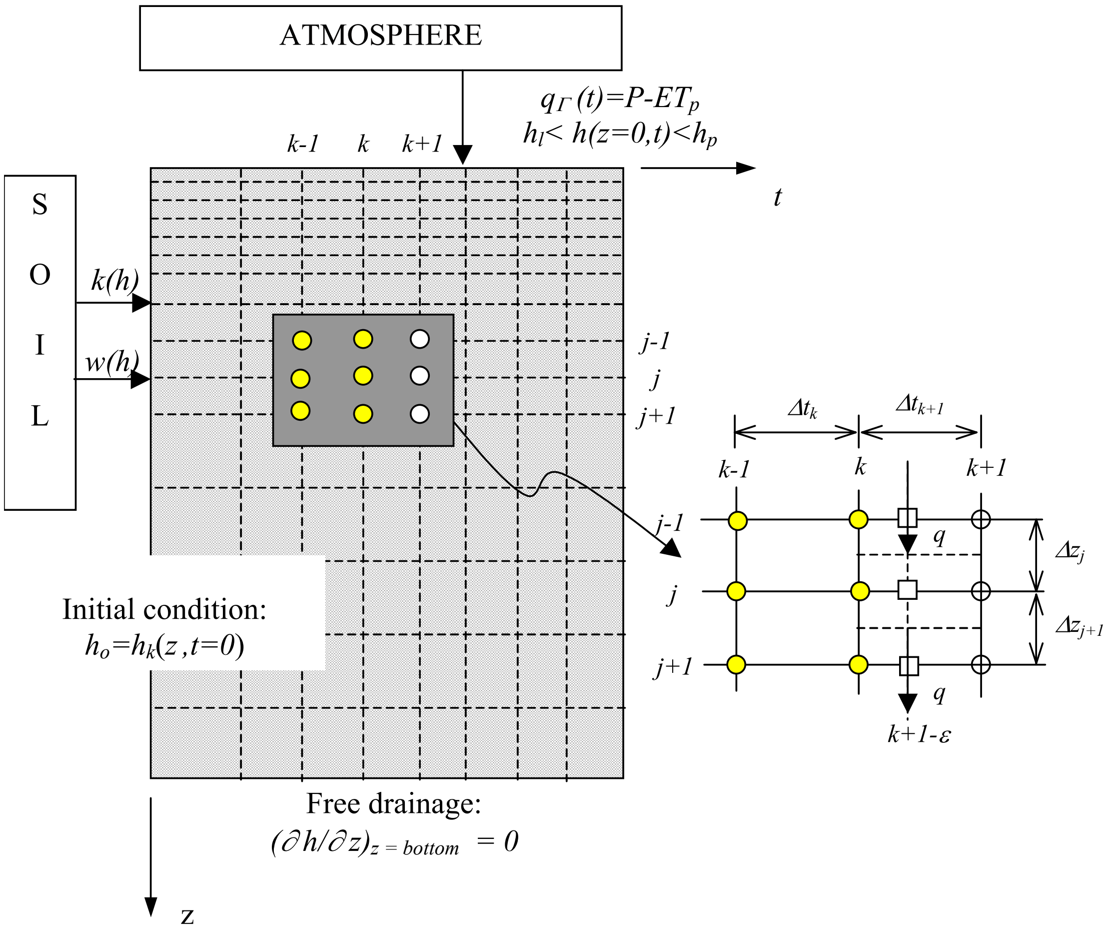


Figure 95. Scheme of computational grid and the data necessary for solving Richards' equation

$$C_j^{k+1-\varepsilon}\frac{h_j^{k+1}-h_j^k}{\Delta t_k}+\frac{2(q_{j+1/2}^{k+1-\varepsilon}-q_{j-1/2}^{k+1-\varepsilon})}{\Delta z_{j-1}+\Delta z_j}+\alpha_j^{k+1-\varepsilon}S_{\max}^{k+1-\varepsilon}=0$$

Flux (q) in the discretised form of the basic equation, which can be written as follows:

$$q_{j-1/2}^{k+1-\varepsilon}=-k_{j-1/2}^{k+1-\varepsilon}\left(\frac{(1-e)\cdot h_j^{k+1}+e\cdot h_j^k-(1-e)\cdot h_{j-1}^{k+1}-e\cdot h_{j-1}^k-\Delta z_{j-1}}{\Delta z_{j-1}}\right)$$

$$q_{j+1/2}^{k+1-\varepsilon}=-k_{j+1/2}^{k+1-\varepsilon}\left(\frac{(1-e)\cdot h_{j+1}^{k+1}+e\cdot h_{j+1}^k-(1-e)\cdot h_j^{k+1}-e\cdot h_j^k-\Delta z_j}{\Delta z_j}\right)$$

where e is the weighting parameter which defines the position of the flux approximation in the time interval (k, k+1).

The result of the discretisation is a set of linear algebraic equations of tri-diagonal form, with unknown capillary potential (h^{k+1}) for the next simulation step (k+1). A final result for each soil column is the drainage from the soil to ground water.

B. Simple physically based model for simulating unsteady water movement in the horizontal plane

The simplified physically-based model is made up of nodes (reservoirs and channel junctions) and links (pipes, channels, weirs or orifices) that are connecting the nodes. The graph that is made from the set of nodes and connections is non-oriented, which means that the flow can be in both directions (positive and negative).

Each node can have its own catchment area, and therefore its own inflow as a result of leakage from the unsaturated zone.

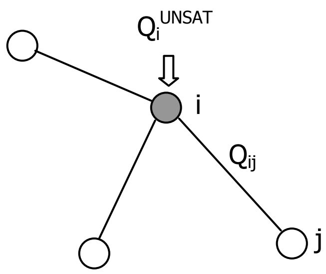


Figure 96. Scheme of node "i" connected with neighbour nodes and inflow and outflows from that node

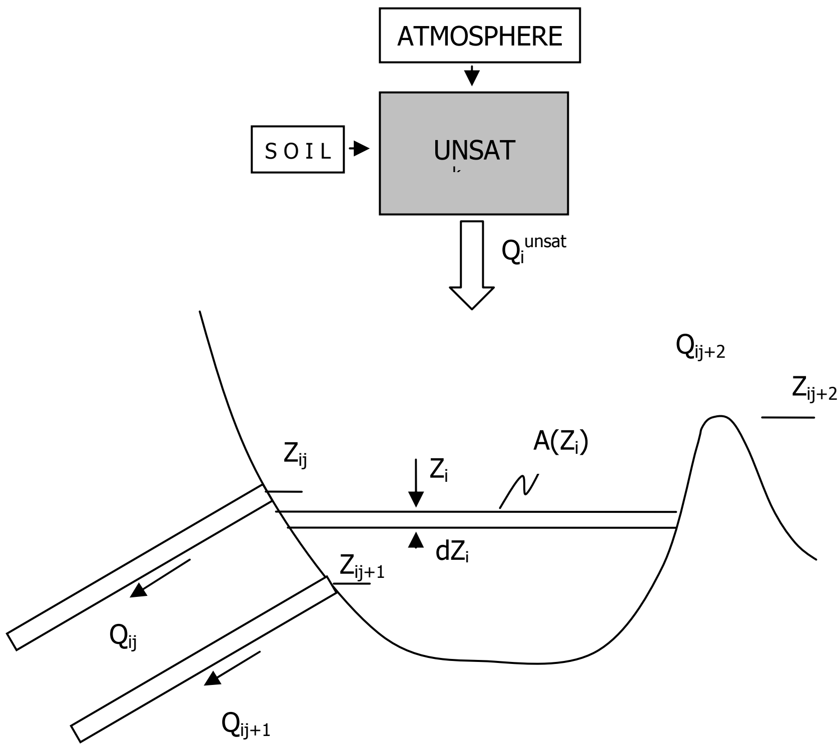


Figure 97. Scheme of reservoir "i" and water balance for that node

The basic equation describing the water balance for reservoir "i" is:

$$\frac{dZ_i}{dt} = \frac{Q_i^{UNSAT} - \sum_j Q_{ij}}{A(Z_i)}$$

$$Q_{ij} = K_{ij} \Delta H_{ij}^{x} \frac{\Delta H_{ij}}{\left|\Delta H_{ij}\right|}$$

where Z_i is water level in node i, $A(Z_i)$ is the cross-sectional area, K_{ij} is the discharge coefficient for ij connection (generally depends on connection type and water level in both nodes i and j), and x is a coefficient that depends on the connection type (e.g. x=3/2 for a weir).

A set of ordinary differential equations is solved simultaneously for the whole network. The number of equations is the same as the number of nodes in a graph.

The results of the simulation are water levels for each node ($Z_i(t)$) and discharges for each connection ($Q_{ij}(t)$).

C. Detailed model (SIPSON)

The SIPSON simulation model is an integral part of the 3DNet software. It is the acronym for Simulation of Interaction between Pipe flow and Surface Overland flow in Networks.

Simultaneously for all network elements, SIPSON solves four groups of equations:

1. The continuity equations for nodes (channel joints and reservoirs).

$$F\frac{dZ}{dt} = q + \sum_{m=1}^{M} \pm Q_m \quad \textbf{Equation 3}$$

where F = node horizontal area, Z = water level at the node, q = external inflow to the node, M = number of links joining the node and Q_m = discharges flowing from the link to the node or v.v..

2. The full dynamic-wave (St.Venant) equations of flow in channels and pipes.

$$\frac{\partial z}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} = 0 \quad \textbf{Equation 4}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \quad \textbf{Equation 5}$$

where z = cross-sectional water level, B = water table width, Q = discharge, A = cross-sectional area, g = gravitational constant and S_f = friction slope.

3. The energy conservation equations for nodes and channel ends (where applicable, as for free outflow conditions the alternative to energy equation is critical or normal depth criterion, depending on the flow regime).

$$z + \frac{v^2}{2g} = Z \pm K\frac{v\,|\,v\,|}{2g} \quad \textbf{Equation 6}$$

where v = cross-sectional average velocity and K = local energy loss coefficient (velocity head at a node has been neglected here, which can be justified in most cases).

4. Equations of flow through structures (weirs, orifices, inlets).

The algorithm for solving all these equations for one time step can be summarized as follows:

1. The St. Venant equations are discretised using the Preissmann four point implicit finite difference method.
2. Systems of difference equations for single channels are reduced to equivalent two-equation sets in which, after linearization, the discharges at channel ends are expressed in terms of water levels at those ends.
3. By applying energy equations and/or free-outflow criteria, discharges at channel ends are expressed in terms of water levels at network nodes.

4. Those relations, plus the relationships for other types of links (weirs and orifices) that can be written in the same form, plus surface runoff hydrographs, plus dry weather flows, are replaced in the node continuity equations.
5. Node continuity equations are discretised by the Euler modified method, retaining water levels at nodes at the next time step as unknowns.
6. After converting a sparse node matrix into a row-indexed sparse storage form, system of equations for node levels is solved by the conjugate gradient method.
7. Once water levels at the nodes are known, then the discharges and the water levels at channel ends are computed from energy equations and, at free outlets, from critical/normal depth criteria.
8. Those discharges and water levels are internal boundary conditions by which finally the St. Venant equations and the equations for other links are solved.

If F(Z) > 0, **Equation 3** is solved by the Euler modified method:

$$Z^{j+1} = Z^j + \frac{\Delta t}{2}\left(\frac{\varphi^j}{F^j} + \frac{\varphi^{j+1}}{F^{j+1}}\right) \quad \textbf{Equation 7}$$

where φ = right-hand side of **Equation 3**. For point-type junctions, **Equation 3** reduces to $\varphi^{j+1}=0$.

St. Venant equations are solved by the Preissmann implicit finite-difference method in which the discretisation is as follows:

$$\frac{\partial f}{\partial t} \approx \psi \frac{(f_{i+1}^{j+1} - f_{i+1}^{j})}{\Delta t} + (1-\psi)\frac{(f_i^{j+1} - f_i^{j})}{\Delta t} \quad \textbf{Equation 8}$$

$$\frac{\partial f}{\partial x} \approx \theta \frac{(f_{i+1}^{j+1} - f_i^{j+1})}{\Delta x} + (1-\theta)\frac{(f_{i+1}^{j} - f_i^{j})}{\Delta x} \quad \textbf{Equation 9}$$

$$f \approx \theta[\psi f_{i+1}^{j+1} + (1-\psi) f_i^{j+1}] + (1-\theta)[\psi f_{i+1}^{j} + (1-\psi) f_i^{j}] \quad \textbf{Equation 10}$$

where f = any function and ψ,θ = spatial and temporal weighting coefficients, respectively. Commonly, ψ = 0.5 and θ = 0.67. Where f is a product or a ratio of variables, no separation is done i.e. the products/ratios are discretized as such. Where any variable ϕ is in front of the differentiation operator, the discretization is as follows:

$$\phi\frac{\partial f}{\partial x} \approx \theta \frac{(\phi_i^{j+1} + \phi_{i+1}^{j+1})}{2}\frac{(f_{i+1}^{j+1} - f_i^{j+1})}{\Delta x} + (1-\theta)\frac{(\phi_i^{j} + \phi_{i+1}^{j})}{2}\frac{(f_{i+1}^{j} - f_i^{j})}{\Delta x} \quad \textbf{Equation 11}$$

Substitution of **Equation 8** - **Equation 11** into **Equation 4** and **Equation 5** and linearization lead to:

$$a_i Q_i^{j+1} + b_i z_i^{j+1} + c_i Q_{i+1}^{j+1} + d_i z_{i+1}^{j+1} = e_i \quad \textbf{Equation 12}$$

$$a'_i Q_i^{j+1} + b'_I z_i^{j+1} + c'_i Q_{i+1}^{j+1} + d'_i z_{i+1}^{j+1} = e'_i \quad \textbf{Equation 13}$$

where a_i, b_i, …, e_i' = abbreviations, most of which include variables Q or z at time level j+1. **Equation 12** and **Equation 13** for all pipe/channel sub-reaches form the system of algebraic equations (for i=1, 2, …, N–1, where N = number of cross-sections). By eliminating the unknowns at internal cross-sections (from i=2 to i=N–1), this system of 2N–2 equations is reduced to the equivalent system of two equations:

$$Q_1^{j+1} = f_1 z_1^{j+1} + g_1 z_N^{j+1} + h_1 \quad \textbf{Equation 14}$$
$$Q_N^{j+1} = f_N z_1^{j+1} + g_N z_N^{j+1} + h_N \quad \textbf{Equation 15}$$

where $f_1, g_1, \ldots, h_N$ = abbreviations.

Substitution of free-outflow conditions and/or Equation 6 into **Equation 14** and **Equation 15** transforms them into:

$$Q_1^{j+1} = f'_1 Z_U^{j+1} + g'_1 Z_D^{j+1} + h_1' \quad \textbf{Equation 16}$$
$$Q_N^{j+1} = f'_N Z_U^{j+1} + g'_N Z_D^{j+1} + h'_N \quad \textbf{Equation 17}$$

where indices U and D denote network nodes at upstream and downstream channel ends, respectively. After possibly some linearization, relationships for other link types can be expressed in the same form as well.

Further substitution of **Equation 16** and **Equation 17** for all joining links **into Equation 7**, and doing so for all the nodes, lead to the system, which can be written in matrix form:

$$P \cdot Z = q \quad \textbf{Equation 18}$$

where Z = vector containing unknown water levels at network nodes and p, q = coefficient matrices.

As node matrix p can be rather large but with a lot of zero terms, it is converted (banded) into a row-indexed sparse storage form. Then the system (**Equation 18**) is solved by the conjugate gradient method considering the function:

$$\Phi(Z) = \frac{1}{2} | p \cdot Z - q |^2 \quad \textbf{Equation 19}$$

and minimizing the expression $\Phi(Z + \lambda u)$ where vector u is the gradient of function Φ from the previous iteration, $u = \nabla\Phi(Z^*)$, and scalar $\lambda = -u \cdot \nabla\Phi / | p \cdot u |^2$.

Once system (**Equation 18**) is solved, discharge at any link end can be determined from (**Equation 16**) or (**Equation 17**). For pipe/channel links, where flow direction is from a node to the link, and for the time being supposing the sub-critical flow throughout, thus obtained discharge becomes the BC at that channel end, else water level calculated from Equation 6 or from free-outflow condition is the BC. Although any of the two variables Q or z, or a discharge curve Q=Q(z), can be used as the BC at either end, stated choice appears to be the most physically sound one, and in some cases the most stable one. Finally, these BCs, plus external BCs where applicable, are added to system of **Equation 12** and **Equation 13**, it is rearranged to a tri-diagonal form and solved using double-sweep technique and Newton-Raphson method.

All solving procedures are iterative – at each time step there is one global iteration cycle (for the entire network) and many local iteration cycles (along particular channels and at their ends).

SIPSON applies various advanced techniques for handling modelling difficulties such as:

1. Supercritical flow and hydraulic jump are modelled by retaining the structure of boundary conditions inherent to sub-critical flow and by gradual reduction of convective acceleration term in the momentum equation as Froude number approaches critical value.
2. Pressurized and mixed (free-surface/surcharged) flows are treated by open slot concept.
3. Smooth transitions (from submerged to free outflow and vv., from one flow direction to the other, etc.) are ensured by the iterative nature of the solution techniques.
4. Automatic choice of optimal computational steps is made on the basis of mixed theoretical/empirical criteria, etc.

SIPSON has been tested on a number of systems of various size and complexity, ranging from laboratory experimental installations, small and medium size catchments to ten thousand pipes networks. It has mainly been used for simulation of sewer systems and urban flooding, but also for prediction of flow in irrigation network. The model was adapted for use in this particular karstic catchment modelling work.

5.3.3. System decomposition

Invariant of the modelling approach are the decomposition principles that were implemented:

A. Decomposition in space:

Based on the hydro-geological assessment (Chapter 2), the system can be decomposed into three (geologically and physically different) subsystems (Figure 98):

1. Dabarsko polje – Indirect catchment area of Bregava springs
2. Direct catchment area of Bregava springs
3. Fatničko polje - part of Trebišnjica springs catchment area

Thus these subsystems were created. Further decomposition in space relays on the common approach in modelling that separately treats flow in the unsaturated zone that is primarily vertical, and flow in saturated zone that is mainly horizontal:

a) Vertical water balance in unsaturated zone is modelled with UNSAT model
b) Water balance in the horizontal plane is modelled as a system of links and reservoirs in both modelling approaches

Dabarsko polje discharges water from the indirect catchment area of the Bregava springs, as there is an impervious hydro-geological barrier beneath the Dabarsko polje (see Chapter 2). The indirect catchment area is divided into 3 parts - subsystems: Trusina (Trusinsko polje), Lukavačko (Lukavacko polje) and Indirect c.a. (the rest of the indirect catchment area). These subsystems simulate vertical water movement and leakage from unsaturated zone.

In the period of high precipitation Dabarsko polje is flooded, so it is modelled as a reservoir. Inflows to this subsystem are the outflows from subcatchments: Trusina, Lukavačko and Indirect c.a. Water from this subsystem, through a system of links, discharges into the Bregava springs.

Another part of the Bregava springs catchment area is defined as direct catchment area. There are two parts of the subsystem: UNSAT model (Direct c.a.) simulating unsaturated zone, and Direct catchment area defined as a reservoir (Direct reservoir - Figure 98), which discharges at Bregava springs.

The third subsystem – Fatničko polje, is a part of Trebišnjica springs catchment area. This part is included in the model due to fact that certain quantity of water from this polje discharges into Bregava springs, but the major part discharges into the Trebišnjica springs.

Inflow in Fatničko is calculated from correlations between flows measured at gauge station Srdjevići and inflow to Fatničko polje. That is why Fatničko polje does not have its own sub-catchment in physically based models. In the period of high precipitations Fatničko polje is flooded, and it acts as a reservoir (similar to Dabarsko polje). So Fatničko polje is defined as a reservoir, with two outlets:

1. One at the bottom of the polje, discharging at Trebišnjica springs
2. Another one, whose outlet is 10 m higher, discharging into the Bregava springs (the level of outlet is defined according to hydro-geological report (Chapter 2), as water discharges at Bregava springs only when water level in Fatničko polje is higher than 10 m).

Under natural conditions (before 1986) all three reservoirs were connected, through a system of links, with a single outlet - Bregava springs (except Fatničko polje, which is connected with the Trebišnjica springs as well). After 1986 a tunnel was built between Dabarsko and Fatničko polje, so the connection between these two reservoirs was incorporated in the model. It was assumed that in the future the new tunnel between Fatničko polje and Bileća reservoir will be finished and used. This tunnel is modelled as another outlet for Fatničko polje (Figure 98).

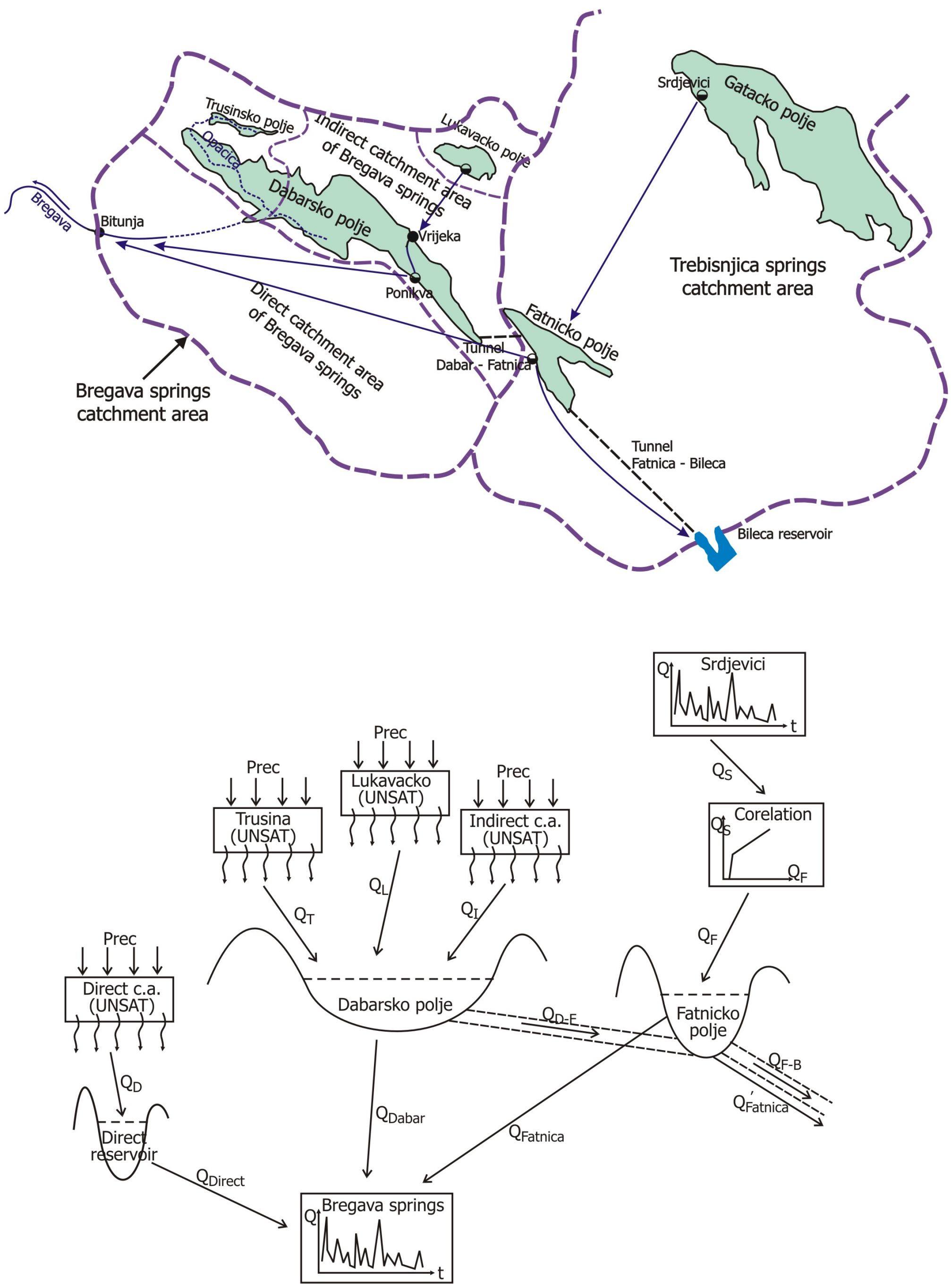


Figure 98. System decomposition in space

B. Decomposition in time

The modelling period is divided in 3 sub-periods:

1. **Before 1986 when the tunnel between Dabarsko and Fatničko polje was not built.** Considering the fact that measurements of discharge at gauge

station Srdjevići were established in 1976, only that period is simulated with physically based models.

2. **After 1986 when tunnel was operational, and regulation rules were known**. The regulation rules were not strictly according to the BUILDING PERMIT NO.UP-I-03-78-1/69 OF 29.7.1969. Instead, the tunnel was closed only when the water level in Fatničko polje was above the water level in Dabarsko.
3. **Future scenario when the new tunnel between Fatničko polje and Bileća reservoir will be finished and used**.

During a single year, there is a clear distinction between wet and dry period. Results for those two periods were compared separately with measured data.

5.3.4. Simulation results

A. Results of UNSAT simulation model

According to the principles of space decomposition it is obvious that simulation in the unsaturated zone, with predominantly vertical flow, is invariant of the modelling approach (Simple or Detailed).

The global water balance performed for the Bregava catchment area for the entire simulation period shows that only 16% of rainfall does not contribute to discharge that is measured at the gauge station Bitunja.

From the global water balance it is clear that a part of rainfall is lost through actual evaporation, and the rest of precipitation contributes through the unsaturated zone to surface and underground reservoirs that are presented as nodes in the models.

Due to the low availability of input data, the model is primarily calibrated to satisfy the components of the global water balance. Actual evaporation is not determined in detail in the model. Instead, the net precipitation is calculated as the part of precipitation that enters the soil, i.e. the difference between measured precipitation and evaporation losses: P_{eff}=0.84 P. Therefore, potential and actual evaporation were not calculated in the model.

For the implementation of the UNSAT model, soil data had to be defined. The most important soil parameters are **porosity** and **saturated hydraulic conductivity** (Ks). Previous investigations and reports clearly show that the accumulation capacity of the soil is very low and therefore a rather small value for that parameter is adopted (Porosity=0.1). On the other hand, very high values for hydraulic conductivity are expected, so that the precipitation can infiltrate very fast and actual evaporation and runoff stays low, to be consistent to the global water balance. The calibration of the UNSAT model has shown that saturated hydraulic conductivity is K_s= 5 10^{-4} m/s. Unsaturated flow is simulated for the first 2 meters of the soil. Identification of the size of the soil reservoir was also part of the calibration process. Soil reservoirs influence the transformation of the precipitation peeks and therefore the shape of the input hydrograph and also the time delay in the hydrograph's peeks (Figure 99). It is therefore a very important parameter in the model that significantly affects input hydrographs.

Simulation results are shown on Figure 99 for the period of one "hydrological" year that starts at the 1st September, which is the end of a dry season. The light blue line on Figure 99 indicates measured precipitation and the outflow from the UNSAT model (leakage) is presented with dark blue line.

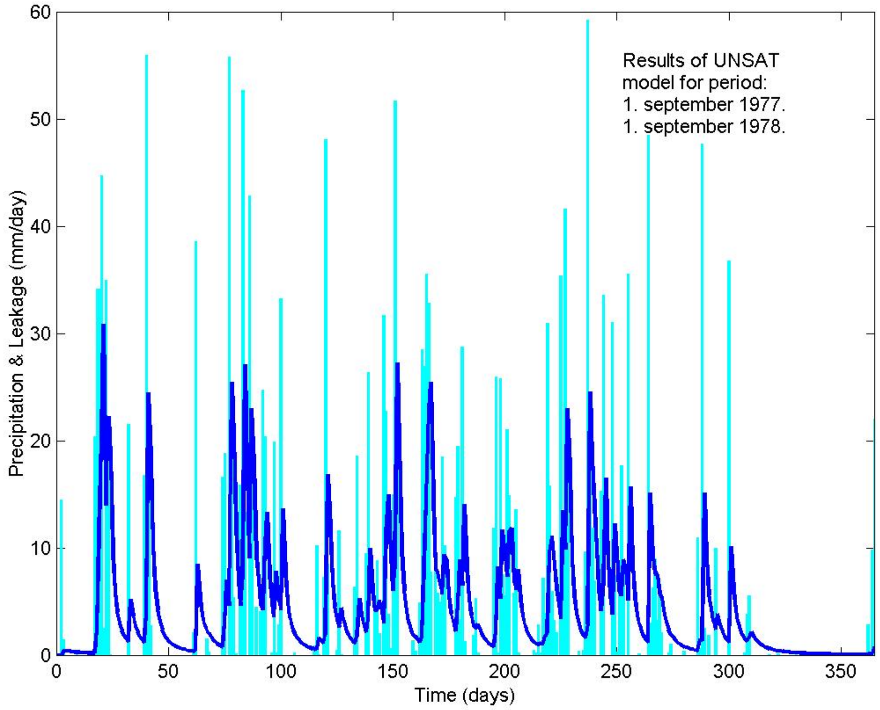


Figure 99. Results of UNSAT model for period: 1st September 1977 to 1st September 1978. Light blue histogram indicates measured precipitation and dark blue line is simulated Leakage.

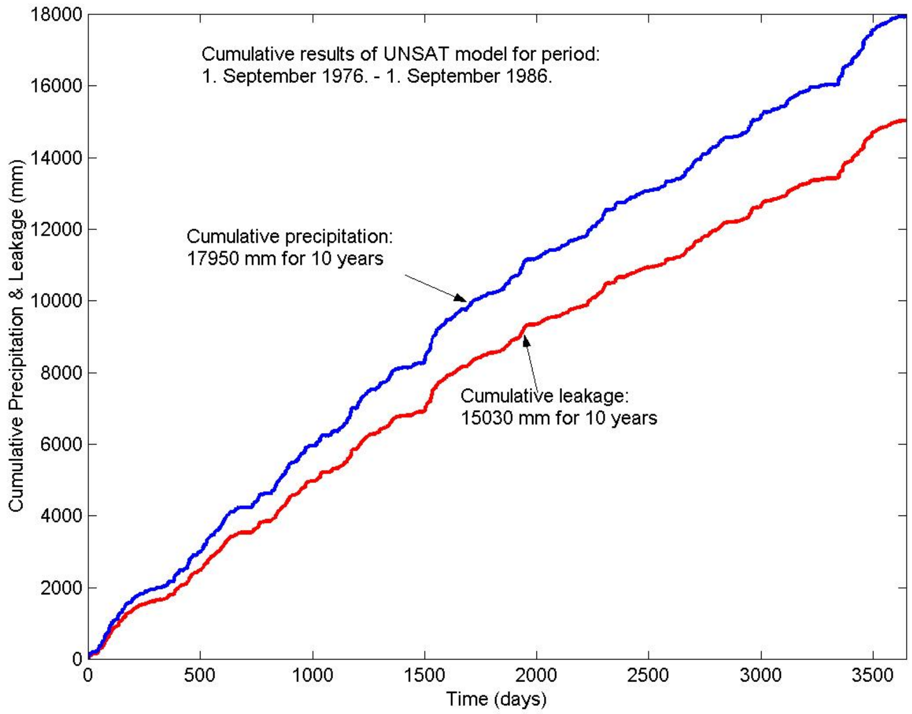


Figure 100. Cumulative results of UNSAT model for period: 1st September 1976 to 1st September 1986.

B. Simulation results of Simple physically based model

The Simple physically based model was calibrated in several steps:

- First the indirect catchment area calibration (see Figure 98) was performed on the basis of input hydrographs (obtained by the UNSAT model) and measured water levels in Dabarsko polje. Results of the calibration were the dimensions of equivalent tunnel (tunnel that simulate all outflows from Dabarsko polje – flowing into the ponor zone of Ponikva, Kuti and a number of smaller ponors). In this phase of calibration, measured and simulated water levels in Dabarsko polje were fitted.
- The second step was calibration of the direct catchment area, with its own underground reservoir, that represents the accumulation capacity of the karstic aquifer. Input hydrograps in the reservoir is the leakage output from the UNSAT model. Calibration was performed by a comparison with the measured flows at gauge station Do.
- Inflow in Fatničko polje was not calibrated, because it was obtained from the regression curve that gives well known and reliable relation between the measured flows at the gauge station Srdjevići and inflow in Fatničko polje. The only parameters that were calibrated are the dimensions of the swallow holes in Fatničko polje. Two swallow holes exist in the model: one at the bottom of Fatničko polje, and the other is positioned 10 m above the bottom (based on the hydrogeological report). Calibration was performed by comparing simulation results and measured water levels in the Fatničko polje.

Typical simulation of the Simple physically based model lasts about 50 seconds for one year. Due to the fact that there are numerous parameters to be determined, implementation of some automatic calibration method was deemed time consuming and unrealistic. A trial and error technique was therefore adopted assisted by the extensive experience and knowledge of this system by the modelling team. Experience and understanding of the complex system provided bases for system decomposition, and opened the possibility to simplify the calibration process.

The model simulated a period of 10 years (for which data were available) and the detailed results are shown in the following figures (Figure 101 - Figure 103) for hydrological year 1977 – 1978. In the period of simulation the tunnel Dabarsko – Fatničko was not operational. The simulation models were therefore initially implemented for the period of ten years when the tunnels did not exist (natural conditions). To simulate the effects of the tunnels on flooding in Dabarsko and Fatničko polje and the discharge in the Bregava springs, two more scenarios were simulated: a) The tunnel Dabarsko - Fatničko being operational (DP-FP) and b) The tunnel Fatničko – Bileća reservoir (that is presently under construction) also being operational (DP-FP-BR).

The simulation results clearly show:

- That the operation of the DP-FP tunnel *negligibly influences water levels in Dabarsko and Fatničko polje as well as discharges in Bregava springs*. The duration of discharges below 10 m^3/s almost not affected by the operation of this tunnel.
- Operation of the tunnel FP-BR drains Dabarsko and Fatničko polje almost during the entire flooding season. It is also assessed that discharges on the Bregava springs that are below 10 m^3/s are not affected.

The simulation results and conclusions are attributed to following facts:

- The Bregava springs have their own sub-catchments (direct catchment area – Figure 98) that is bigger than the indirect catchment of Dabarsko polje.

- The only permanent stream Vrijeka, which flows into the Ponikva sink, is not affected by the operation of the tunnels during dry periods.

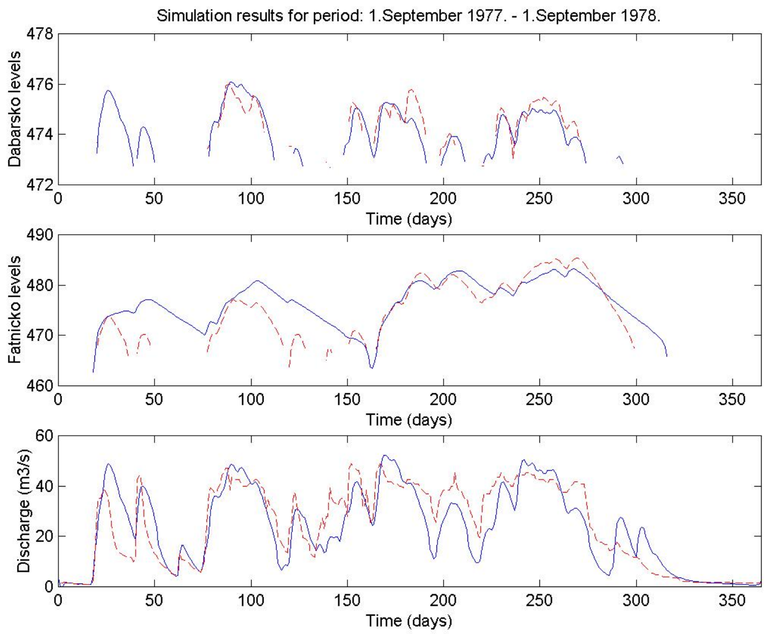


Figure 101. Simulation results of the *simple model* for period: 1st September 1977 to 1st September 1978 (without tunnels). Solid lines - simulated results, Dashed lines – measurements. Discharge is calculated for station Do on Bregava stream.

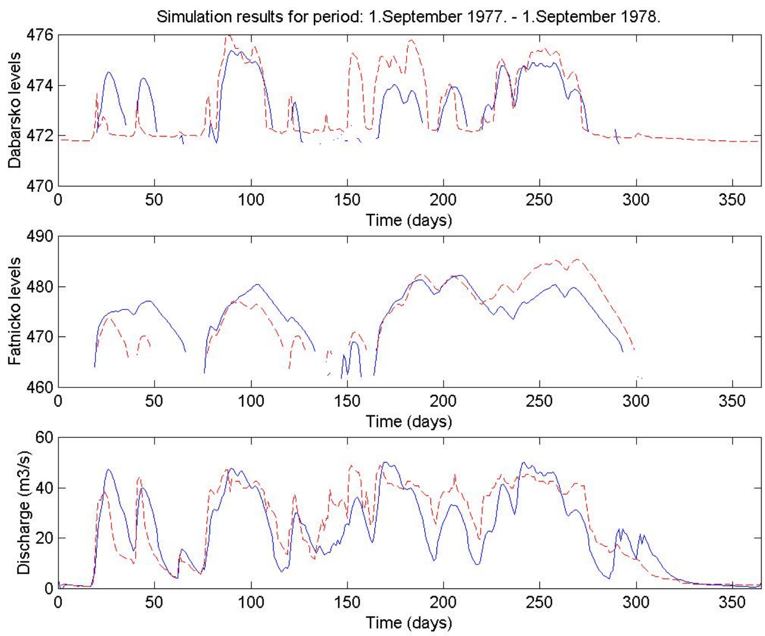


Figure 102. Simulation results of the *simple model* for period: 1st September 1977 to 1st September 1978. (with tunnel Dabarsko polje – Fatničko polje). Solid lines - simulated results, Dashed lines – measurements. Discharge is calculated for station Do on Bregava stream.

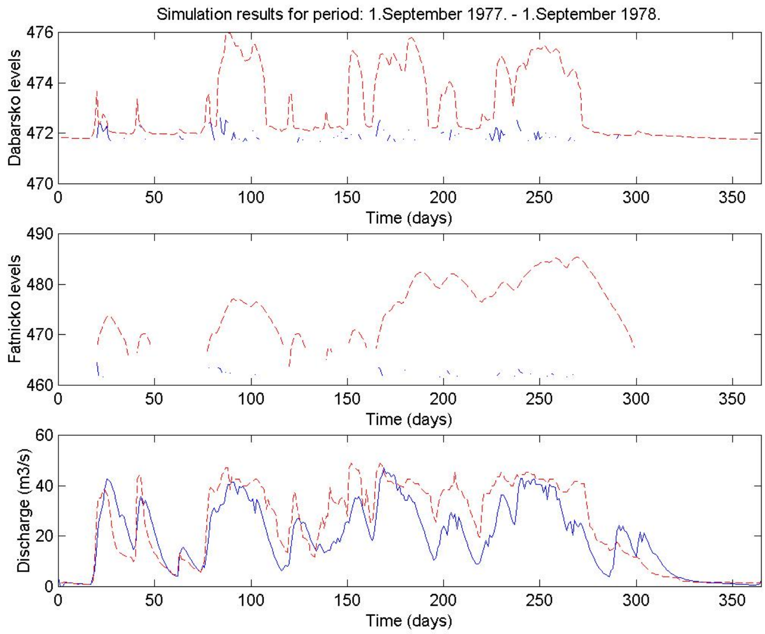


Figure 103. Simulation results of a Simple model for future period with historical data: 1st September 1977 to 1st September 1978 (with tunnels Dabarsko- Fatničko and Fatničko -Bileća reservoir). Solid lines - simulated results, Dashed lines – measurements. Discharge is calculated for station Do on Bregava stream.

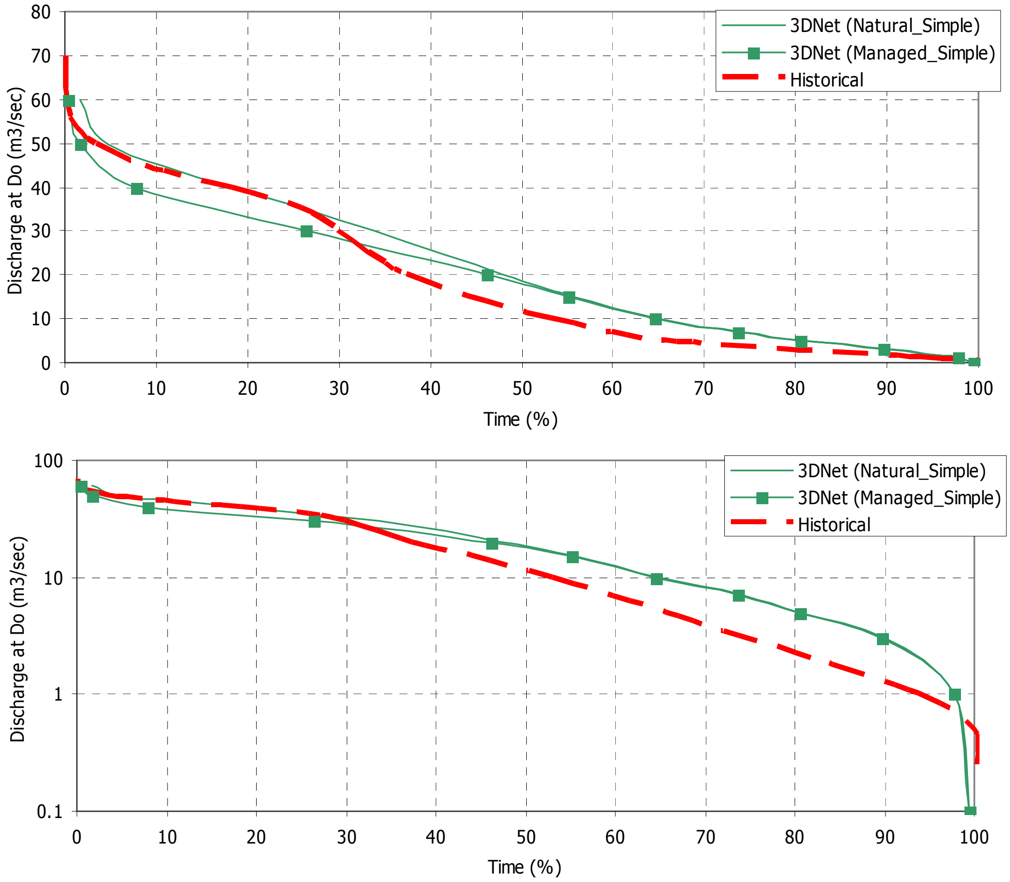


Figure 104. Simulation results of the *simple model* presented in the form of duration curves for discharges in Bregava. The simulation is performed with historical data: 1st September 1976 to 1st September 1986 without the tunnels and with both tunnels Dabarsko-Fatničko and Fatničko - Bileća reservoir. Solid lines - simulated results, Red Dashed line: measurements. Duration curves are presented in linear and logarithmic scale.

As can be observed from Figure 101, simulated and observed discharges at the Bregava springs show substantial discrepancy for specific periods. An explanation for this is provided below:

- Precipitation data for the whole direct catchment area were collected by only one meteorological station. That was the meteorological station Trusina that actually belongs to the indirect catchment area. There were no meteorological stations in the direct catchment area. Therefore the model could not accurately simulate the spatial distribution of the precipitation in that area. There are periods when rainfall events cover only part of the catchment. In Figure 101, for a period of around 300 days from the beginning of the hydrological year (approximately the beginning of July) there are certain differences between measured and simulated results. It is suggested that the rainfall event that happened in that period (see Figure 99) covered only the indirect catchment area, so there was only a small increase in measured flows, while flows simulated by the model were significantly affected.
- The model did not simulate the effect of hysteresis (Figure 15) that is usual for karst areas, where discharge and water level relations differ for periods when water level increases and decreases. Due to limitation in available time for the

project and availability of input data this significant aspect of the problem was not addressed.

C. Simulation results of the Detailed physically based model

The model simulated a period of 6 years and detailed results are shown in the following figures (Figure 105 - Figure 106) for the hydrological year 1977 – 1978. In the period of simulation the tunnel Dabarsko – Fatničko was not operational. So the simulation models were implemented for the period of six years when the tunnels did not exist (natural conditions). To simulate the effects of tunnels on floods in Dabarsko and Fatničko polje and discharges in Bregava springs, one more scenario was simulated: both tunnels Dabarsko - Fatničko and Fatničko – Bileća reservoir (that is presently under construction) being operational.

Simulation results of the detailed model are similar to the results obtained by the simple model (Figure 107).

The largest possible time step with which the numerical solution of the full dynamic model could be stable was Dt=45sec, which meant half a million time steps per year of simulation period. In addition, total tunnel length was in excess of 100km, so the computations were laborious and typically lasted several hours per simulated year. Therefore a more precise calibration of the model parameters could not be done in the short time available for the project – otherwise much better agreement between observed and simulated results might have been obtained.

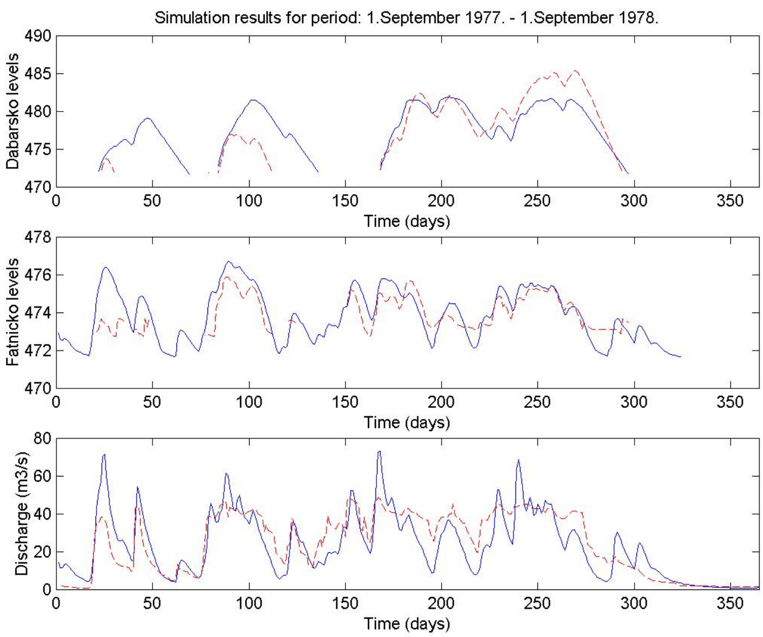


Figure 105. Simulation results of the *detailed model* for period: 1st September 1977 to 1st September 1978 (without tunnels). Solid lines - simulated results, Dashed lines – measurements. Discharge is calculated for station Do on Bregava stream.

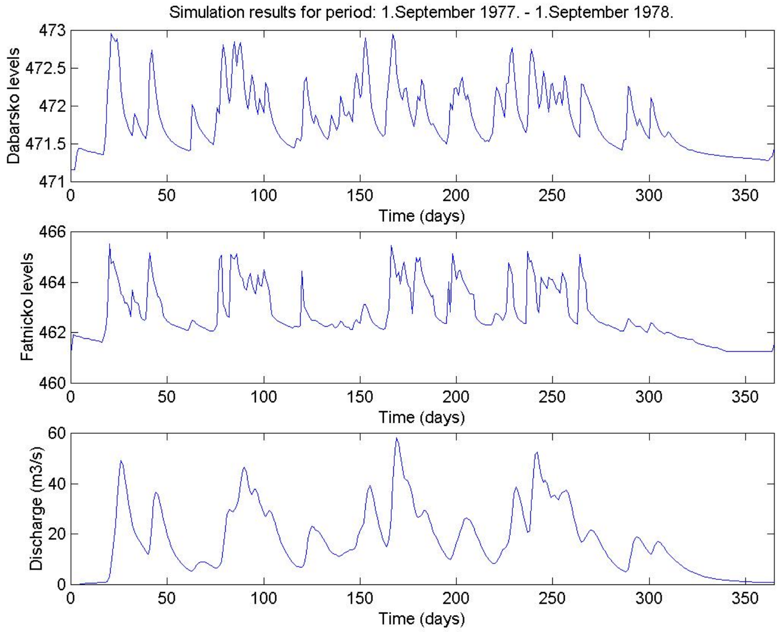
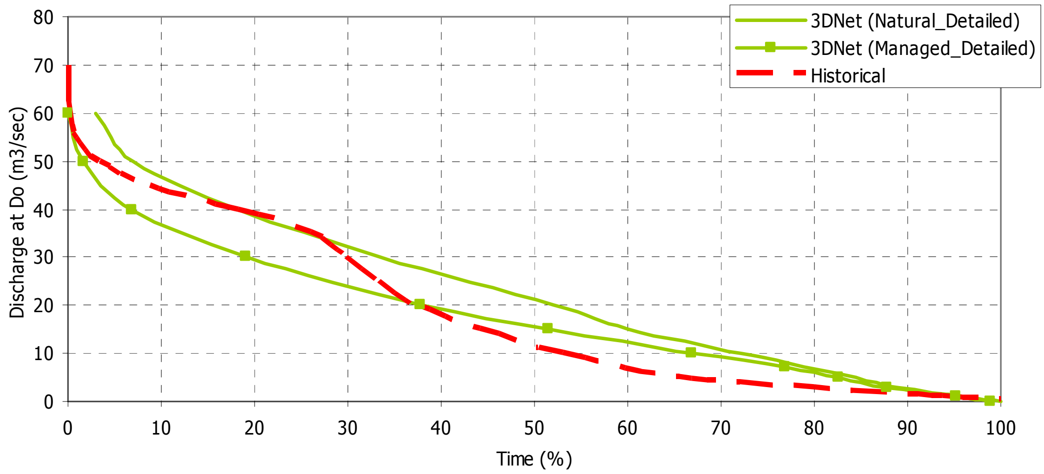


Figure 106. Simulation results of the *detailed model* for future period with historical data: 1st September 1977 to 1st September 1978 (with both tunnels: DP-FP and FP-BR). Discharge is calculated for the Do station on Bregava River.



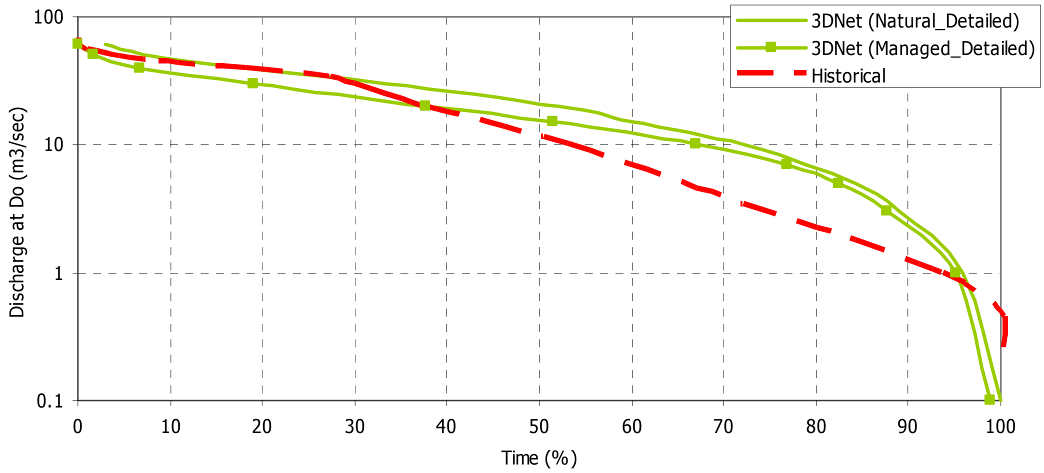


Figure 107. Simulation results of the *detailed model* presented in the form of duration curves for discharges in Bregava. The simulation is performed with historical data for one year (1977-1978) without the tunnels and with both tunnels Dabarsko-Fatničko and Fatničko -Bileća reservoir. Solid lines - simulated results, Red Dashed line: measurements for the overall period 1976-1986. Duration curves are presented in linear and logarithmic scale.

5.3.5. Uncertainty analysis

Calculating simulation error is an intrinsically difficult task and, unlike the uncertainty estimation process in the duration curves, could be defined in a number of different ways:

Integral volume error, determined by dividing simulated and measured volumes at station Do during simulation (Ts) and defined by:

$$Volume\_error = \frac{\int_0^{Ts} Q_{simulated} \cdot dt}{\int_0^{Ts} Q_{measured} \cdot dt} - 1 \qquad \textbf{Equation 20}$$

In terms of integral volume, the calculated error of the model is 1.4%. That is the result of the system decomposition and step-by-step calibration that takes account of the global water balance at the first step of calibration process.

The simulation error can also be expressed in terms of flow range (see Figure 108). Here the simulation error is calculated as the average of the ratio between measured and simulated discharge for different flow ranges.

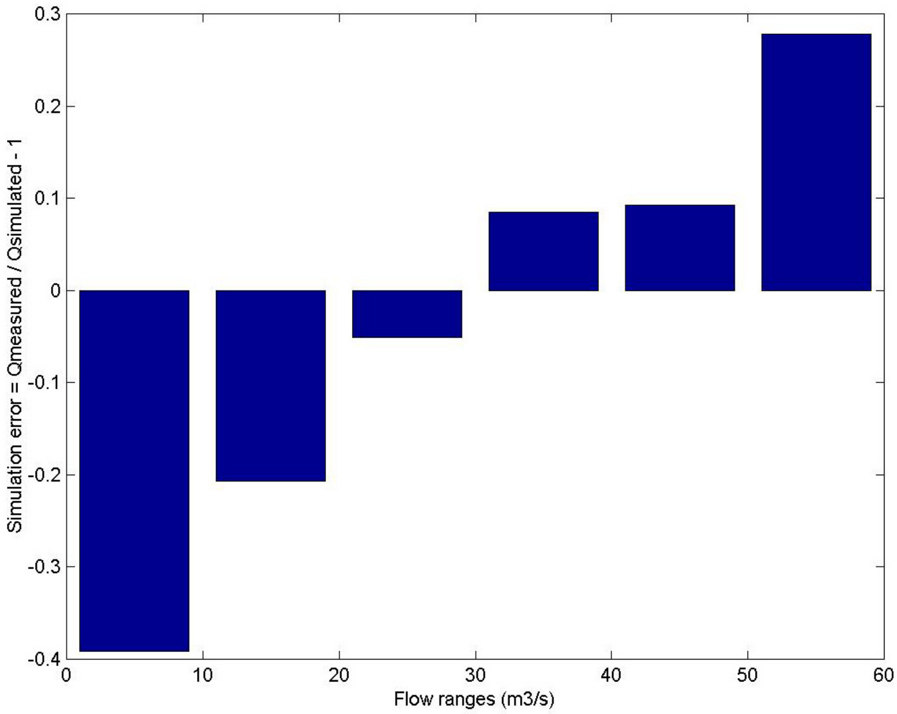


Figure 108. Average of ratio between measured and simulated discharge for different flow ranges

The diagram shows that the model exhibits the highest errors in the range of flows that are related to "rare" or rather low duration events. That is to be expected due to fact that the model is not calibrated to simulate "extreme" events but a whole simulation period where the aim is to satisfy the global water balance and most frequent events, and this is well in line with the aim of this work. It is assessed therefore, that the main conclusions that are stated in the text are not significantly affected by the modelling errors identified.

5.3.6. Discussion

In summary the physical modelling simulations, for both Simple and Detailed modelling level seem to indicate:

- That the operation of the DP-FP tunnel *negligibly influences water levels in Dabarsko and Fatničko polje as well as discharges in Bregava springs*. He duration of discharges below 10 m^3/s almost not affected by the operation of this tunnel.

- Operation of the tunnel FP-BR drains Dabarsko and Fatničko polje almost during the entire flooding season.
- Operation of the tunnel FP-BR does not affect discharges in the Bregava springs that are bellow 10 m^3/s (low flows).

The simulation results and conclusions are attributed to following facts:

- The Bregava springs have their own subcatchments (direct catchment area – Figure 98), which is bigger than the indirect catchment of Dabarsko polje.
- The only permanent stream Vrijeka that swallows at the Ponikva sink is not affected by the operation of tunnels in dry period of year.

It has to be noted however that there were considerable uncertainties and gaps in the datasets, and time constraints limited the ability of the teams to perform a detailed calibration the models developed.

6. Results Discussion

When the program of this study was conceived it was deliberately agreed to use three different modelling groups applying different modelling approaches, different levels of modelling area coverage and temporal and spatial discretisation as well as different solving algorithms to enhance the reliability of the results, as each independent approach would serve as a quality assurance mechanism for the rest. Naturally, all three groups have been given the same datasets, the same set of operational rules, the same geometrical characteristics of the poljes, the same capacity functions of the tunnels and very limited time to fine tune their models. They have all been asked to concentrate on providing an unbiased assessment of the effect of the water transfer from Dabarsko to Fatničko polje and from Fatničko polje to Bileća reservoir using the hydrometric station Do as the reference point. However the modelling groups have been left free to use their own scientific and professional expertise, modelling skills and to draw their own conclusions based on the results of their modelling. It should be noted that several innovative modelling techniques have been implemented in various phases of the project.

When assessing the accuracy and uncertainty in modelling one should bear in mind that the quality of data was modest, as after the major construction works finished (Grančarevo dam and the relevant power plants Trebinje I, Trebinje II and Dubrovnik), several monitoring stations were abandoned and measurements discontinued. The recent conflict in the region made the situation even worse, since lack of funding and proper care reduced both the amount and the reliability of the data collected.

At the time of the production of the final version of this report all modelling groups handed over their results and reports, and to the knowledge of the co-ordination team based at Imperial College London, the teams had no insight in one other's results.

When making comparisons between the final results obtained by the three groups, one should always keep in mind that every modelling exercise is just an approximation of reality, influenced by the uncertainty of measurement (data) and the robustness of the modelling tools and thus subject to various types of uncertainty, which in this particular case were not easy to precisely quantify, due mainly to time and resource limitations.

A qualitative comparison of model structural features is shown in Table 12.

The physically based model (3DNet) is the most consistent in representation of the physical processes and the most complex one, whereas the K Sim^2 model is the simplest and loosest, in terms of description of the natural processes, but simultaneously is the one with the most sophisticated calibration procedure as it used automatic nonlinear optimisation procedures to estimate parameters. The features of the Cerni model place it in between the two other models.

Table 12. Qualitative comparison of structural features of the three models.

Model feature	**Characterisation**	**3DNet**	**Cerni**	**K-Sim^2**
Hydro-system structure representation	Detailed Rough			
System dynamics representation	Detailed Rough			
Consistency in representation of physics	Physics-based Conceptual			
Complexity of mathematical model	Complex Simple			
Number of parameters used	More Fewer			
Model calibration procedure	Sophisticated Empirical			

Figure 109 presents a combined plot of all model results. The results (in the form of duration curves for the Do hydrometric station at Bregava River) for managed and natural conditions of the three models are plotted together with the historical (observed) data series for the pre 1986 period (i.e. before the tunnel DP-FP was constructed), to assist the understanding of goodness of fit of the different models. To improve readability, only the results of the detailed 3DNet model are included in this comparison. The goodness of fit of the different modelling approaches is more clearly illustrated in Figure 110.

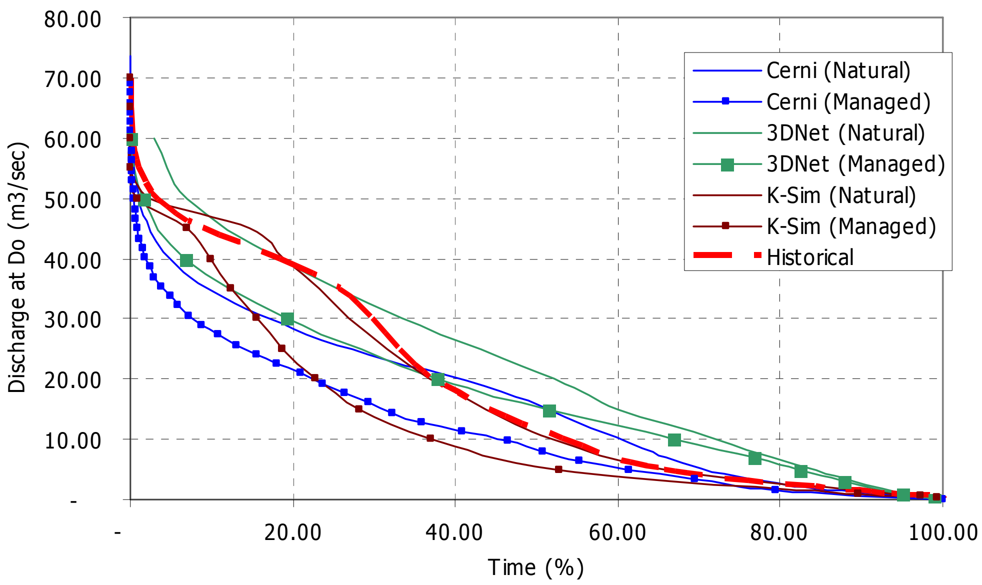


Figure 109. Combined results (duration curves at Do station) from the three modelling approaches for both natural and managed conditions

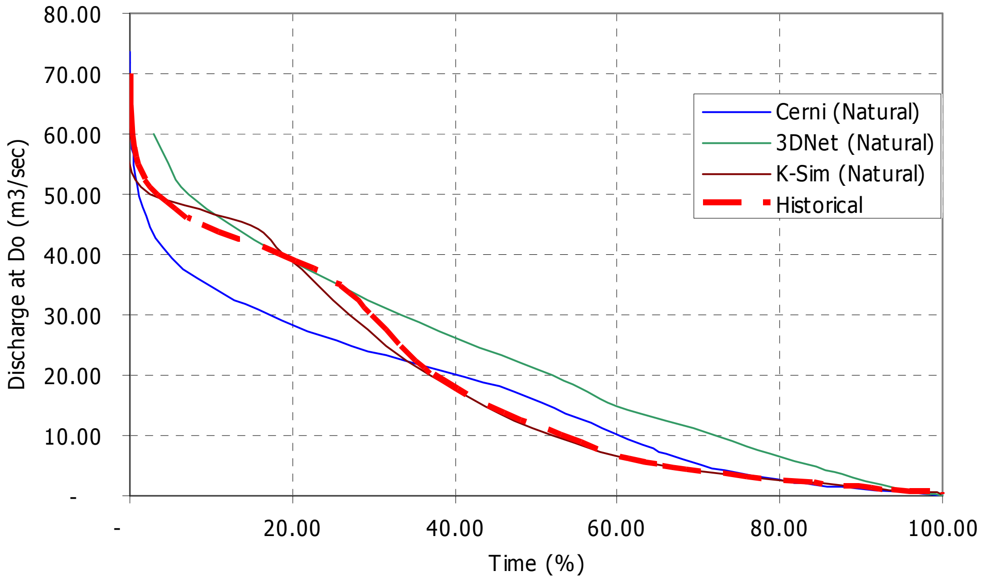


Figure 110. Comparison of simulated natural (unmanaged) conditions in the three models

It can be observed that *all three models have successfully reproduced observed field measurements*, with the K-Sim^2 model providing the closest fit. Contrary to intuition and also to current scientific trends which favour physically based and mathematically complex models, the above results indicate that conceptual modelling approaches may yield better results if combined with state-of-the-art optimisation-based calibration tools (for details on individual model calibration see Chapter 5). A more efficient and effective calibration procedure sometimes proves to be more important than a detailed description of the physical system which is generally restrained by the large amount of spatially distributed data required to represent heterogeneity of physical processes and the intrinsically deficient knowledge of the physical system (e.g., geometry of karst) (Rozos et al., 2004).

Figure 111 presents the results of the three models on the effect of the tunnel operation to Bregava (at the location of Do station). Again, the recorded flows at Do prior to 1986 are plotted for comparison purposes. It should be noted that the reason why the 3DNet model results appear to be slightly larger than the observed values for part of the time is because the simulated time of the detailed model was less than the simulated time of the hydrologic models due to the computational burden inherent in this approach.

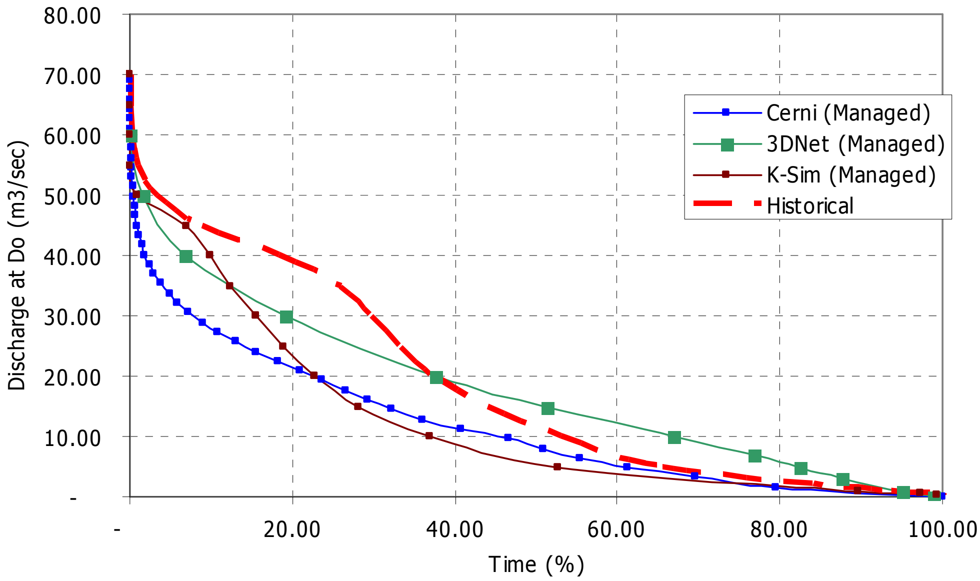


Figure 111. Comparison of simulated managed conditions in the three models

The results for all three groups are very similar and indicate that the effect of the tunnel operation (under the operational assumptions described in Chapter 1 and the modelling/schematisation assumption described in Chapter 5) to low flows (below 5 m^3/s) is minimal.

The IJC model, which is subject to the most significant discrepancies between the field measurements and model results for the natural conditions, also exhibits the most pronounced differences between modelled natural conditions and managed conditions for mean-to-low flows. Even in this case however, the differences between modelled results in natural and managed conditions for low flows, which are of primary interest of this particular study, are small.

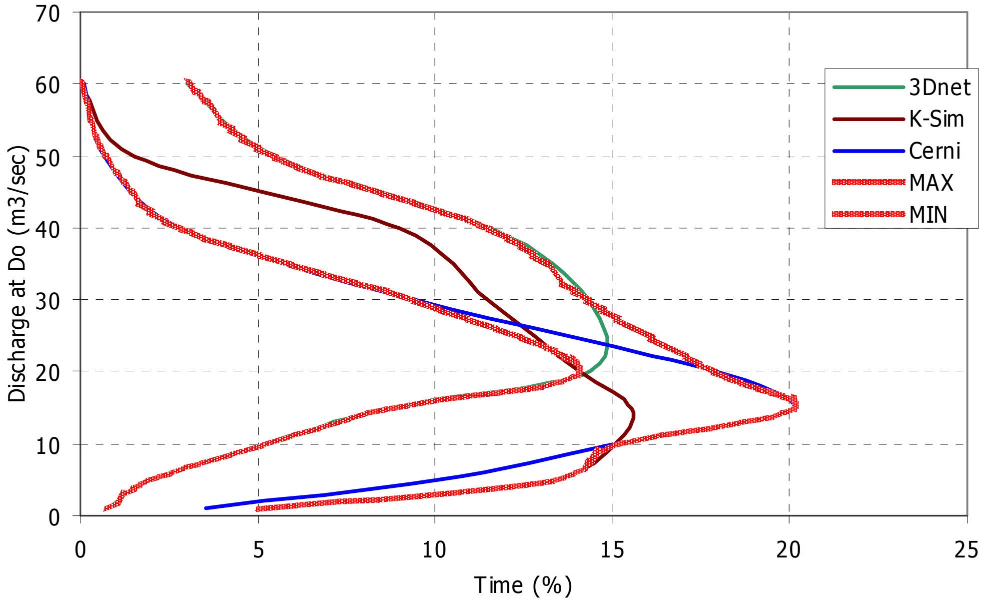


Figure 112. Difference in duration time between natural and managed conditions in the three models and associated envelop of uncertainty (red lines)

The K Sim² model, which achieved the best fit between observations and model results, suggests some effects from tunnel operation for mean flows (a reduction of the order of 10-15% of time in the duration of events) and little effect below 5 m^3/s.

Finally, **the 3DNet**, physically based model (in both levels of detail in which it was applied) predicts the smallest difference between simulated values for both natural and managed conditions. The particularly small effect of flow diversion which is predicted by this model is attributed (in addition to model and data imperfections and to the intrinsically deficient description of the system heterogeneity mentioned above) to the fact that the direct catchment of the Bregava River is much larger than the one that feeds Dabarsko polje, which was not explicitly incorporated in the other two models. This model also suggests that the effect on low flows will be negligible similar to the other two.

Figure 112 displays the difference between managed and natural conditions for the three models, in terms of duration of events, expressed in % of time when an event (in this case a specific discharge at station Do) is expected to be observed. The envelope of uncertainty derived from the modelling efforts is depicted in the form of the upper and lower boundary of the results obtained (red lines). This figure shows that *the uncertainty related to differences between model predictions is not significant* (maximum differences are of the order of 5% in time) and is equally distributed for all levels of flow. This means that the results are equally reliable for high, medium and low flows. Specifically, the models agree that:

- The effect of the tunnel operation on very high flows (above 50 m^3/s) will be significant. The duration of these very high flows in Bregava is expected to be reduced by approximately 1.5% of time on average (from 2.5% of the time when such a flow (and above) could be observed in Bregava it is anticipated that it will now be observed 1% of the time). This represents a significant reduction in very high flows (greater than 60% reduction). This reduction should have a positive impact on flood prevention in Bregava. However, due to the short duration of such events, this should have no significant effect on the water balance of the Neretva River.

- The effect of the tunnel operation on low flows (below 5 m^3/s) is not significant. The anticipated reduction is of the order of 2% of time on average (from 92% of the time when such a flow (and above) was available in Bregava it is anticipated that it will now be available 90% of the time) which represents a reduction in low flows less than 5%. Therefore, the tunnel operation **will not contribute to the drying up of the Bregava River basin**, or to the 'desertification' of the area.
- The effect of the tunnel operation on medium flows (between 10-35 m^3/s) is between the other two: the anticipated reduction is of the order of 10-15% of time. From 35% of the time when flows of around 20 m^3/s (and above) were available in Bregava, they are expected to be now available approximately 22% of the time. This represents a mean reduction of approximately 40%.

Figure 113 presents a comparison of predicted changes in duration of events which illustrates that the three models provide similar results for all flow ranges. All three models also support the conclusion that the effect of the tunnel operation is more pronounced on high flows and is reduced as flows decrease (see general trend in Figure 113).

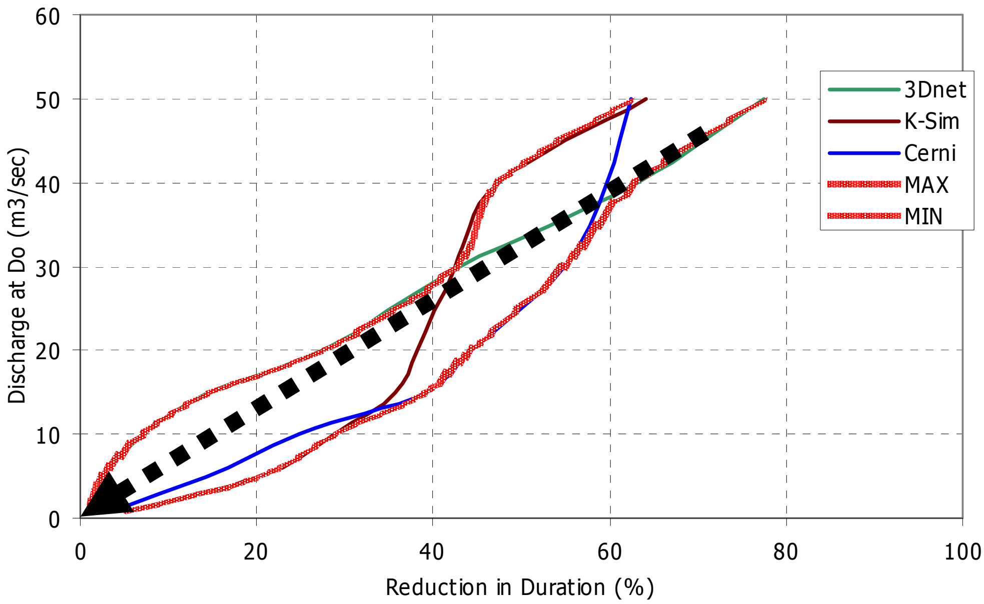


Figure 113. A comparison of predicted changes in the reduction of duration of flows between the different models. The dotted black line represents the combined general trend for the three result sets.

For a more detailed discussion of the results of individual models, the reader is referred to the relevant sections in Chapter 5.

7. Conclusions

In summary the main conclusions from this work are:

a. The Trebišnjica catchment has already undergone partial development in accordance with projects and concepts subject to regular planning and approval procedures in force at their planning stage.
b. In general the methodology applied in the assessment and planning of the multipurpose use of water resources in the area was sound and in accordance to the standards of the period and suitable data bases were created to support the planning process. These databases were at the time of a high standard.
c. In its planning stage the whole system of the Trebišnjica catchment, of which the "Upper Horizons" are an integral part, was conceived as a multipurpose one, based on optimal water resources management principles for flood protection, irrigation, hydro-energy production, water supply and environmental mitigation under unfavourable karst conditions.
d. During the past twelve years, due to conflict in the area, a lot of monitoring and data acquisition practice has deteriorated thus both quantity and quality of data for the most recent period has significantly degraded.
e. Despite unfavourable conditions most of the vital physical assets have been preserved in good working condition and this is especially true for the hydro-energy sub-system.
f. In the meantime several attempts have been made in order to assess the status of the environment and infrastructure and to revitalise other parts of the system and provide better conditions for revival of the economical activities in the area.
g. One of the projects that preceded this study is the EU co-funded LIFE-INFRARED project in which assessment of the environmental pressures and impacts of various alternative activities was performed and innovative informatics techniques have been developed and have been used in the present study.
h. The present study focused on the Bregava river catchment which shares resources with the Trebišnjica catchment depending on hydrological and meteorological conditions, **under the assumption that the whole system will be completed and that the provisions of the design conditions and permits will be strictly observed**.
i. The results of the study supports the claim that the system of tunnels from Dabarsko polje to Fatničko polje and from Fatničko polje to Bileċa reservoir has a favourable effect in reducing flood hazard (especially depth and duration) in these two poljes and thus liberating scarce land resources for agriculture.
j. The study has taken into account the assumption that the outflow from Dabarsko polje to Bregava river will be regulated (a flow regulation gate-valve) to be built on to entrance to Ponikve ponor. The rules for operation of the flow regulation are taken form the above mentioned building permits.
k. The study has quantified the effect of the diversion of a part of the flood water from Dabarsko polje to Fatničko polje and to Bileċa reservoir on the hydrological regime of the Bregava River in the cross section of the hydrometric station Do, by performing three independent analyses. The results obtained by all three methods are similar: there seems to be little effect on extremely high flows (over 50m^3/s), the most pronounced effect (reduction of flow) occurs in the range between 5 – 50 m^3/s, and the effect is almost negligible for flows lower than 5 m^3/s. **The study cannot therefore support the claim that the tunnel Fatničko Polje – Bileća reservoir will contribute to the drying up of the Bregava River basin, or to the 'desertification' of the area, under the**

assumptions of proper operation discussed above. In fact, our study suggests the reverse in the event that the "Upper Horizons" project is completed and flow regulation provisions are observed by the operators, allowing for augmentation of flows in the Bregava during dry periods (see also item m).

l. It should be noted that **this result is obtained without taking into account the ponor Kutske jame as well as several smaller ones on the southern rim of Dabarsko polje which leads us to believe that the effect on low flows could be even smaller than assessed.**

m. This study has not discussed the conditions that will be in place after the construction of the reservoirs in Nevesinjsko polje on Zalomka River. According to the conditions imposed, after that construction, the low flows to the Bregava River will be additionally enriched for at least 1 m^3/s. To quantify the effects of the works planned in Nevesinjsko polje (Zalomka river) on both Bregava and on Buna and Bunica rivers, a separate study is recommended.

n. **It is also strongly recommended that the crucial hydrometric stations be rehabilitated and equipped with modern and reliable sensors and to closely monitor the post construction performance of the system. Post project monitoring would decrease the uncertainty in the modelling results and predictions identified and discussed in the report and provide a means for tailoring the operational rules of the system to the actual conditions and needs of the area.**

o. Since this study did not include water quality aspects it is suggested that this should be done in a next phase as a part of an overall environmental impact assessment in Trebišnjica and Neretva catchments which is planned to be performed in the near future. The methodology and informatics support developed in this project can be easily incorporated into a broader modelling framework.

p. The authors hope that this study will be used for a broad awareness raising on the interdependencies of catchment processes and for building capacity for regional co-operation similar to the UNESCO endorsed PCCP (from **P**otential **C**onflict to **C**o-operating **P**artnership) principles.

8. References

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9. Appendix

D. Milićević & Lj. Zotović (1985). *Brief explanation on the model applied in the analysis of the effect of water transfer from Dabarsko and Fatničko polje to Bregava river*. Institute for use and protection of water in the karstic region. Trebinje.

Hydrological information

The model has been complied on the basic of the hydrometric data in possession of the HEPS (hydroelectric power-stations) on the river Trebišnjica. In order to make the modelling as efficient analyses as possible, with long data series, data base has been prepared aiming at identification and verification of the model parameters as well as specific analyses using the developed models. The data base included an extensive number of daily and monthly series, historical and derived hydro-meteorological data. The programming system for operation in the data base and with ARMAX models, based on the PARMAX programming system has been applied.

The basic (initial) data, from which all the other required data can be derived, is classifiable under the two categories:

- Series of measured daily data, of different physical quantities
- The data necessary for conversion.

All the data obtained by measuring have been classified into data files that can be divided two ways:

The first group is in accordance with the physical significance of the measuring value:

- Water - levels
- Flow quantities
- Precipitation
- Water - levels in bore-holes
- Temperatures
- Volume of water -storage reservoirs, etc.

The second division is according to the period of time they represent, that is, the mean values within the given space:

- Daily
- Monthly
- Yearly

The model has been calibrated with the above described data as stored in the data base. The analyses have been conducted with daily values of hydrological data. The interval of 13 years has been used (1972.-1984in order to perform the analysis of the effects of the water diversion from Dabasko polje on the river Bregava. This period is considered reliable for as much as the observations in the river -basin were carried out intensively and professionally ever since 1972.

The input data are available in the river Trebišnjica data-base held in the HEP - Trebinje.

Data processing methodology
The modelling objective was to obtain the simulated hydrographs that represent – replicate the natural state, with sufficiently firm correlation link, and later on to use it for simulation of the possible changes of the input data (water transfer), showing the effect of the diversion on the output hydrographs using the previously calibrated model. The obtained correlation coefficients confirm the high – level of confidence into the approach assigned.

The modelling results
The analysis ahs been performed by comparing the diagrams of the measured and modelled hydrographs at the output (Do hydrometric station), comparing the flow distribution curve, using the daily flow values. The deviations between the modelled versus the measured output values, was analysed by comparing the correlation coefficient for the daily values of the measured and modelled output, as well the variation coefficient. The numerical values of the flow quantity (the minimum, mean and maximum) for the simulation model have been also displayed as the representative data, where it can be clearly seen that the mean flows are almost the same, manifesting the correctness of the selected model. The results of the flow mean values have been likewise displayed for the model illustrating the situation after the diversion of the water. It is evident from these results that the influence on the low streams of the water - courses in the environment is only too insignificant, virtually non-existent. The very purpose of this elaboration has been to show the possible influence that might bring about a change in the natural hydrological conditions, which is far and away most easily, that is, graphically seen from the continuance curves of the daily flow mean values, as well the comparative hydrographs of the measured and model quantities. The graphic have been annexed to this report for the above-mentioned reason, notwithstanding that the corporate records and the reports listed in the referential bibliography contain all different measured and model quantities.

A brief decription of the applied model
The auto-regressive models were in current use while the afore-mentioned study was being worked out (i.e. 1984/85), therefore the ARMAX model was selected. Consequently, there had been trials to modelling using the other models available at the time, as with DLCM, SSARR, STANFORD, CATING and similar models. Proceeding from the fact that the ARMAX model produced the results with highest degree of realiability, it was adopted as representative for our design. A detailed description of the afore named model can be found in literature, since is was especially used in the corresponding hydrological analyses in this country and world wide. So far as ARMAX models are concerned we should stress the point that they stand for the fundamental for designing the PARMAX programming system, which in itself is the central part of the completa package that was developed in the Section for System Analyses, Unit for Automation, Mihailo Pupin Institute in Belgrade. This system was developed within the framework of the project "The Study of Hydrometeorlogical Forecasts for steamlining requirements of the HEPS system in the Neretva river-basin".

The same programming package was expanded and adapted within the framework of the project "The Study and development of the programming system for the balanse of ground waters in the Rijeka watershed", financed by the former self managing water-power engineering community of Rijeka. In confirmation of the PARMAX programme quality there was appraisal of the results carried out by Prof. Dr. O. Bonacci and Prof. Dr D. Isailović,). The model was also used for the hydrological study of the Ombla head waters, conducted within the framework of the HEPS Ombla project.

The PARMAX programming system was successfully applied in the analysis of the water transfer from Dabarsko polje.

Deficiency in numerical values does not in any way lessen the validity of the afore - said results, and thereby, as a matter of fact, of the proposals, which by way of their results, as stated trough hydrographs, provide an excellent background for defining the influence that diversion of the waters has upon the environment (the adjacent water courses), that is upon the balance of the river Bregava waters.

The model parameters
In the records of the HEPS on the Trebišnjica there is a fairly extensive list of different model analyses, depending on input parameters. Herewith we include the information on the model based several parameter equations applied in elaboration of the report:
The effects of diversion the Dabarsko polje water on the river Bregava water system.

The model was based on the available hydro-meteorological measurements and observations for the period 1972,-1984. The daily values of the inflow and outflow from the Dabarsko polje, as well of the river Bregava overflow were available. The comparative values of the river Bregava over flow are the following:

- Outflow from the Dabar valley 8.13 m3/s
- The river Bregava flow 17.53 m3/s

The following series of daily values were utilized as input to the model:

u1-outflow from the Dabar valley
u2- precipitation at rain-gauge station Berkovići
u3- precipitation at rain-gauge station Predolje

While the string of flows of the river Bregava at water -gauge station Do, served as output.

For the afore-mentioned period of analysis, the following mean values of the generated overflows with optimised values of the model parameters have been obtained:

Qmin=0.450 m3/s	(measured by comparison Qmin=0.450 m3/s)
Qsr= 17.53 m3/s	(measured by comparison Qsr= 17.50 m3/s)
Qmax= 63.46 m3/s	(measured by comparison Qmax= 58.70 m3/s)

The optimum values of the model parameters without filtering the model errors are the following:

$$
\begin{aligned}
Y1 = {} & 0,133+1,068y1(k-1)-0,155y1(k-2)+ \\
& +0,127u1(k) + 0,029u2(k) + 0,052u3(k) \\
& +0,025u1(k-1)+0,059u2(k-1)+0,022u3(k-1) \\
& -0,074u1(k-2)+0,037u2(k-2) - 0,032u3(k-2)
\end{aligned}
$$

The value of the correlation coefficient between the strings of the measured and modelled flows of the river Bregava is R=0.933, this confirming a good feasibility to apply this model for further analyses.

Periodicity
It was proved in practice that the stationary time series can be modelled with ARMAX models, more over with satisfactory results. Nevertheless, the data series regarding the observations of precipitation and outflow are usually non-stationary, and for the most part, periodically non-stationary. There are available procedures for removal of periodicity from the time series, so that the components of input, output and the corresponding errors can be then considered to be stationary series. Removal of periodicity in the long discreet series with daily values is practically only possible within the value, therefore the remaining process can be taken into account as the stationary process of the first progression. This is exactly what has been done, by introduction into the estimation of the mean value Zt=Zt - u, so that all the estimations have been calculated using this quantity.

Application of linear models with preparation of input data and optimisation of parameters in this manner has already produced satisfactory results in practice. Non-linear models might frequently render distorted and inconsistent parameters and for that reason the usage of the optimum linear models can be viewed upon as justifiable.

Verification of applied model
Within the program package of the applied model there also exists the programme VERIF, for analysis of identification results and verification of conceptual models. The programme compares the original time series with the series obtained by modelling the hydrological systems. The results are produced as numerical values and drawings of graphics compliant with criterions the recommendation of the World Meteorological Organization.

The programme applies the following criterions:

Numerical criterions:

Sum total of series elements

$$x_S = \sum_{k=1}^{N} x(k),$$ where $x \in \{y, m, e\}$

Series mean value

$$\overline{x} = \frac{x_S}{N},$$ were $x \in \{y, m, e\}$

Series maximum elements

$x_m = x(j), x_m \geq x(k)$, za $\forall k = 1,2,...,N,$ where $x \in \{y, m, e\}$ i $j \in \{1,...,N\}$

Series minimum element

$x_n = x(i), x_n \leq x(k)$, for $\forall k = 1,2,...,N,$ were $x \in \{y, m, e\}$ i $i \in \{1,...,N\}$

Standard deviation

$$x_{sd} = \sqrt{\frac{\sum_{k=1}^{N} (x(k) - \overline{x})^2}{N-1}}$$, were $x \in \{y, m, e\}$

- Variation coefficient

$$r_V = \frac{\sqrt{\frac{1}{N}\sum_{k=1}^{N} e(k)^2}}{\overline{y}}$$

Relative error

$$R = \frac{\overline{e}}{y}$$

- Correlation between average absolute error and mean value

$$A = \frac{\sum_{k=1}^{N} |e(k)|}{N\overline{y}}$$

-The time fluctuation coefficient of the maximum values within monthly intervals is determined as the number of occurrences in which the simulated maximum was shifted in time relatively to the corresponding measured maximum for at least one day.

Persistence coefficient

$$PE = \frac{\sum_{i=1}^{f} B_i^2}{\sum_{k=1}^{N} e(k)^2}$$

, where

f-number of positive and negative sections
Bi- area of discrete segments

Series correlation coefficient y(k) and m(k)

$$r = \frac{\sum_{k=1}^{N} y(k)m(k) - N \cdot \overline{y} \cdot \overline{m}}{\sqrt{(\sum_{k=1}^{N} y(k)^2 - N\overline{y}^2)(\sum_{k=1}^{N} m(k)^2 - N\overline{m}^2)}}$$

Optimum regression straight line coefficients
m(k)=ay(k)+b

On the supposition that there is a linear relation between the produced data of the model response, m(k)=ay(k)+b, the coefficients a and b are determined from

$$(a,b)=\arg\left\{\min_{(a,b)}\left\{\sum_{k=1}^{N}(m(k)-ay(k)-b)^2\right\}\right\}$$

The analytical solution to the designated problem of minimization gives the expressions

$$a = \frac{\sum_{k=1}^{N} y(k)m(k) - N \cdot \overline{y} \cdot \overline{m}}{\sum_{k=1}^{N} y(k)^2 - N \cdot \overline{y}^2},$$

$$b = \overline{m} - a \cdot \overline{y}$$

Graphic criterions:

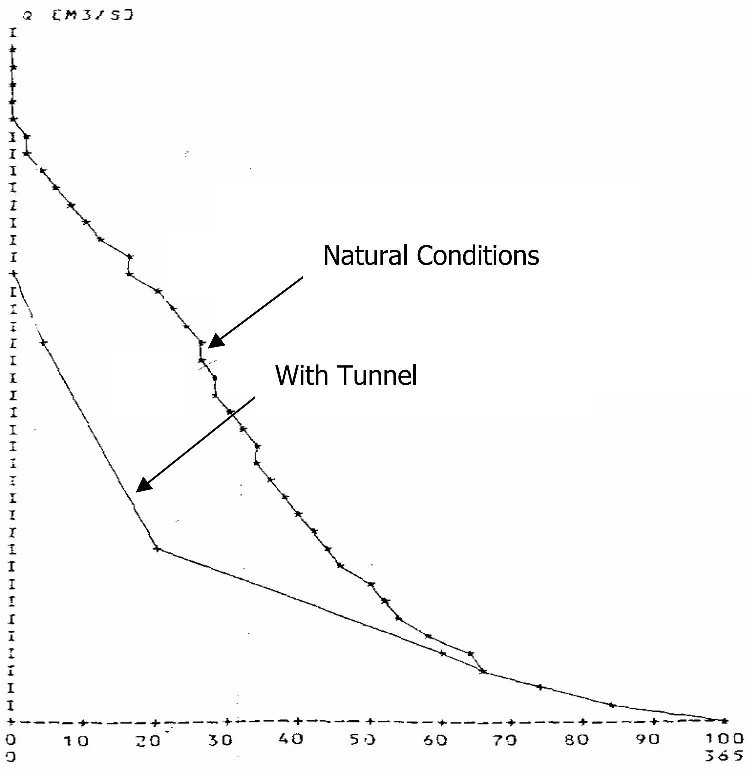
- Graphs of hydrographs (the hydrographs of three series: the series of the measured values, the series of the model output, the series of the model errors, with linear distribution along the ordinate, as well for the entire period of time).
- Double cumulative curve (with entered cumulative values of the data produced by the model and the measured data).
- Continuance curves (with continuance curves continuance ranges shown).

KRIVA TRAJANJA DNEVNIH VRIJEDNOSTI PROTICAJA

R. BRESAVE

PERIOD: 1972 – 1984 G.

RAZRED	TRAJANJE N	TRAJANJE %
58.70		
57.24	0.5	0.1
55.79	1.0	0.3
54.33	1.2	0.3
52.87	2.0	0.5
51.42	3.5	0.9
49.96	5.3	1.5
48.51	9.0	2.5
47.05	12.0	3.3
45.59	19.0	5.2
44.14	27.5	7.5
42.68	33.5	9.2
41.22	44.5	12.2
39.77	56.0	15.3
38.31	60.7	16.6
36.86	73.6	20.2
35.40	80.2	22.0
33.94	86.8	23.8
32.49	91.4	25.0
31.03	96.2	26.3
29.57	100.6	27.5
28.12	104.6	28.6
26.66	110.4	30.2
25.21	116.2	31.8
23.75	120.7	33.1
22.29	125.8	34.4
20.84	129.1	35.3
19.38	135.8	37.2
17.92	143.3	39.2
16.47	153.3	42.0
15.01	160.2	43.8
13.56	171.2	46.9
12.10	179.2	49.1
10.64	188.1	51.5
9.19	198.5	54.3
7.73	209.8	57.4
6.27	230.7	63.2
4.82	243.5	66.7
3.36	267.8	73.3
1.91	306.0	83.8
0.45	365.3	100.0



PRILOG BR. 1