Strategic Assessment of Water Resources for the Erongo Uranium Province

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Abstract The development of uranium mining in the arid Erongo region of central western Namibia has increased pressure on limited water resources. An assessment of available water resources and demand from different stakeholders was carried out. An Integrated Geohydrological Model (IGHMS) was developed. IGHMS produces time series of key hydrological processes such as channel flow, evapotranspiration, transmission losses, lateral subsurface flow and water level of aquifers in key compartments used by mines and other stakeholders in the region. The model uses an explicit visual modelling approach. This approach facilitates model maintenance and integration of stakeholder actions. IGHMS is a framework model. For important aquifers or aquifer compartments more detailed numerical groundwater models have been developed. IGHMS assures the consistency of boundary conditions. The results of IGHMS have led to a new monitoring and licensing strategy in the uranium province of the Erongo Region.

Keywords strategic environmental impact assessment, integrated geohydrological model, aquifer compartment, regional/basin model, water resources allocation, new monitoring and licensing strategy.

Introduction

The current and planned mining activities in the Swakop River Basin and other areas in the Erongo Region of Namibia will have impacts on the availability and quality of water resources. The Erongo region in the central western part of Namibia receives 350 to less than 50 mm of rainfall per year, most of the mining areas are located in the arid part with rainfall of less than 150 mm per year. Groundwater resources in the crystalline basement are scarce and mostly constrained to shallow alluvial aquifers. In order to minimize negative impacts and to develop environmentally sound strategies for social and economic development it is of paramount importance to understand the distribution of water resources (Benito *et al.* 2009). The sustainable yield of alluvial aquifers needs to be estimated as a basis for water allocation to stakeholders and mines.

A Strategic Environmental Assessment (SEA), conducted by the Southern African Institute of Environmental Assessors (SAIEA) under the auspices of the Namibian Chamber of Mines,has assessed all sector development scenarios in the Namib Uranium Province. One part of this SEA was a Water Balance Study for the river catchments in the Namib Uranium Province which aimed at providing information on water balance and groundwater availability from alluvial aquifers (Külls *et al.* 2009). Recommendations about abstraction constraints were derived from the SEA to reduce the negative impact on ecosystems and existing agricultural users.

The Namibian Ministry of Mines and Energy appointed the Institute of Hydrology (Germany) and BIWAC (Namibia) to carry out the hydrogeological specialist study and water balance of both Khan and Swakop river catchments in the Erongo Region. The works programme comprised the development of a conceptual model based on field investigations (groundwater sampling campaign) and exisiting database information, the implementation of numerical groundwater flow models of selected Swakop- and Khan river compartments (BIWAC 2010) and subsequently an Intergated Geohydrological Model of the Swakop/Khan river catchment as basis for an improved monitoring, decision support system and licensing procedure through the regulator. The Integrated GeoHydrological Model of the Swakop basin (IGHMS) integrates hydrological data, calculates key hydrological processes and state variables and thereby defines hydrological boundary conditions of recharge, lateral inflow and outflow for compartments in a hydrologically consistent manner. Numerical groundwater models can be plugged into IGHMS for a detailed and numerical modeling of specific compartments (BIWAC 2010).Results of the IGHMS are used to evaluate impact of water abstraction scenarios on other stakeholders, mines and farmers in terms of groundwater levels and groundwater flow. These components form a decision support system for water right allocation (Fig. 1).

Delineation of river compartments

Hydrogeological data, remote sensing data and information from field campaigns such as water level depths, river bed geometry and vegetation density were used to determine compartment boundaries. Altogether nine Swakop River compartments and 10 Khan River compartments were delineated and their respective sub-catchments calculated (Tab. 1, Fig. 2). These compartments represent surface and groundwater management units defined by natural boundaries. Most of the basin is characterized by crystalline bedrock composed of schist, granite and amphibolite. The fractured basement aquifer has low groundwater yields. Most of groundwater resources are found in alluvial aquifers that act as a linear subsurface drainage. Alluvial aquifers are recharged by transmission losses from infrequent floods. These alluvial aquifers are characterized by a pool-step sequence. Channel sections of several tens of kilometers are typically separated by basement highs where aquifer depth decreases from several tens of meters to few meters and groundwater re-surfaces. At these steps dense vegetation develops. Compartments are separated by these steps at their upper and lower boundaries. These channel sections were then characterized in several ways. Groundwater samples were taken from boreholes in the river alluvium and adjacent basement aquifers and analyzed for major ions, metals and rare elements as well as CFC samples for characterization of the groundwater residence times of all river sections/compartments in

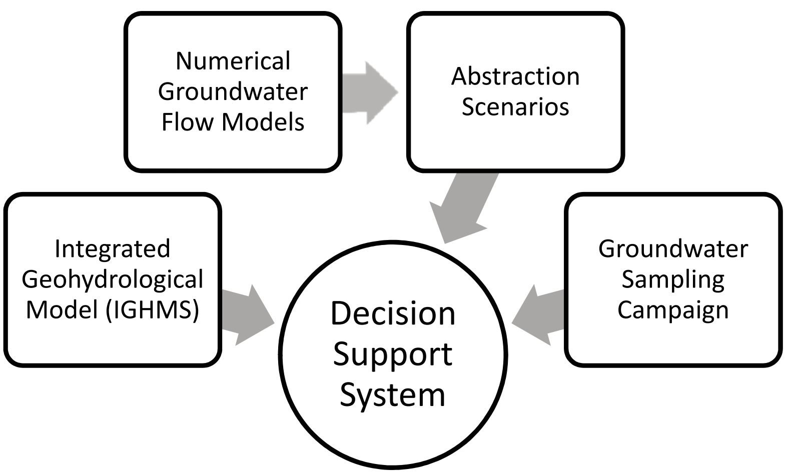

Fig. 1 *Components of a Decision support sytem with Integrated Geohydrological Model stakeholder input*

Compartment	Length of compartment km	Area of compartment km²	Average width compartment m	Average depth m	Average RWL m
S1 WESTFALENHOF	53	8.6	162	8	2
S1 OTJIMBINGWE	26	7.7	296	10	4
S3 POTBERG	42	15.7	374	13	6
S4 HOREBIS	33	10.7	325	23	7
S5 LANGER HEINRICH	26	10.4	401	17	6
S6 HUSABBERG	25	5.3	212	13	5
S7 IDA DOME	36	8.6	240	18	8
S8 ETANGO	20	7.5	376	23	7
S9 FARMING ZONE	29	13.0	449	15	7
K1 SPES BONA	26	5.9	226	14	10
K2 ONGUATI	17	1.6	92	15	8
K3 GROOT ROOIBERG	8	2.1	262	15	8
K4 KLEIN ROOIBERG	11	1.3	114	15	10
K5 NAOB/USAKOS	30	7.5	250	7	3
K6 KHANBERGE	31	5.6	182	23	7
K7 VALENCIA	5	0.8	162	12	4
K8 RIO TINTO	14	1.4	102	18	8
K9 ROSSING	25	4.1	164	18	4
K10 CONFLUENCE	17	3.6	213	22	14

Table 1 *Information on compartment characteristics: Swakop River (S) and Khan river (K)*

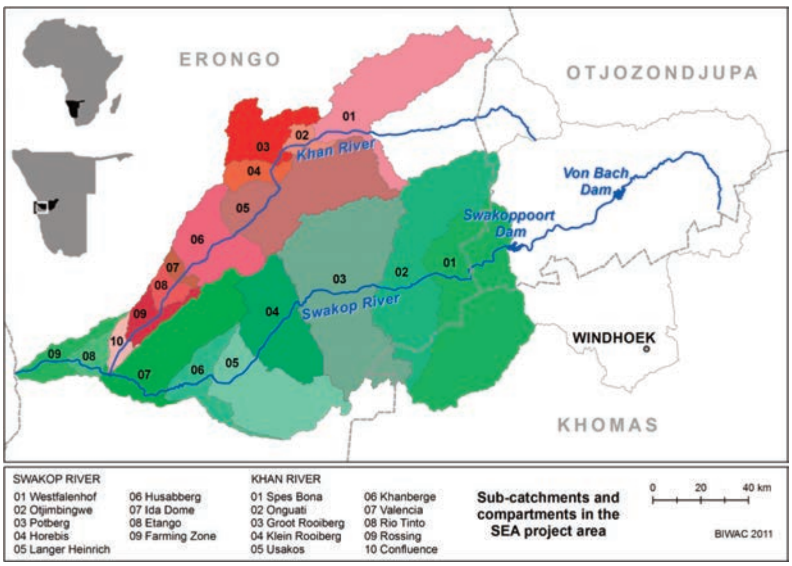

Fig. 2 *Delineation of river compartments and sub-catchments as basis for IGHMS*

the Swakop/Khan catchment within the Erongo Region. For several of these compartments specific numerical groundwater models were developed: Compartments 07 (Valencia) and 08 (Rössing) of the Khan River and 02 (Otjimbingwe) and 05 (Langer Heinrich) of the Swakop River (BIWAC 2010). For these compartments specific hydrogeological investigations using geophysics and available borehole logs were carried out based on which aquifer geometry was defined. The hydrogeological information obtained from the models was incorporated in IGHMS.

Surface and sub-surface flow from each sub-catchment was modeled based on a daily rainfall records and catchment parameters. A unit runoff map of Namibia developed by Namwater based on existing runoff data was used to convert rainfall into direct runoff. Evaporation was calculated based on climate data including temperature and relative humidity using an approach specifically developed for Namibia and calibrated in the study area by Hellwig (1977).

Methods

IGHMS was developed with the software package SIMILE of Simulistics©. This software has been proposed for explicit environmental modeling, especially for integrating processes of different disciplines. The software allows visualizing the complete program structure. Non-programmers can follow the flow of water and resources and relate to different modules and compartments or processes of the model. This was an important aspect as the model will be used by local stakeholders and decision makers in situations of potential conflict.

The model consists of a sequence of compartments. For each compartment all inflows and outflows are calculated based on hydrological processes. Each sub-model (Swakop/Khan) represents all relevant geo-hydrological processes: channel flow, evapotranspiration, transmission losses and groundwater recharge, pumping, lateral groundwater inflow and outflow, and groundwater exchange with the basement aquifer.

Average runoff coefficient (r_c) defined as the percentage of runoff generated from rainfall is estimated as 4 % (DWA 1992). This percentage varies depending on geology, soils, antecedent moisture and vegetation. Runoff coefficient can be used as a calibration parameter to fit modeled to measured channel runoff. Channel inflow controls transmission losses and indirect recharge to the alluvial aquifer. Surface and groundwater flow are routed through all compartments. The time step of the routing module is hourly for surface and daily for groundwater flow. Water evaporates during rainy season from wet and moist sand as well as from groundwater (evaporation and transpiration).Evaporation was calculated based on the approach of Hellwig (1973) for wet sand and vegetated areas in terms of potential evaporation (ETp). Data on the extent of vegetated areas, sandy surface and permanently or temporarily wet areas

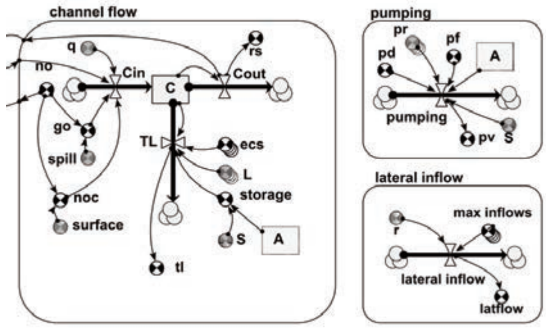

Fig. 3 *Part of the model structure showing surface runoff, transmission losses, pumping and recharge: q=runoff, C_{in}=channel inflow, C_{out}=channel outflow, r_s=surface runoff. TL=transmission losses depend on L=length of the compartment (km), ec_s=extinction coefficient (m^3/s per km) and are limited by storage (S) of the alluvial aquifer (A). The model also takes into account spill flow from an upstream reservoir (spill), while no, go and noc are indices for the compartment number. Pumping is controlled by pumping rate (pr), borehole depth (pd) and a flexibility (pf) of pumping at low storage volume (S) of the alluvial aquifer (A) resulting in a lower pumping rate (pv). Lateral groundwater inflow to the compartment depends on max. inflows calculated from Boussinesqs law and basin recharge (r).*

were obtained from satellite images. Response of evapotranspiration (ET) to groundwater water level was accounted for by implementing parameters for extinction depth (ETd) and flexibility (ETf). ETd simply specifies the maximum evaporation depth. ETf introduces the adaptation of plant transpiration to declining water levels: When water levels drop resistance increases and evaporation rates decrease. In addition, some sub-segments of the river compartment fall dry and as a consequence, overall compartment transpiration decreases. Lateral inflow was calculated based on Boussinesq law for drainage of an unconfined aquifer with a sloping impermeable base. The maximum lateral inflow was estimated taking into account hydrogeological properties of basement rock as well as compartment and sub-catchment characteristics. The average slope was derived from a digital elevation model for either side of the compartment. Transmissivity was derived from pumping tests. The alluvial module describes inflow and outflow as a function of actual storage of the alluvial aquifer (A). Time step is daily. Inflows consist of indirect recharge from floods, groundwater inflow from upstream compartment (and from the Khan compartment at the confluence) and lateral groundwater inflow from the basement. The outflows are: groundwater abstraction through pumping and flow to the downstream compartment (or the sea).Pumping rates can be included and specified for each single compartment. The module features a pumping depth (pd) and a pumping flexibility (pf). Pumping flexibility reflects the feedback between actual pumping rate and groundwater level. If no flexibility is specified, predetermined pumping rates are applied until the borehole is dry. This feature can be used to establish a quantitative relationship between adaptation to lower water levels and the reduction of no-production risks.

Scenario development and decision making

One of the main purposes of GHMS is to enable the mines and regulators (GSN/DWAF/SEMP) to predict the impact of potential groundwater abstraction from the Swakop and Khan rivers on downstream aquifer compartments. Changes in stored water volume, average water level and impacts on water quality can be calculated. Cumulative effects of abstraction from different river sections and the influence of one single borehole on a number of downstream compartments can be shown. The impacts can be calculated for a period of time that has to be defined by the user. Groundwater abstraction in a specific river compartment will not only lower the groundwater level but will also influence recharge rate, transpiration rate, outflow and transmission losses in that compartment as all these processes depend on groundwater level. All these resulting indirect impacts in the compartment and in all lower compartments are calculated and can be visualized. Environmental impacts can be quantified and their respective risks specified.

Results

Several abstraction scenarios were run and evaluated. The impact on downstream compartments was calculated in terms of runoff and groundwater level in compartments. In general impact of groundwater abstraction was found to be mainly local and constrained to the compartment. The propagation of impacts on downstream compartments was found to be low. Only if abstraction increases transmission losses from floods and thereby reduces the size and frequency of flow events in lower compartments, a significant reduction of water resources availability results. The time scale of system response was found to be at the scale of few years to few decades. Local impact of abstraction, however, is significant due to low recharge rates and limited aquifer volume. The model also revealed a significant impact of previous dam construction in the upper part of the basin on present water groundwater resources (CSIR 1997). Three different groundwater abstraction scenarios of 100,000, 200,000 and 500,000m^3/year were modeled for Langer Heinrich (left) and the adjacent downstream compartment Husabberg (compartments 5 and 6, Fig. 4). The water level in the compartment strongly depends on flood recharge; the recession of aquifer water level is slightly affected by different pumping rates. Impact on the lower compartment is not significant; all three time series of water levels are superimposed and cannot be discerned (Fig. 4, right hand side).

Conclusions

A series of important recommendations were derived from a Strategic Environmental Impact assessment of the Erongo Uranium Mining Province including the need of a model based abstraction management for shallow

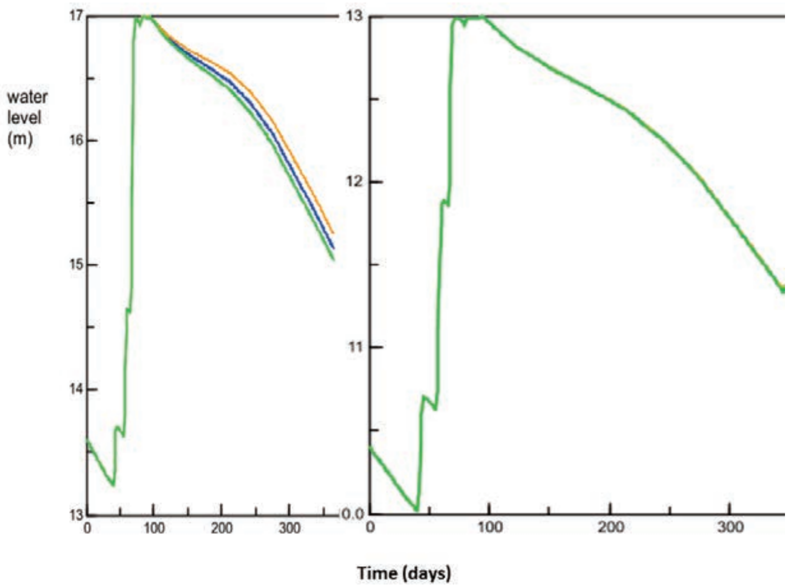

***Fig. 4** Groundwater water level in the Langer Heinrich (5) and Husabberg (6) compartments for three pumping scenarios of 100,000, 200,000 and 500,000 m³/year.*

groundwater resources. The total water demand of mines in the Erongo region was found to exceed natural resources in alluvial aquifers by far and the development of alternative sources of water was therefore encouraged. An integrated GeoHydrological model of the region was developed (IGHMS). IGHMS provides a DSS for groundwater management. Scenarios such as reduced/increased rainfall, adaptive dam management and impact of dam releases, vegetation management such as removal of invasive species can be modeled and evaluated.

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