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Control model Spree/Schwarze Elster — a tool to optimise rehabilitation of water resources in the Lusatian mining district

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Abstract

The river basins of the Spree and Schwarze Elster have been disrupted by the long-lasting intensive lignite mining process in the Lusatian district, resulting in a large cone-shaped groundwater depression of 4000 km^2. Its volume is about 10 billion m^3, or about 15 times the annual groundwater recharge of that region. Special problems relate to the flooding and future use of remaining pits. With regard to water quality (acidification) it is necessary to accelerate the natural filling process by supplying surface water. This depends on its availability, as well as on the regional water balance. For the Lusatian river basins, long-term water resource planning models exist. These models combine on a monthly basis a stochastic simulation model of runoff with a deterministic analysis of water demand and availability of water resources. Based on these models, the overall and long-term water management strategies are developed. To control the daily water balance and to supply water for flooding the remaining pits, a short-term control model is now under development. It is based on the long-term strategy, but takes into account the actual runoff of the region, discharge in the rivers and water consumption. In this paper both the models and their applications are discussed. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

One of the crucial problems in the post-mining landscapes of the Lusatian lignite mining district is the rehabilitation of the water-resource system. The river basins of the Spree and Schwarze Elster rivers have been disrupted by the long-lasting intensive mining process, resulting in a large cone-shaped groundwater depression of about 4000 km^2, with a total volume of about 10 billion m^3. This volume is equal to about 15 times of the annual groundwater recharge in the mining region and causes a significant impairment of the natural drainage regime of the surface waters. Making up this enormous water deficit in an area of relatively low precipitation, such as Lusatia, is a process that will take years, probably decades. For more details see Kaden (1997).

In the post-mining landscape, the remaining pits from open-cast mining are particularly important; the filling and subsequent use of the pits involves special problems for water quality (acidification). As a result, it is usually advantageous to accelerate the natural filling process from groundwater by supplying surface water. But the availability of surface water is limited, so that it is essential to keep track of the available

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water supply over time and space, taking into consideration all requirements for use.

Since 1992, management models — the GRM model family — for the catchment areas of the Spree and the Schwarze Elster have been developed by WASY Ltd as planning instruments, to help evaluate alternative water-management measures such as the building of reservoirs or artificial flooding to be taken in time. These management models have been and are being used by the states involved —Saxony, Brandenburg, and Berlin — to develop a co-ordinated management concept.

The strategies developed with the management models should be implemented in a short-term control model for routine operations of the water system. One of the major objectives is to employ the available water on a short-term basis, as well as for covering demands, and, in particular, for flooding the pits left by open-cast mining. From the modelling point of view, this means implementing the long-term management algorithm as the core of a control model to be developed.

This work is currently being done on commission from the LMBV Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH, and in close co-operation with it and the responsible water-management authorities of Saxony, Brandenburg, and Berlin.

2. ArcGRM Spree-Schwarze Elster management model

The management models developed since 1992 and 1995 for the river basins of the Spree and Schwarze Elster, GRMDYN Spree and GRMDYN Schwarze Elster (Kaden et al., 1995; Schramm, 1994), respectively, were combined last year into the model ArcGRM Spree-Schwarze Elster, since the management of the two river basins should not be considered separately. These models are long-term management models, whose general function is to cover a wide variety of user requirements of the available water resources by suitable measures of water management in the long term with a high degree of reliability.

Fig. 1 presents a greatly simplified diagram of water management in mining regions. It shows that water management is integrated into the hydrological cycle, which is shaped by precipitation and evaporation as the dominant factors in runoff generation, and runoff into the surface waters and into groundwater. Superimposed on these natural processes are anthropogenic components, such as use of surface water and groundwater, and water-management measures, such as reservoir control or transfers. In mining regions, the discharge of mine drainage as well as the remaining pits have to be considered too.

The goals of this management are, for example, covering the water needs of the users, maintaining minimum discharges (for ecology reasons), and effective protection against floods.

Water management is a stochastic problem. It is true that the drainage process itself is a deterministic one, but lack of knowledge of the hydrometeorological processes driving it, and of the spatial–temporal distribution of runoff generation, forces us to regard the runoff process over the long term as a random process. The user demands, on the other hand, are deterministic in time and space from the planner's point of view, although they may well depend on meteorological variables, for example.

Based on the stochastic character of runoff, and thus of water management, the methodology of stochastic long-term management has been developed, mainly for areas characterised by a large demand for water and small water resources available. Insofar as the territory of the former German Democratic Republic (GDR) is concerned, these are mainly the mining areas of Lower Lusatia and of the Leipzig region.

The stochastic management models of the GRM type divide the stochastic management problem into three parts:

- Stochastic simulation of meteorological and hydrological processes
- Deterministic simulation of the processes of water use
- Recording of relevant system states

This results in the flowchart shown in Fig. 2.

If the month-by-month simulation is done over sufficiently long periods, a statistical analysis of the recorded system states will give satisfactory approximations to the probability distributions sought, for reservoir levels and discharges for certain water-balance profiles, or safety margins for water provision, for example.

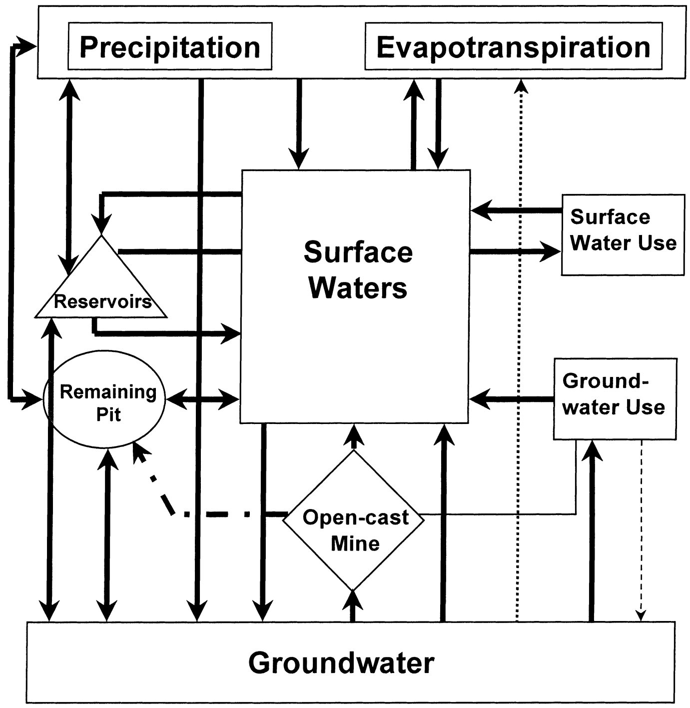

Fig. 1. Scheme of water management in mining regions.

In many riverine areas, it may be assumed that the conditions for runoff generation are time-invariant, and that the stochastic flow simulation may be performed with invariant characteristics (distributions, correlations, etc.). In the GRM management model, the flows thus generated are contrasted with demands belonging to a particular water-budget year. By means of variation calculations, suitable management concepts for the corresponding year can then be determined. The procedure is illustrated in the upper right corner of Fig. 2.

In mining regions with wide-ranging, time-variant groundwater depression cones, the mode of operation of a GRM described cannot be maintained. The boundary conditions for the drainage conditions are no longer constant. A change-over from a water budget year to a budget era became necessary. This must then be subdivided into sections several years long (5 years, for example), called 'periods', in which approximately constant conditions for flow generation and water use may again be assumed. The sequence of the 'dynamic' management model thus created, GRMDYN, is shown in the lower right corner of Fig. 2.

In order to obtain stable results, the runoff and water use processes during the budget era must now be simulated often enough, and the system states recorded separately for each period. Thus, the distributions and safety margins for each period are obtained. In this way, the development of the river basin under consideration can be estimated, and the times at which water management measures to preserve a stable provision of water become necessary can be determined.

When setting up such a dynamic management model, the simulation of natural runoff in the areas of a river basin disrupted by mining presents great difficulties. The available time series of water levels in these areas cannot serve as the basis for a stochastic flow simulation because these series are subject to pronounced time-variant anthropogenic overlaying factors. In addition, the changes expected in the future budget era cannot be taken into account directly in the probability characteristics needed. A way out of this dilemma is offered by an indirect flow simulation, making use of precipitation–runoff models. Here, meteorological processes such as precipitation or

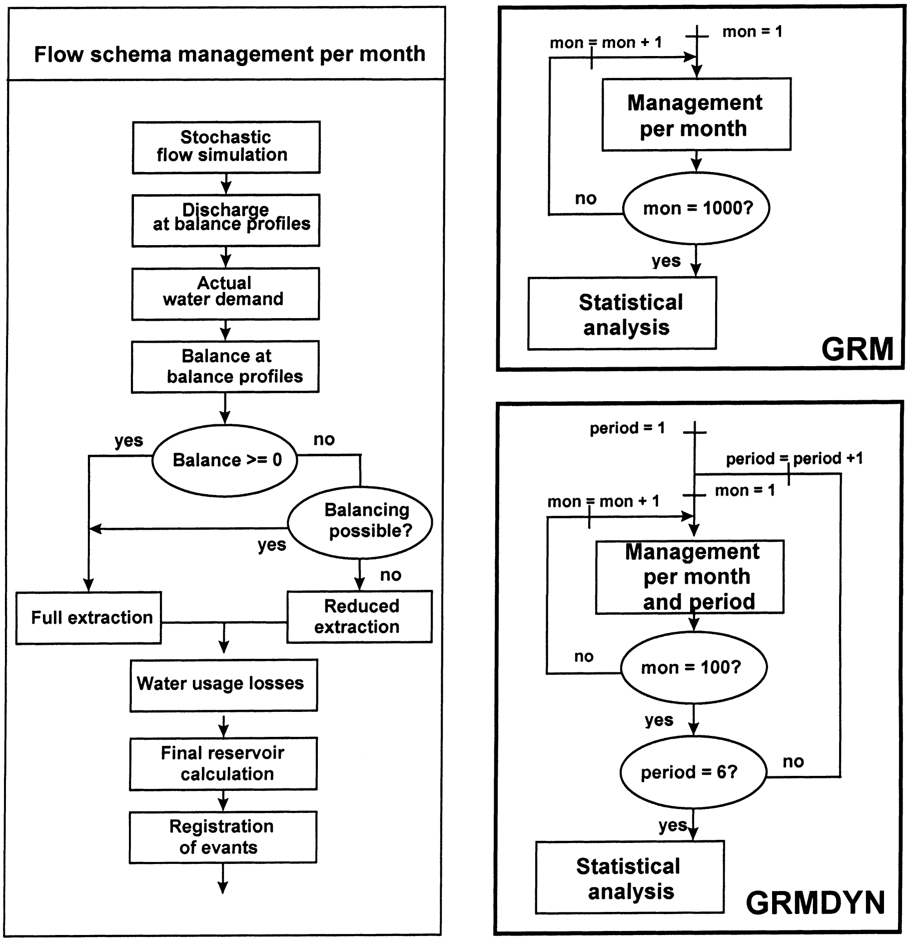

Fig. 2. Flowcharts of stochastic water management models of the GRM type.

evaporation are generated stochastically, and used as input variables for the models. The changes over time of the influence of mining are included by considering for runoff generation only those parts of a region that do not lie in groundwater-depression cones. The 'wandering' of the boundaries of the cone causes the portions generating runoff, and thus the runoffs themselves, to vary. The position of the cone boundaries is computed by means of regional groundwater models, which are based on a given mining development plan.

The ArcGRM management model is a refinement of GRMDYN under the desktop-GIS ArcView. Its application to the Spree and the Schwarze Elster means the integration of the two GRMDYN mentioned above on the basis of an agreed flow simulation model for both river basins. The management algorithm on which it is based, which has been agreed upon among the States of Saxony, Brandenburg and Berlin, is the core of the control model being created and described below.

3. GRMSTEU control model

3.1. Methodological principles

The GRM water management algorithm is strictly demand-oriented, i.e. just enough water is provided or redistributed by means of reservoirs and transfers in addition to the natural water resources to cover the water demands of the users. This economical handling of the available water is especially significant in the basins of the Spree and the Schwarze Elster for the following reasons:

- the discharges of mine-drainage water will continue to decline in coming years;
- the natural water resources are only increasing again very slowly; and
- substantial amounts of water are needed to flood the remaining pits left by open-cast mining and for subsequent follow-up measures.

Water distribution control based on the advantageous GRM algorithm is, therefore, urgently required.

Such a control system will have the general sequence shown in Fig. 3. Starting with a particular system state (flow, water use) at time *w*, flow forecasts for a subsequent period of time are generated, considering water requirements, in accordance with the agreed management algorithm.

With the help of this algorithm, the permissible actual values of water extraction, and the reservoir discharges and transfers necessary for this, are calculated. In other words, based on *state variables* (flows, reservoir levels, extraction, inputs, etc.) for previous days, values for the *control variables* of the system (reservoir discharges, transfer or extraction amounts) for the coming days are determined.

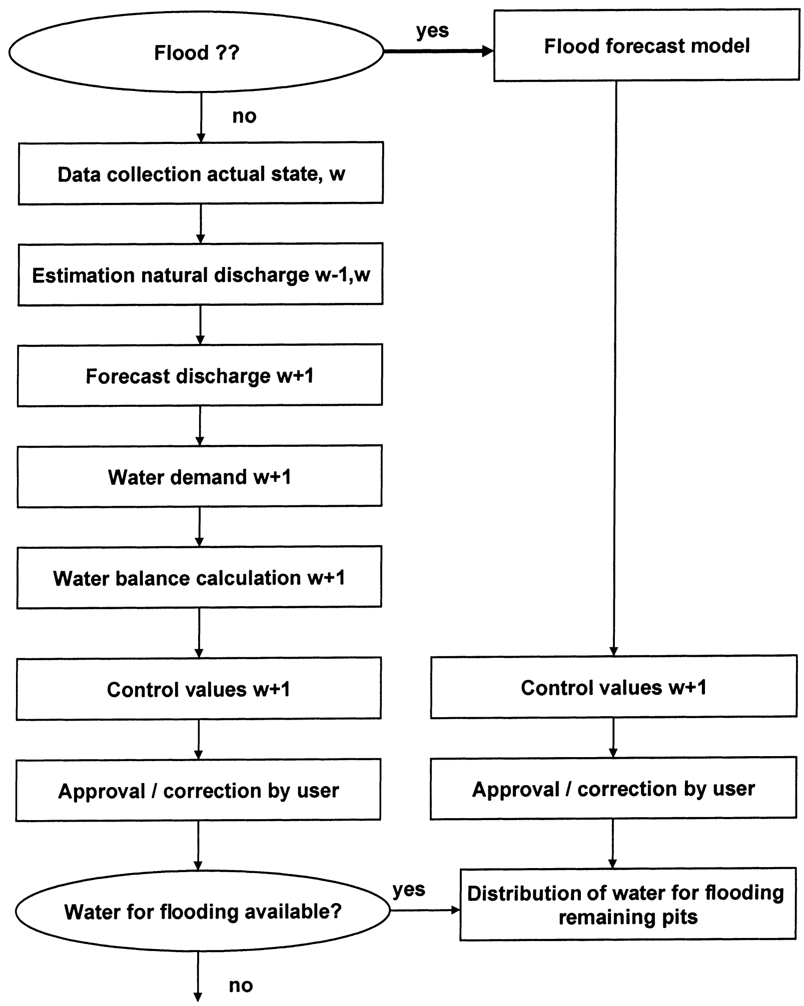

Fig. 3. Generalised flowchart of the control model GRMSTEU.

The one-month interval of ArcGRM is considerably too long for short-term control. To revert to a one-day basis is surely not only impossible for organisational reasons, but would also violate a basic precondition of the GRM, that all changes of state must occur within the time interval selected. But this is not even approximately true in the two river basins under study. As a compromise, the interval of 1 week seems suitable. However, such a pragmatic determination has three consequences:

1. If runoff changes greatly in the coming week (e.g. transition from a low-water period to mean flow), then the control model must be activated again before the week ends.
2. If flow augmentation by reservoir releases take place over lengthy stretches of river (e.g. assistance to drainage in the Große Tränke from the Spremberg reservoir), then it may be necessary to calculate the transit times and consider them in the release calculations. Otherwise, there is a risk of flow augmentation occurring too late or for too long.
3. During flood, the GRM module of the control model must not be used at all; instead, flood forecast modules should be employed, which calculate the significant control variables. These include reservoir releases, and above all, water available for flooding of the remaining pits.

3.2. Computational implementation

The control model GRMSTEU comprises the following modules:

GRM	GRM base module for using the agreed management algorithm for the two river basins,
BEREIN/PROG	calculation of the natural runoff for all defined sub-districts from the state variables, and a runoff forecast for the coming week based on this,
ERLK	distribution of the extraction for flooding from four hydrographic profiles among the remaining pits to be filled in the Senftenberg area,
LAUF	calculation of the transit times of reservoir releases for flow augmentation from the Spremberg reservoir to the Spree gauge Große Tränke.

For reasons of sovereign water authority, the flood forecast does not become part of the control model. The coupling of the two models is done off-line: essential results of the flood forecast models, such as potential extractions for flooding, or reservoir releases, are transmitted to the control model, and the ERLK module is activated.

All the state variables needed for the control model are registered in the form of a message schema, and filed in an external MS-Access database. This filing is done on a daily basis, and must be complete up to the day before the control model is used. The control variables estimated by the control model can then be modified manually by the users, if the specific system conditions require it, for example if there are malfunctions in reservoirs.

3.3. Adjustment and prediction of the runoff

The required quasi-natural runoff of all sub-basins for the coming week are estimated on the basis of known discharges at river gauges of the previous weeks. The generation of the sub-basin runoffs follows the general schema

$$Q(\mathrm{TG})_{\mathrm{adjust}} = Q_{\text{lower-level}} - Q_{\text{upper-level}} + \text{extractions} - \text{inputs}$$

Thus, a sure determination of the natural outflows of the sub-basins requires reliable records of water levels and water usage, as well as realistic assumptions about usage in the future.

The runoff forecast is done for gauges on the upper reaches of the rivers without mining influences with the help of simple second-order regression equations in the logarithmic range:

$$\ln(Q(w+1)) = a^{*}\ln(Q(w)) + b\ln(Q(w-1)) + c,$$

where w represents week number.

The regression coefficients have been estimated by means of long time series of these gauges, separately for phases of increasing and decreasing flow. Especially for increasing phases, the accuracy is naturally not very high. The mean ratio $Q(w+1)/Q(w)$ is assumed to hold for the sub-basins in the mining regions.

An increase in prediction accuracy cannot be achieved in the future until observed precipitation or even precipitation forecasts can be included in the message schema, and thus also as regressors in the regression equations.

3.4. Flooding distribution module

Of decisive importance for the remediation of the water budget in Lower Lusatia is a factor called the ‘Extended Chain of Remaining Pits’, which comprises nine remaining pits with numerous connections between them and the river system. The flooding quantities are usually the input to the flooding distribution module on a weekly basis, but, of course, at intervals of a few hours during a flood. It is then the task of this module to distribute the available amounts among the remaining pits in such a way that the specified water-level set-points in them are reached in an optimum fashion, taking into account the times of going into operation, the capacities and the gradient of the distribution pipelines, as well as the differing water levels in the individual pits. In addition, the module must regulate the follow-up activity in the form of provision of pass-through quantities if a pit has reached its final water level. At a later time, it will be necessary to take account of water quality criteria in the module, as well.

At present, a variant for this module that includes optimisation of the flooding distribution is being examined. The goal function is the deviation between the set-points and actual values of the water levels in the remaining pits, which should be minimised by the flooding. The result of the optimisation consists in stating the distribution factors for dividing the available flooding water among the individual pits.

The practicability of such an approach is thus determined by the specification of sensible water level set-points as a time function. As an alternative, the distribution can be done on a heuristic basis by the model user.

3.5. Potential effects of the control model

The extraction of water for flooding the remaining pits forms a use that requires authorisation by the water authorities. The problem is that there is no simple fixed rule governing the extraction. The quantity of flooding water depends on the current hydrogeological circumstances as well as on the usage in the entire catchment basin (including, downstream parties). If an optimum utilisation of the available water resources for this flooding is to be achieved, then a GRM-based usage authorisation and control is absolutely necessary. In order to prove this, the following variants have been considered:

Variant A	Open-loop control according to the GRM algorithm
Variant B	Stepped closed-loop control

For Variant B, the outflow at the reference river gauge Bärwalde was divided into 1 m^3/s steps. As part of a GRM calculation, the respective sure flooding discharge for Lohsa II and Bärwalde was calculated separately for summer and winter. The results are presented in Table 1.

If the flooding of the two future reservoirs were undertaken with the help of this stepped regulation, instead of the GRM algorithm, the date when the reservoirs would be operational would be shifted almost two years into the future, on average.

If this is applied analogously to the entire region, the potential benefits of the a GRM-based control system becomes clear. Through optimum exploitation of the available resources, the flooding process can be speeded up considerably. Positive effects on the water quality in the remaining pits may also be expected from this.

An initial test of the control model was done on the basis of concrete values of the state variables from the

Table 1
Guaranteed flooding quantities (m^3/s) for the Lohsa II and Bärwalde reservoirs in 1998–2002, as a function of the discharge at the gauge Bärwalde

Discharge Bärwalde	Sure available discharge for flooding remaining pits during summer period	Sure available discharge for flooding remaining pits during winter period
<5	0	0
5–6	0	1,2
6–7	0	4,2
7–8	0	6,0
8–9	0	7,0
9–10	0	8,0
10–11	0	9,0
11–12	9,7	10,0
$12 < x < 20$	$x - 2$	$x - 2$

Table 2
Sample comparison of real, and proposed, control of the model

	Control actually performed	Proposed control by the model	Percentage change
	(1)	(2)	$((2) - (1))/(1) \times 100$
Reservoir release (m^3/s)			
TS Bautzen	1,9	0.8	−47%
TS Quitzdorf	0,6	0.1	−83%
TS Spremberg	15,4	6.9	−55%
Volume of reservoir (hm^3) *on 25 September 1998*			
TS Bautzen	32,5	33,7	+4
TS Quitzdorf	16,2	16,8	+4
TS Spremberg	11,3	14,6	+29
Storage Knappenrode	4,6	5,0	+9
Storage Niemtsch	3,6	6,1	+69

months of August and September 1998, which had been provided by the regional water authorities. Interesting results are obtained if one lets the control model start on 19 September 1998, after the completion of a phase of increased discharge into the Spree and Schwarze Elster. If one compares the control actually carried out during the week of 19–25 September 1998 with that of the control model, one sees that the latter provides more economical management of the reservoirs and increased filling of the them, without breaching important minimum discharge values. As an example, consider the following comparison values (Table 2).

The two floodings of the Gräbendorf and Seese/Schlabendorf remaining pits from the Spree that are already underway could be running at full capacity according to the control model, while in practice, less has been fed in; for reasons not known.

This example must not be generalised quantitatively, since these are only initial test results. But, regardless of this, even a preliminary application of the model demonstrates what potential for accelerated flooding of the remaining pits there is in the application of the control model — which is in the interests of practical all parties involved in the region.

The development and introduction of the flood-control model will be completed in the course of 1999.

4. Conclusion

Long-lasting intensive lignite mining process in the Lusatian district in East-Germany causes significant water resources conflicts, both in terms of water balance and water quality. To find, and to implement, sustainable strategies for water management in the region modelling tools are required. Long-term management models should cover the wide variety of user requirements on the available water resources by suitable management measures of water management in the long term with a high degree of reliability. Short-term control models should help in implementing the long-term strategies in the daily control of the water resources system. With the management model ArcGRM and the control model GRMSTEU model, such tools are available for the Spree and Schwarze Elster river basins. Their application will help to rehabilitate the water resources system in these basins.

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