# J2000 – A Modelling System for Physically Based Simulation of Hydrological Processes in Large Catchments

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**Abstract:** In this paper the J2000, a new modelling system for the distributed simulation of the water balance in large river basins, will be introduced and described briefly. The introduction comprises an overview of the model's purpose and concept, the simulated hydrological processes, the distribution concept for the spatial subdivision of the catchment as well as the methods for regionalisation of climate data from point sources. As an example for the model's capabilities simulation results of a large catchment in Germany are shown.

*Keywords:* J2000; Large basins; Distributed hydrological modelling system

## 1. INTRODUCING THE J2000

The growing awareness of environmental and economical problems related to mismanagement and overuse of the water resources in the last decade is reflected by new laws and guidelines like the EU-Water Framework Directive (WFD). For the implementation and control of the WFD, models or modelling systems like the J2000 are needed, which can be applied to large river basins of more than 1000 km² and provide the ability of modelling the hydrological cycle in a spatially distributed and process oriented manner. Such models can be considered as valuable tools for the quantification of decisions and strategies aimed at a sustainable and environmentally sound management of the water resources in large river basins as addressed by the WFD.

For micro- to meso-scale applications a large number of process oriented hydrological models have been developed in the last decade. Such models have in common, that they are able to simulate the processes influencing the runoff generation and concentration with a reasonable degree of certainty on their specific scale. The major problem which is limiting the transfer or up-scaling of the small scale models to large catchments is the increasing heterogeneity of the catchment's environmental parameters complemented by decreasing data accuracy and availability on the larger scales. Most of the small scale models cannot reflect these constraints properly because of:

(i) Their implemented methods which often need data sets for parameterisation and validation that are not available in sufficient temporal and spatial resolution.
(ii) Missing routines taking the processes and in particular the increasing temporal and spatial heterogeneity influencing the water balance in large basins into account.
(iii) The changing dominance of single processes at different scales which is often not reflected by the model concepts.
(iv) Their often monolithic software design and slow computing performance, which is limiting their applicability to a relative small amount of spatial entities or input data sets.

Additionally it can be stated, that most of the small-scale models were developed for the investigation of specific key questions, reflecting the research focus of the development team. As a result most models address only some aspects of the hydrological cycle in a very detailed and sophisticated way but often neglect others by simulating them with simplifying algorithms.

Compared to the large number of models for micro- and lower meso-scale catchments only few process based models are available which were explicitly developed for applications in large river basins. The concept of such models compared to small-scale models is mostly much simpler concerning the simulation of the single processes and the implemented algorithms and methods as well as their distribution concept and their temporal resolution. To help in bridging the gap between the small and the large-scale models the J2000 was developed, which is described briefly in this paper. A detailed description of the model including three case studies can be found in Krause [2001].

### 1.1 Concept of the J2000

The J2000 should not be understood as "just a new model", as it was designed as an open modelling system. It provides functionalities for the pre-processing of input data, e.g. precipitation correction, regionalisation of climate data from point sources, calculation of potential evapotranspiration etc. besides the model core where methods for distributed, process oriented simulation of the runoff generation and concentration are incorporated. The methods for each process are implemented as encapsulated program modules which are supplied by the modelling framework with the data they need and are returning their output back to the modelling system for ongoing processing in following modules. This object oriented, modular approach keeps the whole system open for enhancements and provides the possibility to exchange single program modules without rebuilding the whole model from scratch.

### 1.2 Distribution Concept

The distribution concept of the J2000 is realised by three different aggregation levels reflecting the different spatial and temporal dynamics of specific process levels: (i) the processes concerning the spatial and temporal distribution of the climatic input data; (ii) the processes of runoff generation; (iii) the process level of the runoff concentration and flood routing. Because the three process levels are showing a decreasing dynamic concerning their spatial and temporal variability they can be modelled with decreasing spatial resolution without losing to much information or certainty.

The most important aggregation level is the subdivision of the catchment into Hydrological Response Units (HRU) following the physiogeographic delineation concept introduced by Flügel [1995]. The HRUs are delineated by overlay techniques of the data-layers elevation, slope, aspect, land-use, soil-type, hydrogeological units and sub basins inside a GIS providing a pattern of single units with similar data-sets. It has to be noted that the single units resulting from this delineation method are not spatial enclosed entities, moreover one single HRU can be scattered throughout specific regions of the catchment. The largest advantage of the HRU-concept is the reduction of modelling entities without losing information resulting in a hydrologically sound discretisation of the catchment complemented by clearer model concepts and faster modelling performance. The largest disadvantage can be seen in the fact, that the single units are not separate entities and therefore cannot be located or geocoded exactly. Because the exact location is needed for sound regionalisation of climate data from point sources a second layer called *discrete sub-area layer* is derived by disaggregation of the HRUs into single enclosed entities. Those can be located precisely inside the catchment providing the spatial basis for the regionalisation routines. The third aggregation level of the J2000 is obtained by subdivision of the whole catchment into sub-basins providing the spatial distribution for the calculation of the runoff concentration processes and the flood routing in the channel network.

The entities or units of the three different aggregation layers are parameterised by GIS routines to provide the physiogeographic data needed for the calculation of the single processes inside the three process levels.

### 1.3 Pre-processing

The pre-processing part of the J2000 comprises the delineation of the units of the three different aggregation levels, their parameterisation as well as the regionalisation and correction of the climate data and the calculation of the potential evapotranspiration, providing spatially distributed input data-sets for each time step for subsequent use during the simulation runs.

#### 1.3.1 Regionalisation of climate data from point sources

For the J2000 daily values of the climate data-sets precipitation, minimum and maximum air temperature, wind speed, relative humidity and sunshine hours are needed as driving variables. These data sets are commonly provided as routine measurements from the climate stations of national weather agencies. For the transformation of this point data into spatially distributed data-sets, regionalisation methods are implemented into the pre-processor of the J2000. These methods analyse the vertical (e.g. decrease of temperature with increasing elevation) and horizontal (e.g. horizontal variation of rainfall) variability of each data set for each time step. The vertical variability is quantified by a linear regression between station elevation and parameter value, providing a daily gradient and the coefficient of determination. If this coefficient is greater than a user-defined threshold, the parameter values are adapted to the elevations of the discrete sub-areas by the gradient of the regression line. By this approach the vertical variability is only considered for data values which show a significant dependency from the elevation at the specific time step. The horizontal variability is considered by an inverse distance weighting method also incorporated into the J2000. The use of more sophisticated regionalisation methods is indispensable for macro-scale hydrological modelling because they reproduce the larger heterogeneity of the spatial distribution of climate input data much better than e.g. monthly lapse rates or Thiessen-polygon approaches, often found in hydrological models.

The regionalisation methods are complemented by correction functions for eliminating systematical errors in precipitation measurements. Those functions take underestimation induced by wind drift and losses resulting from wetting and evaporation from the measurement equipment into account.

### 1.3.2 Evapotranspiration calculation

The potential evapotranspiration (ET) is calculated according to Penman-Monteith inside the preprocessing part of the J2000 using the regionalised climate data-sets and the parameters of the specific landuse class of each HRU. The implemented equation takes physical constraints, (e.g. temperature and wind speed) as well as vegetation specific parameters (e.g. aerodynamic resistance, bulk resistance, effective height) of different vegetation types into account. The seasonal dynamics of these vegetation parameters are derived throughout the year by continuous functions extrapolated from discrete values taken from various literature sources. During the modelling the actual ET is calculated based on the potential ET and the actual soil moisture using either a linear or a non linear relationship.

## 2. MODELLING OF RUNOFF GENERATION

The runoff generation is simulated inside the modelling core of the J2000 considering the single processes for each HRU. For this purpose the regionalised input data sets are used as driving parameters together with the physiogeographic parameters of each HRU derived from the GIS data-layers. In a preceding step it is determined whether the precipitation is falling as snow or rain or a mixture of rain and snow by a probability function determined from the air temperature. In the next step the precipitation is passed to the modules described in the following sections, and underlies the different transformation processes and finally produces the runoff separated in up to four components which will be described later in this paper.

### 2.1 Interception Module

The first simulated process, the interception is modelled with a simple approach where a maximum interception storage capacity of the vegetation cover is calculated by multiplying the Leaf Area Index (LAI) with a specific storage value. In the J2000 the option was implemented to use different storage values for rain or snow depending on the air temperature in order to reflect the higher storage capacity of the vegetation cover for snow. Any precipitation exceeding the maximum interception storage capacity is passed as throughfall to the following module. The interception storage is depleted by evaporation only, with one exception that occurs when the storage value is changing from snow storage to rain storage. This reduces the maximum storage capacity significantly producing a higher amount of throughfall, resulting from the interception excess.

### 2.2 Snow Module

For the simulation of the processes of snow accumulation, compaction and snow melt, two optional modules are implemented into the J2000. The user can choose between a simple day-degree-method or a more complex calculation method according to Knauf [1980]. Only the latter will be described here. The complex snow-module simulates accumulation and compaction of the snow pack caused by snow melt or rain on snow precipitation events. During the life time of the snow pack two phases are differentiated: (i) the accumulation phase and (ii) the compaction and melt phase. The model switches between those two phases depending on the air temperature. If the temperature is lower than the specific temperature threshold and the whole precipitation falls as snow, only the accumulation phase is active. If the temperature is above the second threshold where the whole precipitation falls as rain, only the setting and melt phase is active. Between the two thresholds both phases are active, allowing the modelling of snow accumulation and snow melt inside one time step.

Snow accumulation is calculated by simply adding the snow-water-equivalent of the snow precipitation to the dry snow water balance and increasing the snow depth. If the compaction and melt phase is active a potential snow-melt-rate is calculated using either a day-degree-method or a more complex equation taking energy input from air temperature, rain fall and soil heat fluxes into account. The liquid water from the snow-melt seeps into the snow pack and implicates a compaction of the snow. The same processes are occurring if rain falls on the snowpack. The liquid water is stored in the snow pack until a specific threshold, described by a critical density, is reached. After that snow-melt-runoff from the snow pack occurs which is passed to the next module.

### 2.3 Soil Water Module

The central part of the modelling core of the J2000 is the soil-water module, reflecting the central position of the soil, acting as a regulation and distribution system, influencing nearly all processes of the hydrological cycle. The concept of the soil-module is shown in Figure 1.

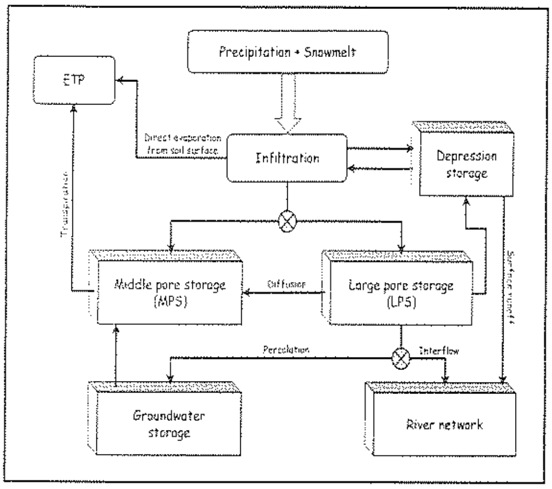

**Figure 1** The concept of the soil-water module of the J2000, showing the storages and processes.

Infiltration is the first process the water encounters. Because the J2000 simulates the water balance in daily time steps physically based algorithms like Richard's equation or the Green & Ampt model for simulation of Horton's overland flow cannot be used, because they need higher temporal resolved input data. Nevertheless surface runoff resulting from infiltration excess is an important process which should be considered. In order to deal with this, a simple empirical approach was implemented in the J2000 to reproduce overland flow resulting from snow-melt on frozen soils or inside the snow-pack and from infiltration excess during rainfall with high intensity, mostly occurring in the summer period. For this purpose three different threshold values for maximum infiltration capacity can be set by the user. These values are multiplied during the simulation with the relative saturation of the soil-water storages resulting in a maximum infiltration rate in mm/d. Any water exceeding this rate is passed to the depression storage from where it can either produce surface runoff or it remains for infiltration until the next time step, depending on the slope of the specific HRU. Rainfall or snowmelt on impervious areas partly results in surface runoff depending on the grade of sealing.

The storage concept used in the J2000 considers the hydrological conditions inside the soil profile by two different storages (Figure 1). The first one is the Middle Pore Storage (MPS) describing the water storage capacity of the middle sized pores (diameter 0.2 to 50 μm) in which stored water is hold against gravity and can only be drained by an active tension. The second storage called Large Pore Storage (LPS) describes the water storage capacity of the large and macro pores (diameter > 50 μm), which are not able to hold the water against gravity and which is therefore considered as the source for any vertical and horizontal flows. The storage capacity of the MPS and LPS is determined by the description of the soil profiles together with the effective rooting depth of the landuse class for each HRU. The distribution of the infiltrated water between the two storages is calculated using the relative saturation of the MPS as an indicator. The more saturated this storage is, the less water it receives and vice versa. This approach ensures that the LPS always gets some part of the infiltrated water, except when the MPS was completely depleted during the preceding time step. By this method vertical or horizontal runoff can occur before field capacity is reached. Therefore fast runoff resulting from preferential flow paths or macro pores is reproduced much better than by the very often used methods where runoff can only occur after field capacity is saturated.

The Middle Pore Storage is depleted by transpiration by the vegetation cover only. The amount of water which is drawn out by the vegetation depends on the actual evapotranspiration deficit and the relative saturation of the MPS by using either a linear or a nonlinear, s-shaped relationship between the two variables.

As already mentioned the Large Pore Storage is the source of the vertical and horizontal flows occurring inside the soil. The total amount of outflow from LPS is calculated by a nonlinear relationship taking the relative saturation of the storage into account. The well known significantly faster response of a catchment with high antecedent soil moisture compared to one with dry soils can be reproduced much better by a nonlinear outflow function in comparison to a linear relationship. In the next step the total amount of outflow is distributed to the horizontal (interflow) and the vertical (percolation) component. The contribution to each of the components is calculated by taking geomorphological (e.g. slope) as well as pedological (e.g. hydraulic conductivities, thickness of soil horizons) parameters extracted from the input data layers and specific relate tables derived for the model into account. In other words a HRU with steep slope and a highly permeable soil horizon above a dense non permeable one produces more interflow whereas the outflow of a flat HRU with good permeable soil horizon throughout the profile results in higher percolation rates or groundwater recharge. If the HRU is linked to a highly saturated groundwater storage, the percolation rate is reduced and the excess is passed back to the LPS. If there is still water left in the LPS after the subtraction of the two components, this amount is partly used for replenishing the MPS depending on its actual relative saturation.

## 3. MODELLING OF RUNOFF CONCENTRATION

After the calculation of the runoff generation processes on the basis of the HRUs as described above, the runoff concentration, the groundwater balance and the flood routing in the river channels is simulated on the next aggregation level, the sub basins. Each of the sub-basins is described by a concentration index taking the terrain energy into account, together with the flow-length and slope of the main channel. For each of the four runoff components distinguished by the J2000: surface runoff (RD1), interflow from soil zone (RD2), interflow from the weathering layer of the underlying hydrogeological unit (RG1) and baseflow (RG2) different concentration storages receiving the runoff components from the HRUs are defined for each sub-basin. These concentration storages contribute their specific outflow to corresponding channel storages of each sub-basin by transforming their input with suitable retention functions taking different conditions and constraints into account. For this purpose additional, temporal dynamic parameters like antecedent soil moisture or saturation of groundwater storages are calculated for each time step.

The flood routing inside the channel network is simulated by connecting the channel storages, receiving the water from the concentration storages of the single sub-basins by a hierarchical storage cascade and calculating the flow velocity inside the river bed with the Manning-Strickler equation.

## 4. MODEL RESULTS

To assess the model's performance it was applied to three large catchments (4200 – 6200 km²) in Eastern Germany. Only the modelling results of the Mulde catchment will be shown here. The catchment of the Mulde river, lying in the federal state of Saxony, comprises an area of 5940 km². The basin encompasses the mid-mountain range of the Erzgebirge in the southern and central part with elevations up to 1200 m a.s.l., characterised by steep slopes and deep valleys. The northern part can be described as relatively homogenous and flat with elevations below 100 m. 55% of the basin is used for agricultural purposes, whereas the higher regions of the Erzgebirge are covered by coniferous forests (26 %). Inside the catchment, the larger cities of Chemnitz, Zwickau and Freiberg besides numerous smaller villages are located. The geology is dominated by fractured hard rocks in the mid-mountain part and quaternary loose rocks with loess cover in the northern part, resulting in sandy to loamy soils in the southern part and loamy to clayish soils in the northern half. The hydrological regime is dominated by high floods during snowmelt between December and April and low flow periods in the summer months. The low flow conditions in summer can be interrupted by short high flow events resulting from convective rainfalls with high intensity. The parameterisation of the catchment was done by data bases which are available on national scale, resulting in 3264 HRUs with areas between 0.5 and 40 km², 8779 discrete sub-areas and 23 sub-basins. A ten year time series from 1980 to 1990 was chosen for the simulation with the J2000 consisting of precipitation measurement from 80 stations and climate measurement from 5 stations. The first year was used for model initialisation, the next 5 years for calibration and the remaining 4 years for model validation.

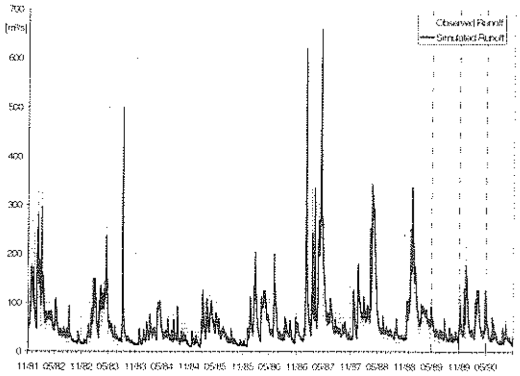

**Figure 2** Simulated and observed runoff of the Mulde catchment at gage Bad Düben.

Figure 2 shows the simulated and observed runoff demonstrates that the model is able to reproduce the dynamics of the runoff quite well, but underestimates some high flow peaks. The good concordance of the simulated and observed runoff is shown by the Nash-Sutcliffe efficiency which was calculated as 0.84 for the whole period. In the years 1987 and 1988 the efficiency was even higher with values of 0.89 and 0.90. In only one year of the 10 year time-period an efficiency lower than 0.7 was seen in 1984 where only a value of 0.18 was achieved resulting from the significant underestimation which can also be seen in Figure 2. To validate the model's quality not only at the basin's outlet but also inside the catchment observed runoff measurements of the 23 sub-basins were compared with the simulated runoff. These measurement were not used during the model calibration to ensure independence. The comparison (not published here) shows that the runoff of nearly all sub-basins were reproduced reasonably well by the model, providing the evidence that the J2000 is able to simulate the runoff generation and concentration processes not only for the whole basin but also inside it with a sufficient degree of certainty.

The spatial distribution of the modelled runoff generation (Figure 3) as well as the spatial distribution of the precipitation and evapotranspiration showed a clear dependency on elevation. The highest values of precipitation (1300 mm/a) together with the lowest actual ETP (350 mm/a), resulting in a runoff generation of 970 mm/a occurred in the highest part at the mountain ridge in the south. The runoff generation and precipitation values decreased in direction north together with the elevation resulting in values of less than 100 mm/a runoff generation and 600 mm/a precipitation in the northern part.

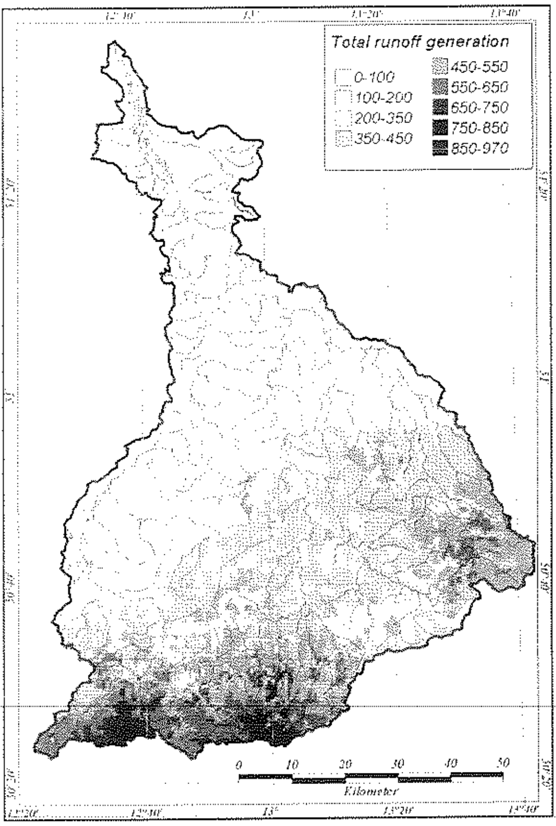

**Figure 3** Spatial distribution of mean annual runoff generation in mm/a (1980-1990)

The runoff separation carried out by the J2000 showed that the fast base-flow component RG1 (43 %) dominated the total runoff and in particular the high flow peaks during the year. The slow base-flow component (RG2) contributes continuously throughout the year (34 % of total runoff) and became the dominant component during low flow conditions in the summer period. Surface runoff RD1 (13 %) and subsurface runoff RD2 (10 %) were only contributing significantly during high flow events in the winter and summer periods. The spatial distribution of the runoff components showed that the mid-mountain range was dominated by component RG1, whereas in the flatter northern parts RG2 became dominant. On the impervious areas of cities and villages RD1 was dominant, whereas RD2 was only important on valley sides. To validate the correctness of the runoff separation performed by the J2000 the relative contributions of the runoff components were compared with the results of an independent investigation of the runoff components in some sub-basins of the Mulde published by Schwarze et al. [1999] using the DIFGA method. The comparison of these results and those achieved with the J2000 showed that the relative contributions of the different components are quite similar and both were identifying the fast groundwater component RG1 as dominant in all catchments.

## 5. CONCLUSIONS

The described modelling system J2000 can be considered as a valuable tool for the simulation of the water balance in large catchments. The model results showed that the runoff at the catchment outlet is reproduced quite well. A rough validation of the model's correctness inside the basin has been made by comparison of the model results with measured runoff from various sub-basins. The results not shown in this article showed a reasonably good fit for these sub catchments. The principle correctness of the runoff separation was shown by comparison of the contribution of the four runoff components of various sub basins as modelled by the J2000 with an independent investigation with the DIFGA method in the same sub catchments. Both methods identified the fast baseflow component as the dominant runoff component and estimated the relative contributions as percentages of the total runoff for all four components quite similarly.

The implemented opportunity to observe each of the calculated variables in a spatially distributed manner makes the J2000 suitable for quantifying the impact of different management or landuse/climate change scenarios on the water balance of large catchments.

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