GROUNDWATER MODELING AND COMPREHENSIVE MODELING OF THE WATER RESOURCES IN CHILE
Cases of application in arid and semiarid regions

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ABSTRACT

In the last years, groundwater has played a central role in satisfaction of the water demand in Chile, principally in the arid and semiarid regions of the North. From 1995, the socio-economical pressure on the water resources has focused principally to the aquifers, and groundwater became the principal source of development. This problem has forced government to look for new technologies for management of the demands for groundwater supplies and efficient assignment of water rights by utilization of mathematical models.

The Chilean Law of Waters, promulgated in 1981, leaves in power of the government the assignment of water rights, which are delivered without cost to anybody interested, in permanent form. The number of requests for water rights has increased constantly over the last 20 years, which reflects a strong pressure to the resource so much superficial as underground. Besides, up to the date most of the superficial water rights have been assigned already, for what the groundwater resource and its sustainability takes increasing importance.

Currently there are about 100 exploitable aquifers identified in the Central and Northern parts of the country. Some of them apply mathematical modeling and others only water balance. For most of these aquifers, the granted water rights already exceed the natural capacity of the source and, in consequence, they might suffer an overexploitation in a short term.

The National Water Agency of Chile (DGA) is a governmental agency responsible for the Investigation, Evaluation and Planning of the national water resources. The present paper presents two cases of water resources modeling: 1) hydro geological modeling in the aquifer of the Copiapó River valley, typical for arid, Northern part of Chile, in which the results of water balance do not allow to assure the answers and prediction of the model; 2) integrated modeling for the Elqui River valley that perfects in the calculation of superficial recharges to the groundwater system, considering all the uses and water activities in the basin. This type of modeling gives accurate entry data for detailed hydro geological modeling, thus improving the closing balance.
INTRODUCTION

The National Water Agency of Chile (Dirección General de Aguas, DGA) is a governmental agency responsible for investigation, evaluation and planning of use and utilization of the national water resources, regulation the use among different users, and orientation of the consumption towards national interests.

Chile is a long and extreme country, where the hydrologic characteristics give place to glaciers and deserts. Wide variation of precipitation and evapotranspiration causes the existence of arid and semiarid zones in the north where the groundwater is the only resource for economical development and subsistence.

In the last years Chile is facing an increasing demand for the water resources complicating the tasks of management and planning of the water use. Also, the hydrologic characteristics of different basins in the Northern regions of Chile, has led the DGA to the use of support tools that allow more reliable perception of the behavior of waters, specially the groundwater. The DGA uses hydro geological modeling for the analysis and evaluation of the groundwater resources and for long term planning, and develops integrated simulation models in order to show in detail the different flows and interconnections existing in superficial and underground waters.

The present work shows in a synopsis two application cases of hydro geological modeling for basins located in the arid and semiarid zones of Chile. The modeling was carried out to evaluate the behavior of water resource with the purpose to contribute with a methodology of calculation or work in the obtaining and later incorporation of the data about superficial recharge that enters to the groundwater system.

CHARACTERIZATION OF ARID AND SEMIARID REGIONS OF CHILE

The index to classify the arid zones in the world, based on the Index of Aridity (According to the UNEP, United Nations Environment Programme, 1997) is calculated:

\[ I_a = \frac{P_a}{ET_o} \]

Where: 
- \( I_a \) = Index of Aridity
- \( P_a \) = Annual Rainfall
- \( ET_o \) = Potential Evapotranspiration of Reference.
For the arid and semiarid zones $I_a$ fluctuates in a range between 0.05 and 0.5 or in other words, when the $ET_o$ exceeds more than double of the annual rainfall of a zone.

There are clear indexes of aridity in the northern regions of Chile - I, II, III and IV. The application cases worked in the III region, correspondent to the Copiapo River basin and in the Elqui River basin, IV region. See figure 2 and 3 for location and characterization of $P_a$ and $ET_o$ in the Study Zones.

The water efficiency is crucial in these regions due to its shortage. Nevertheless, the demand increases day after day for municipal water use, irrigation, agriculture and industry (mining industry in particular). It is also necessary to add increasingly important environmental demands. Regrettably, natural offer of water seems to diminish due to the great climatic variability (CAZALAC-RODHOS, 2006).

**EVALUATION AND GROUNDWATER MODELING**

The DGA target is to develop and apply a groundwater or hydro geological modeling that will help to predict the behavior of aquifer in the long term (decreases, flows between zones, inflows, outflows, connection between river and aquifer, etc.) and with diverse settings of exploitation. The evaluation is carried out on the level of basin, adding detailed analysis and more accurate diagnosis, depending on the case.
1ST CASE OF STUDY: AQUIFER OF THE COPIAPO RIVER VALLEY

The aquifer of the Copiapo River valley is located in the III region, between 26°30' and 28°30' S latitudes and 69° and 71° W longitudes. The hydrographic basin has a surface of 17,100 km² and is almost entirely constituted of arid and desert mountains. The orographical conformation is a discontinuous plateau with a soft inclination starting from the Andes Mountains between 2500 and 3000 meters above sea level and reaching the Pacific Ocean at the sea level. The configuration is divided by deep and eroded ravines of which the most important is Copiapo Valley. The valley has an average width of 1.5 km and a length of 145 km. The annual rainfall is 28 mm in the basin and centers between May and August.

The fluviometric regime is mixed, supplied by scarce rainfalls and nivales; however, it is of paramount importance for the human activities. Besides, the river flow is boxed, though in some sectors it forms terraces that are used for agriculture.

The aquifer is composed by landfills that reach thickness of 40m to more than 500m. Its functioning is determined primarily by the available superficial resources, especially for the superficial flow of the Copiapo River and its tributaries. The most important recharge sources are the infiltrations from irrigation systems, the contribution of the lateral gullies, and mainly the river. The most important discharges are pumping wells and surfacing of springs. It is worth noting that given to the magnitude of the aquifer it presents certain inertia with respect to the superficial fluctuations.

The first studies and research using preliminary modeling on the water resources of the Copiapo River valley date back to 1987. The last study of the DGA corresponds to the groundwater modeling in 2003.

The methodology of modeling basically consists of hydrological, geological, hydrogeological information compilation and subsequent characterization, as well as investigation of uses and demands in the basin. The conceptual model is designed once all the background information is analyzed. This model serves as a base for determining the theoretical framework inside which the processes of the above-mentioned basin unfold. See Table 1.

Visual MODFLOW Software was used for the hydrogeologic modeling of the Copiapo aquifer, involving the sector from the downstream at the Lautaro Reservoir up to the river mouth, dividing it in two sections to ease data handling and convergence of results. See Figure 4 for the first section of modeling.

Characteristics of the first section of the modeling are analyzed in this paper, including the sector from the Lautaro Reservoir up to Copiapo town. The aquifer of this sector is modeled as one stratum due to the shortage of information about the landfill depth. The calibration period is from April 01, 1987 until September 30, 2001. Hydrological information covers 14 years, with a temporary discretization of 6 months (stress period). The final permeabilities (K) vary in a range from 1 to 70 m/day and the coefficient of storage (S) for free aquifer varies between values of 0.008 and 0.15 for the whole aquifer.

The objective of showing this application case, beyond the implementation of the model itself and the results, is to show the importance of the quantification of flows, both - inflows and of outflows of the system in the first stage of development, which corresponds to the conceptual model.

The adjustment patterns of calibration were very satisfactory for the Copiapo River basin. The DGA measured twenty one observation wells. The error of adjustment between simulated adjusted levels and the measured levels was 0.5% with the normalized RMS, and the balance of mass closed with an error of 6.7 % in average for the whole period.
Table 1 compares the overall results of calibration and the conceptual model of the aquifer of the first section of mathematical modeling.

Table 1: Overall results of conceptual model and calibration

<table>
<thead>
<tr>
<th></th>
<th>Conceptual Model</th>
<th>Calibration Results</th>
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<tbody>
<tr>
<td><strong>IN</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant head</td>
<td>1.00</td>
<td>1.09</td>
</tr>
<tr>
<td>(Reservoir)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant head</td>
<td>0.35</td>
<td>0.41</td>
</tr>
<tr>
<td>(groundwater</td>
<td></td>
<td></td>
</tr>
<tr>
<td>catchment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>2.48</td>
<td>2.92</td>
</tr>
<tr>
<td><strong>OUT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant head</td>
<td>0.53</td>
<td>0.53</td>
</tr>
<tr>
<td>(inflow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drain</td>
<td>0.85</td>
<td>0.64</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>0.82</td>
<td>0.12</td>
</tr>
<tr>
<td>wells</td>
<td>3.03</td>
<td>2.88</td>
</tr>
<tr>
<td><strong>IN-OUT</strong></td>
<td>-0.15</td>
<td></td>
</tr>
</tbody>
</table>

REF: Inform SIT 87- DGA 2003

It is important to emphasize, that the results of the calibration were satisfactory, because of the low level of errors of obtained adjustments, fitting into the ranges and values of the previous quantifications of the elastic parameters and some flows that get involved in the basin (conceptual model).

Amid the calculations to estimate the inflows and outflows before the modeling, some flows will always remain with a certain degree of uncertainty. In case of the Copiapo valley, the groundwater flows with underground entrances and exits were estimated properly by applying Darcy’s law, and geophysical and stratigraphical values obtained from wells. Also, there were some identified filtrations from the reservoir causing a groundwater inflow of approximately 1 m$^3$/s.

Nevertheless, the calibration might lose its accuracy in case of remarkably diverse values of the calculations of superficial recharges produced by the river, channels and irrigation and also of the evapotranspiration.

Generally, the values of the recharges incorporated in a model for a detailed groundwater modeling acquired using discretization with Visual MODFLOW are secondary, sometimes calibrated when lacking the thorough information or for obtaining the levels for specific sector or basin.

The conclusions in connection with given magnitudes are that the recharge values of the system must be bigger than the theoretically or empirically estimated ones. Furthermore, these values are justified by the existence of the certain groundwater levels in the zone below the observed ones. On the other hand, the evapotranspiration would be underestimated by the modeling, explained by the great variability of the evapotranspiration depending on the section of the valley and the uncertainty of the theoretical estimations of this variable in the available examples.

In the application case of hydro geologic modeling in the arid zone of the Copiapo valley, the evapotranspiration and natural evaporation of the system are important variables for the water balance of the basin, directly related with the recharges of the system. In consequence, the good preceding calculations of the recharges of the aquifer and of the discharges generated in the zones of fertile lowlands and outflows must be independent from the calibration adjustments. These adjustments already influence the decisions that are taken when the groundwater modeling is applied in situations of underground stress, for
example, or evaluation and estimation of the long term sustainable flow, furthermore considering that these estimations are at the levels of source and basin.

The objective is to show the application of an integrated model, used in other arid and semiarid zones in Chile, although still lacking a formation of a methodology that includes the recharges to hydrogeologic models of arid zones. The application and integrated model has been a subject of analysis in other aquifers of Chile, located out of arid and semiarid regions.

INTEGRATED MODELING OF BASINS – MAGIC

The MAGIC Software (Modelación Analítica Genérica Integrada de Cuencas, or Integrated Generic Analytical Modeling of Basins) was developed by the DGA for application in any basin. The MAGIC Software is programmed in Delphi 7.0 language.

This software was generated for the simulation of the behavior in a certain period of time of the superficial elements that compose a basin and to relate this behavior with the variations of volume experienced by the underlying aquifers to this basin.

The superficial system is simulated applying the principle of continuity to the water body, and the aquifers are considered as the underground reservoirs modeled by applying simultaneously the equation of continuity and Darcy’s law.

The first step of simulation of a certain basin (assuming the compilation of necessary information) is to recognize the suppositions and simplifications that allow transforming the real basin into a set of mutually interconnected objects with a behavior close to the real one. See Figure 5 for the cases of a section of river, an aquifer and an agricultural irrigation area.

Each of the modeling objects must possess a unique code (XX-ij), which identifies it internally in a biunivocal mode and allows linking it to the rest of the objects of the system. The permitted objects in MAGIC are: aquifers (AC-), derivative channels (CA-), natural influents (AN-), channel sections (CT-), hydroelectric plants (CH-), point caption (CP-), point discharge (DP-), reservoirs (EM-), rainfall or precipitation and waterflow statistics (EST-), catchment areas or lateral basins (CL-), nodes (NO-), wells (PO-), minimum ecological flows (QE-), sections of river (TR-), urban zones (SU-), and irrigation zones (ZR-).

**Figure 5** MAGIC model representing a real interaction between a section of river, an irrigation zone and an aquifer. The flows indicated in the figure above are: \( Q_{\text{evp}} \) = evapotranspiration; \( Q_{\text{irr ret}} \) = irrigation return to the river; \( Q_{\text{canal}} \) = channel of irrigation; \( Q_{\text{irr in}} \) = irrigation infiltration to the aquifer; \( Q_{\text{in}} \) = inflow to the section of river; \( Q_{\text{out}} \) = outflow to the section of river; \( Q_{\text{irr inf}} \) = river infiltration to the aquifer; \( Q_{\text{irr pump}} \) = irrigation pumping well; \( Q_{\text{po}} \) = pumping wells of other purposes; \( Q_{\text{gw in}} \) = groundwater inflow; \( Q_{\text{gw out}} \) = groundwater outflow. REF: Zambrano et al 2003
The MAGIC Software utilizes the model of rainfall–runoff, MPL\textsuperscript{1} to simulate the water path through the soil of the irrigation zones and to create the superficial runoff. The input data for this model is the monthly average rainfall in different irrigation zones, the potential evapotranspiration of the crops of the sector, and some soil characteristic parameters. The MAGIC Software simulates the processes of infiltration, evapotranspiration and deep infiltration, delivering the flow of the resultant superficial runoff and the infiltration towards the underlying aquifer. This model can also be used independently for calculating the superficial runoff, product of the rainfalls in those rain basins that do not possess flow gauging stations and contribute with a flow to the basin in study.

The temporary discretization of The MAGIC Software for the hydrologic information of input and output is on a monthly scale. The compiled data on the basin is input to the MAGIC in Access or Excel format storing the information of all the considered objects of the simulation. For example, 4 related tables exist in the case of aquifers that characterize the system, with a variety of sections (semicircle, triangle, and rectangle), geometric, elastic, topologic characteristics and with different flow for each.

The simulation of the flows that circulate in the basin is carried out from upstream towards downstream for each of the nodes that define the points of balance and correspond to the rivers of the system. MAGIC realizes a cycle for every month of the period of simulation, and within this period it generates another cycle of iterations to calculate all the inflows and outflows in all the nodes of the system.

The first iteration calculates the tributary flow in every node, product of the contributions of main basins and intermediate or lateral basins (tributaries), of the sections of river, the point outsources, and the channel sections. The reservoirs are dealt with after finishing the first iteration for all the nodes of the system, calculating the contributions for irrigation and hydroelectricity. The next step is calculation of the aquifers contribution considering discharges and flows pumped up to the superficial systems; calculating for the irrigation zones the spillages and infiltrations to the underground system.

All the involved flows are considered for the calculation of the tributary flow to the nodes in the later iterations - including the contributions of the reservoirs, the aquifers and the spillages of the irrigation zones calculated at the end of the previous iteration. The model continues iterating within the monthly cycle until assuring that the outflows of the irrigation zones, reservoirs and aquifers match the corresponding tributary flows to the nodes of the system.

The MAGIC software delivers detailed data of every item in Excel or text format. The additional available data consists of the average monthly flows in the sections of river, irrigation security, reservoir volumes, reservoir delivery flows; rain, irrigation and domestic water use infiltrations; volumes of pumping for irrigation, outflows and final condition of the aquifers, among many other results.

The adjustment patterns for the calibration of a model implemented with the MAGIC Software are:

1) Closing balance from the equation of continuity already incorporated in all the MAGIC iterations.

2) Checkup of flows observed in any flow gauging station aligned with the simulated node flows of the river, for previously determined nodes in the basin.

\textsuperscript{1}This model was conceptually developed by the Engineer Pablo Isensee M. at the end of the 80, last updated in 1998. Advanced model, SIMED, featuring finer detailing and on a daily scale was generated in 2005. It is compatible with the MAGIC Software.
3) The adjustment of the observed levels compared with output of the simulated levels in the corresponding sectors of aquifers, obtained indirectly through the condition of the volume of the underground reservoir and its respective geometry, for every month of simulation in the chosen period of calibration.

Hereby MAGIC shapes the environment of hydrological simulation that contemplates all the uses and handlings of the superficial and underground water resource in a basin. This facilitates the obtaining of a clear recharge to the aquifer systems, in order to accomplish an ideal integrated management of the water resource.

2\textsuperscript{nd} CASE OF STUDY: THE ELQUI RIVER VALLEY

The second case of study is the Integrated Modeling of the Water Resources in the Elqui River valley, located in the IV region of Chile (See Figure 1).

This study was developed by the Center of the Water for Arid Zones of Latin America and the Caribbean, CAZALAC with the consultancy of RODHOS Consulting and Projects Ltd. and supervised by the DGA during 2005 and 2006. The research investigated the use of the water in arid and semiarid zones, as is the IV region of Chile, diagnosed the efficiency of use and developed a methodology of analyzing for further applications in arid or semiarid zones.

The implementation of an integrated model to the basin of the Elqui River, supported by MAGIC, as one of the tools for this analysis, allowed representing the different types of demand in a suitable way on each of the offered elements in the basin. The integrated model also provided a reliable work platform that grouped all the information allowing evaluating different settings of usage, always taking into account the groundwater factor.

The hydrographic basin of the Elqui River is located between 29°35' and 30°20' S latitudes, with an extension of 9.800 km². The average annual rainfall in the basin is approximately 79 mm/year.

The Elqui River basin has a mixed hydrological regime, with rainfalls in winter and melting snow in summer. The Elqui River is born from the junction of the Turbid River from the east and the Claro River from the south, approximately 2 km upstream from Rivadavia locality (815 masl). From Rivadavia, the river follows strict East - West direction and practically does not collect any tributaries, except for several gullies of considerable size that normally are dry and only contribute water in case of rain in the humid years. Though it is true that all these gullies do not present a permanent superficial runoff they act as source of recharges to the aquifer.

In general terms, the physical limits of the aquifer correspond to the rocky base that also appears on both sides of riverbank. The sedimentary landfills that constitute aquifers along the basin can be divided in three principal layers that put together do not exceed 250 m of power. The base is located 100 m deep in the high part of the valley, and goes down to 220 m in the coastal zone. The main superficial aquifer accommodates in the landfills basically formed by gravel and sand, showing a free or phreatic character. The hydraulic conductivity of the principal aquifer of the Elqui Valley changes between 1 to 60 m/day (ranges very similar to the aquifer of the Copiapo River).

The main recharge of the aquifer is formed by infiltration in the irrigation and channels, and secondarily by the river, direct infiltration of rainfall and indirect infiltration from rock pediments. The last corresponds to the lateral recharge of the system, which represent a part of the rainfall in the lateral tributary basins.
Although the geomorphologic characteristics are very similar of both observed basins, the agricultural activity is major in the Elqui River basin. The Elqui River flow is also boxed and the recharge of the aquifer is determined by the usage of water which depends directly on the hydrologic characteristics of the basin.

The Model MAGIC-Elqui was applied to the basic objects that compose a basin: main basins, riverbeds (sections of river), aquifers and sectors of irrigation. The topology of the system consist of 21 nodes, 11 aquifers, 22 sub basins, 19 matrix channels, 5 derivative channels, 2 reservoirs of regulation, 11 zones of irrigation, 10 punctual captures, 5 punctual discharges, 20 sections of river, 131 types of crops, 5 rainfall gauging stations with associated statistics, and 22 codes associated with statistics of flow gauging stations for every sub-basin.

According to the hydrologic and hydrogeologic records, the integrated modeling of the Elqui River valley, and integrated modeling in general, remains consequent, always keeping the characterization within the definite margins. Thus, the modeled aquifer remained restricted to the stratum that had information and depth for every sector in no case exceeding 160 meters and belonging to the coastal zone.

The data base used for modeling consists, among many other features, of the characterization of the crops and their efficiencies, the function of infiltration in the sections of river depending on the permeability of the riverbed, the rainfall infiltration depending on the soil and hydrology parameters and the channel infiltration calculated with a correspondent equation.

During the 5 years (1999-2004) of calibration of the model MAGIC-Elqui the data was collected on a monthly basis in 6 control points or nodes associated with flow gauging stations along the river. Additionally, each of the typical curves of reservoir was calibrated, obtaining satisfactory adjustments. Figures 6, 7 show two graphs of calibration for different points of the valley along the river, with magnitudes of average flows for the period of 1999-2004 of 6.8 m$^3$/s observed and 6.7 m$^3$/s simulated at the Turbio station in Varillar and of 9.4 m$^3$/s observed and 9.7 m$^3$/s simulated at the Elqui station in Almendral, records hold by the DGA. The values of adjustment in correlation gave acceptable R$^2$. The RMS residual errors were 0.113 m$^3$/s for the Turbio and of 0.410 m$^3$/s for the Elqui station.
The calibration was carried out also by comparing the volumes and characteristic curves of the reservoirs of regulation. The volumes of the aquifers in terms of level were also compared, obtaining a result that varied in the time with the observed levels in the observation wells.

The results are available in the website of CAZALAC [http://www.cazalac.org/fndr0506.php](http://www.cazalac.org/fndr0506.php) or on the request from CAZALAC Executive Direction of Chile by email: gsoto@cazalac.org.

The results obtained from the groundwater component are of key emphasis for this modeling. These results provide relevant input data for the obtaining the information about superficial recharges that enter to the groundwater system for a more specific hydrogeologic model.

**Figure 10: Total infiltrations and recharge available AC-07**

Figure 10 shows a number of results on monthly scale obtained with the MAGIC software. The total of available recharges to the aquifer can be itemized in order to see the specific recharges that come from infiltration of riverbeds, channels, rainfall and irrigation.

Analyzing the results for AC-04 aquifer, the average total recharge available for the groundwater system for the years of calibration is 292 l/s. Although the recharge has a direct relation with the hydrology of the zone, not all of it reaches the groundwater system. The MAGIC Software delivers more accurate results on flows emerging to the superficial system, showing that on the average only 16.3% of the recharge flow enters into the aquifer. This low net recharge to the system is a product of the usage (pumping wells), characteristics of the soil and initial conditions of the water volume of every month for every aquifer section.
CONCLUSIONS

The groundwater modelling, in arid and semiarid zones, requires a detailed calculation of the recharge and discharge elements of the system, because they are key factors in the behavior of aquifers.

In order to improve water resources management the integrated hydrologic simulation was carried out with the MAGIC Software. It included all water resource applications and processes of the basin, superficial as well as groundwater processes, thus providing more accurate results on net recharges to the aquifers.

Integrated models created with the MAGIC Software allow to quantify the water resource and to itemize the obtained information. This led to the perfection of the balances and allowed to take the decisions that in a long run were better adjusted to the reality. At the same time the detail of the behavior of the water flow was obtained on a monthly scale, allowing pinpointing the errors and cross checking with the observation data.

Modeling with The MAGIC Software was also carried out in arid and semiarid zones of the IV region of Chile, in the Limarí River and the Choapa River basins (CAZALAC – RODHOS 2006) as well as in the other basins in the north and south of Chile.

In order to improve and to assure that the existing flows in a subterranean - superficial system respond to a historic behavior to the source level, the suggested methodology of the present work consists of applying an integrated modeling followed by hydro geologic modeling.

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