USE OF GROUNDWATER MODELS FOR MANAGING SERIOUS URBAN WATER ISSUES IN BAKU, THE CAPITAL CITY OF AZERBAIJAN

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ABSTRACT

Supported by NATO, a research project is currently well advanced that aims to promote economic and social stability in the Azerbaijan Republic through the development of a blueprint for safe and sustainable water supplies. Work focuses on Baku, the capital city located on the Absheron Peninsula which is home to about half of Azerbaijan's 8.1 million inhabitants. Major concerns in the region relate to rising groundwater levels caused by leakage of water from supply canals and distribution networks, wastewater management, and contamination due to urban sourced pollutants, chemicals associated with the oil industry and agricultural fertilizers and pesticides. A major component of the project is the development and calibration of 3-D transient groundwater flow models of the region which are linked to a GIS database and computer-based analytical tools. These models are based on Waterloo Hydrogeologic's version of the MODFLOW finite difference model code, and are well advanced. Microsoft Access, a highly versatile and widely used relational database system, has been adopted to maintain temporal data, and ESRI ArcView, a globally popular GIS system, is being used to maintain spatial data. The models are recognized as the key to effective resource management decision-making in the region and will be used to explore alternative water management strategies, likely involving integrated "conjunctive" use of ground and surface water supplies and "recharge management". They will also be used to identify options for urban waste water management including the potential for re-using wastewater using artificial recharge technologies.
Key words: urban resource management GIS groundwater models

1. INTRODUCTION

Human security can be measured in many ways but one underlying factor for all humanity is access to water of adequate quality and quantity. In the Azerbaijan Republic (Fig. 1), both ground and surface water supplies have been seriously polluted by urbanisation, agriculturally-sourced fertilizers and pesticides, and chemicals associated with the oil industry. The problem is particularly severe in the cities where as many as 70% of Azerbaijan's 8.1 million inhabitants reside.

The region is arid to semi-arid and resource replenishment rates are low. In many cities, including the capital, Baku, water resources are widely regarded as unsustainable. Concerns have been raised that without urgent intervention, dwindling water supplies will promote social decay and threaten national security by undermining economic stability, impacting human health and degrading the urban environment. Reliable data that demonstrate clear links between environment-poverty-health are scarce, but the prime cause of morbidity in children is diarrhea and related diseases caused by contaminated water. There has also been an increase in the incidence of malaria connected with stagnant waste water that collects in pools and low lying areas. Urgent action is required to:

- remediate and improve the existing water supply system,
- secure additional supplies,
- provide effective management of waste water, and
- develop a resource management program that can ensure safe, sustainable water supplies for the future.

2. STUDY AREA

The Azerbaijan Republic (area 87,000 km^2) is located on the western side of the Caspian Sea (Fig. 1). To the north is the Russian Federation, while Georgia and Armenia lie to the west. The separated territory of the Nakhchivan Autonomous Republic (AR) is partially enclosed by Armenia, and is separated from Iran to the south by the River Aras. The Nakhchivan AR is under blockade by Armenia, which occupies almost 20% of Azerbaijan's territory. As a state of the former Soviet Union, Azerbaijan once enjoyed a well developed industrial and infrastructure base. With the collapse of the Soviet Union and the shutdown of industry in the early 1990s, the infrastructure of the cities has significantly deteriorated and the supply of water to urban dwellers has been seriously threatened. The problem was further compounded on November 25, 2000 when Baku was hit by a strong earthquake (measuring 6-6.5 points on the Richter scale) causing substantial additional damage to the water supply systems.

Figure 1. Map of Azerbaijan showing Absheron Peninsula extending into the Caspian Sea.

The study area is located on the Absheron peninsula (~2000 km^2) (hydrogeological region I-4 on figure 2) (Shishkin, 1935; Vaidov, 1956; Samedov and Kalinina, 1976; Israfilov, 1997, 1998) which projects eastwards into the Caspian Sea (elevation approximately -28 m below mean sea level; salinity 12-13 g/l) . Water table contours for the Absheron Peninsula are shown for 1999 in figure 3 (after Israfilov, 2006), and mean monthly precipitation, air temperature and humidity deficit are provided in figure 4.

Due to an influx of refugees and forced migration resulting from the conflict with Armenia and collapse of the Soviet Union, the Absheron peninsula is heavily populated (4.3 million) but has little to no fresh water resources, no useable surface water and much of the groundwater is highly mineralized

(Israfilov, 2002, 2006). The largest city on the peninsula, and the primary focus of the study, is Baku, the national capital where more than 25% of the entire population of Azerbaijan resides.

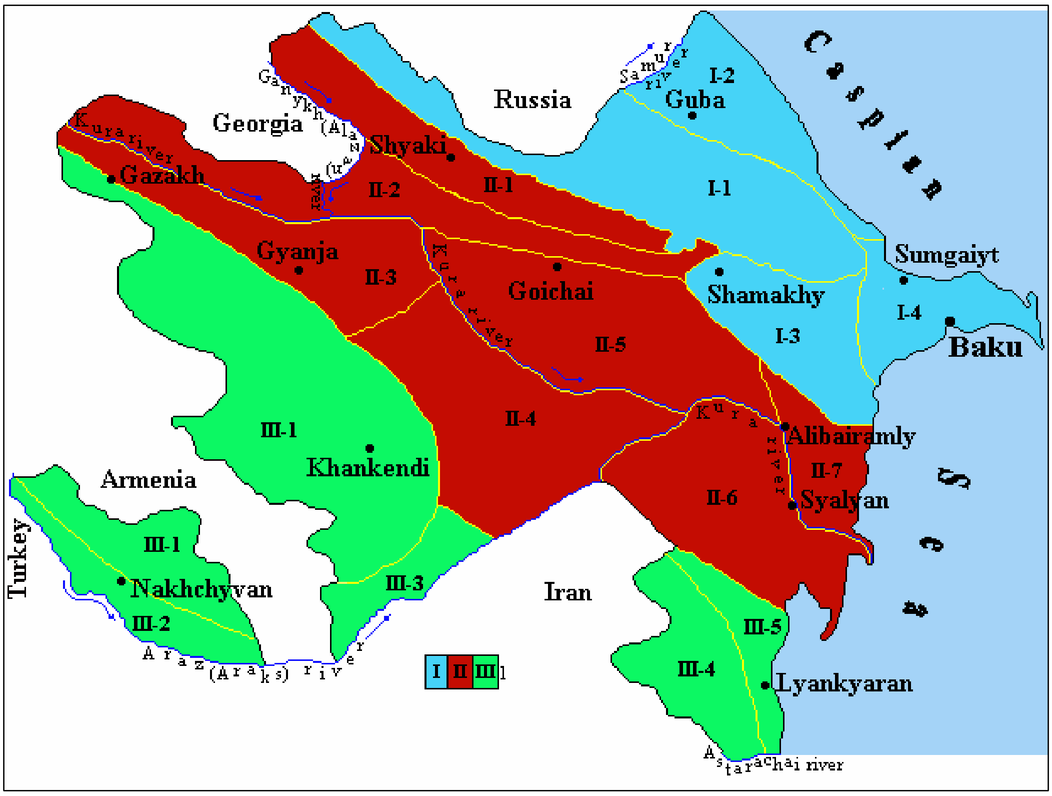

Figure 2. Hydrogeologic zones in Azerbaijan: I - Greater Caucasian hydrogeological basin; II - Kura depression hydrogeological basin; III - Lesser Caucasian hydrogeological basin.

Baku and the Absheron Peninsula as a whole, currently relies on three major sources for its water supply:

1. Good quality groundwater imported from the towns of Shollar and Hachmas 180 km north of Baku;
2. Moderate quality surface water brought via the Samur-Divichi-Absheron Canal from the Samur River catchment in the North of Azerbaijan and treated at the Jeiranbatan Treatment Plant 30 km to the north of Baku, and
3. Poor quality surface water pumped from the Kura River which is treated at the Kura Treatment Plant 140 km to the southwest of Baku.

The Kura River supply is the least acceptable from a drinking water quality standpoint. Concentrations of SO_4 and Cl typically exceed maximum allowable concentrations (MAC) by 50%, and phenol, fatty acids, oil products, heavy metals, etc. occasionally exceed MACs by an order of magnitude or more (Mammadova and Pashayeva, 2006).

Water related issues throughout the region are numerous (Akhundov, 1981; Aliyev et al., 1986; Alizadeh et al., 1990; Israfilov, 1997). Of greatest concern is the leakage of water from water supply canals (Fig. 5) and from poorly maintained, pressurized distribution networks, which has significantly elevated groundwater levels in urban centres. Figure 6 reveals a steady rise in water level between 1955 and 2000 for observation well #N92 in central Baku. The problem is not isolated but proliferates throughout the city (Fig. 7). Figure 8 shows the site of a landslide that was triggered by a combination of water leakage from utility lines and heavy rainfall over the prior winter. The landslide occurred abruptly on March 7, 2000 over an area of some 15 ha and cost between $5 and $10 million to repair and restore.

Secondary problems in the region relate to the management of urban wastewater and the degradation of ground and surface water quality from uncontrolled urbanisation, chemicals associated with the oil industry, and agriculturally-sourced fertilizers and pesticides. Oil and gas production has polluted large areas of the Absheron Peninsula (Fig. 9), including heavily populated areas (Fig. 10). Leaking sewage pipelines have further degraded the water quality in the surficial aquifer, while agricultural production has contributed to nitrate and pesticide pollution. Water supply contamination is further aggravated by spills from chemical plants and aerial deposition of pollutants from highly industrialized areas of Baku and Sumgayit.

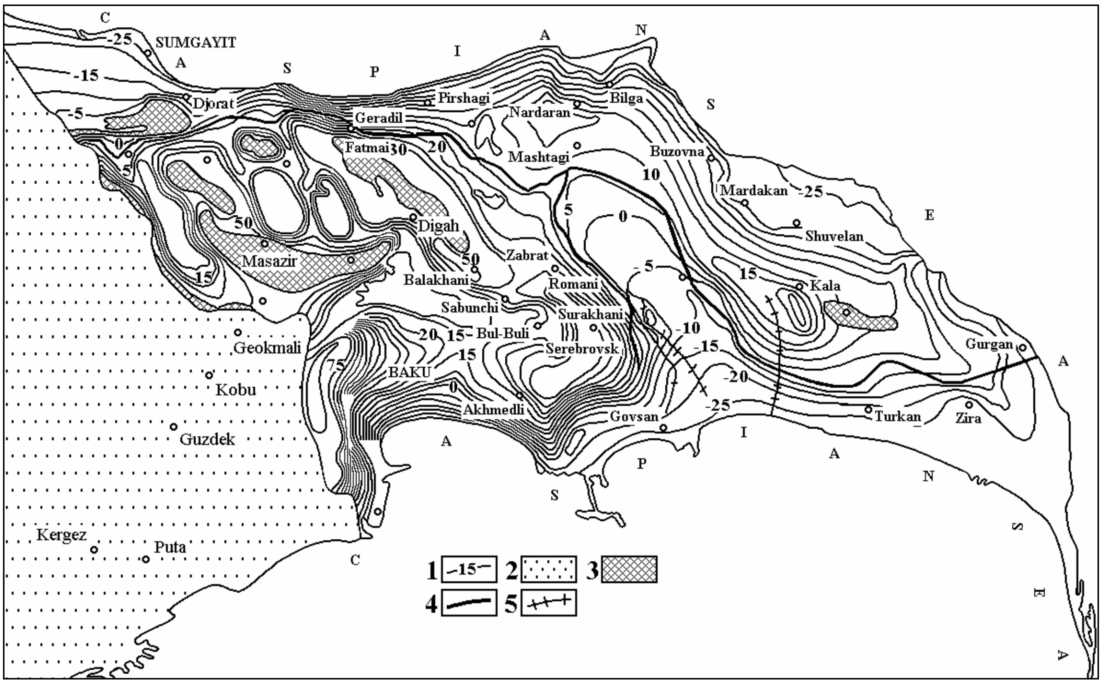

Figure 3. 1999 water table map for the Absheron peninsula; 1-Water table contours; 2 - Region where there is only sporadic development of the aquifer; 3 - impermeable deposits; 4- Samur-Divichi-Absheron Canal; 5- Channels for waste oilfield waters. (after Israfilov, 2006)

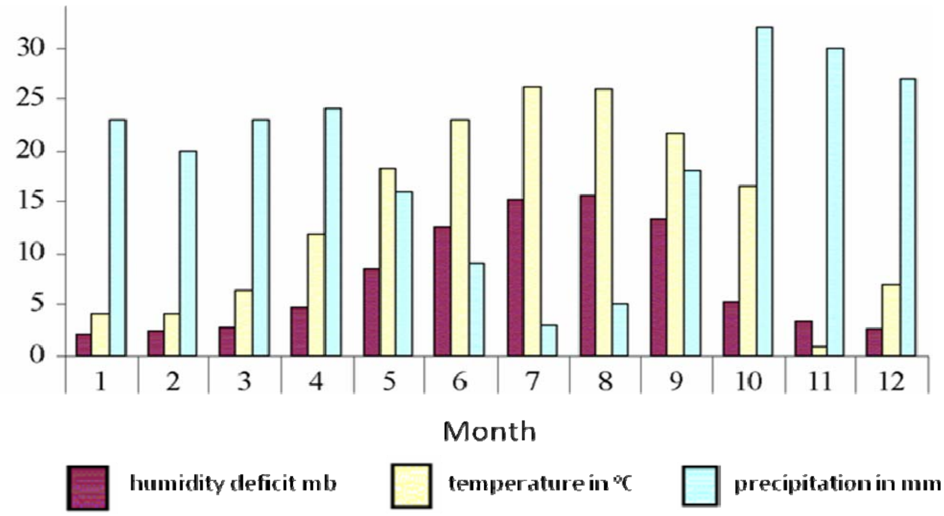

Figure 4. Mean monthly precipitation, temperature and humidity deficit for the Absheron Peninsula.

Figure 5. Samur-Divichi-Absheron Canal on the Absheron Peninsula

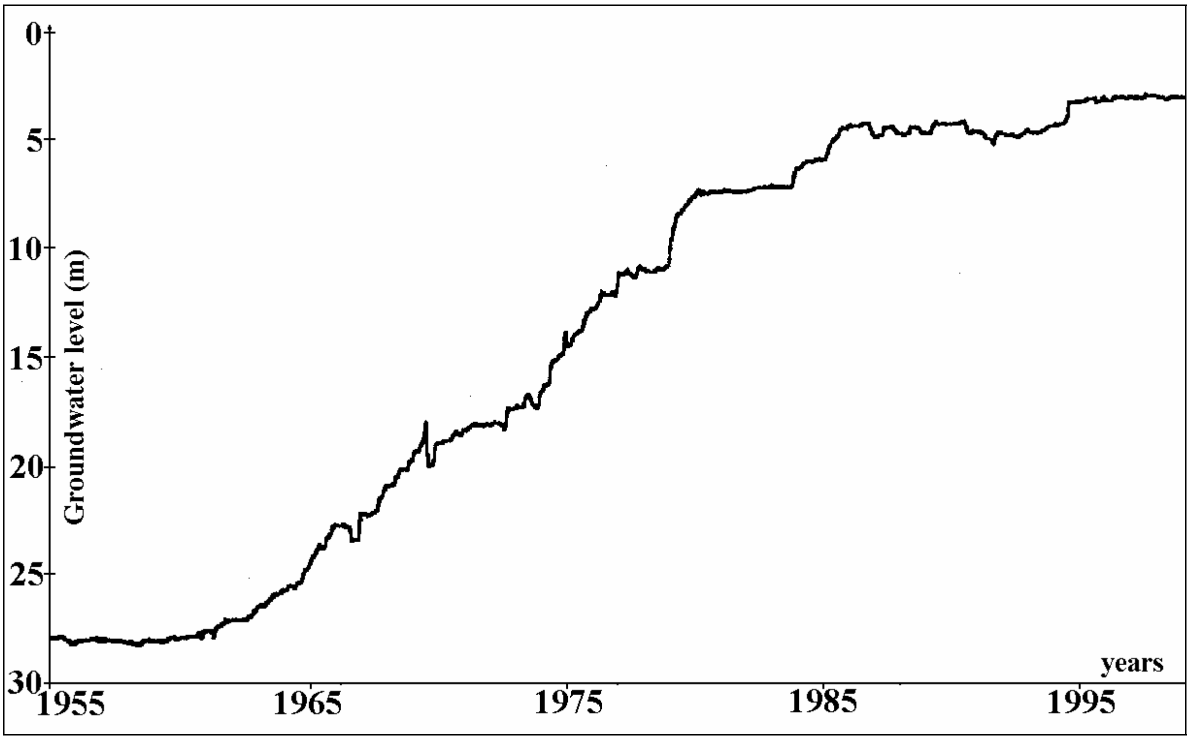

Figure 6. Leakage from water delivery canals and the pressurized distribution network has caused a steady rise in groundwater levels beneath Baku during the period 1955 to 2000. Data are for Well #N92.

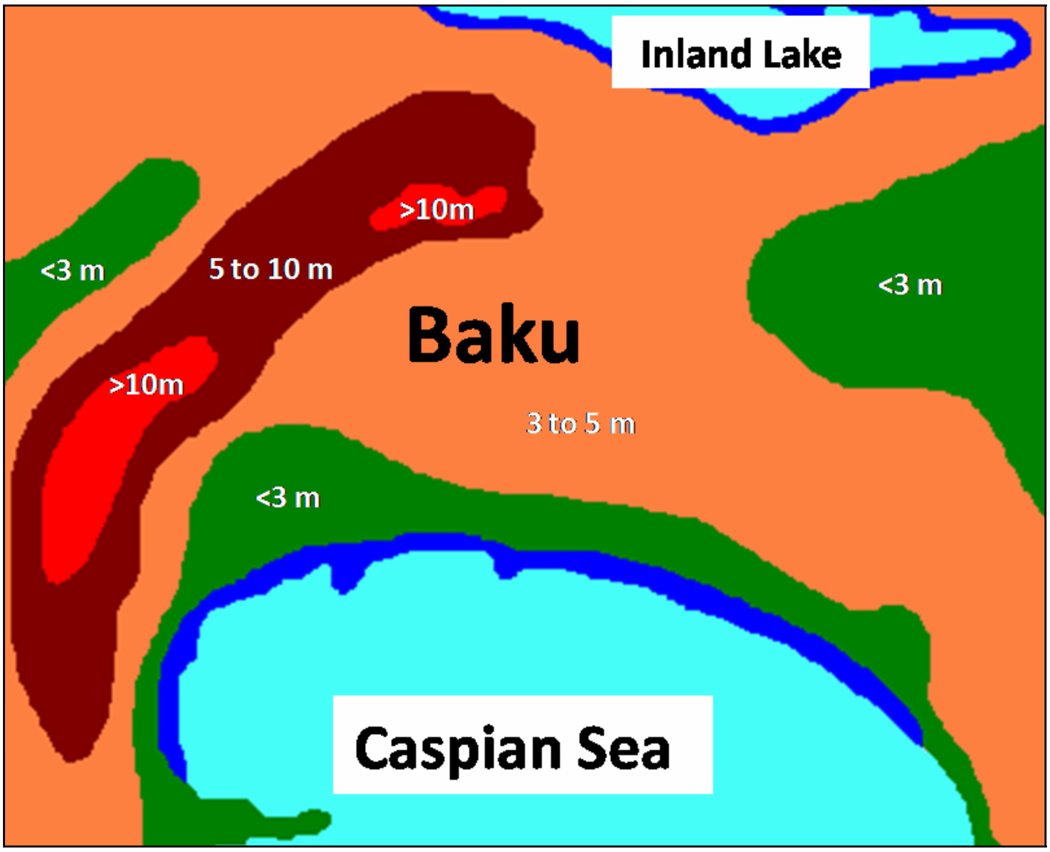

Figure 7. Rise in groundwater level over the period 1955 to 2000 beneath the City of Baku.

Figure 8. The Baku landscape showing areas sensitive to landslides triggered by a combination of heavy winter rain and leaking water mains. Cleared area (X) shows site of major landslide due to high water levels. Water table is now just 1-2m below main square in foreground.

Figure 9. Leaking oil pipelines contaminate salt lakes on the Absheron Peninsula.

Figure 10. Oil production in heavily-populated areas of Azerbaijan's capital city Baku, seriously degrades groundwater in shallow aquifers.

3. PROJECT OBJECTIVES

Most cities in the Azerbaijan Republic are now experiencing a serious deterioration of their potable water quality which, in turn, will impair public health and promote disease. Evidence of water contamination is frequently observed throughout the water distribution network and most of the population is supplied with drinking water that does not meet generally accepted standards of potabilty. In many regions of Baku and Sumgayit, city water is supplied for only several hours each day on a rotating schedule that is incompatible with sanitary requirements. This shortage of water causes many people in the suburban regions of Baku city, areas where there is no centralized sewer system, to use untreated groundwater for their needs. Serious concerns have been raised that the increasing stress on the water supply and the growing pollution problems may lead to social instability in an already volatile region. The major cities of Baku and Sumgayit and settlements of the Absheron peninsula are especially threatened.

Ultimately, the aim of the research is to promote economic and social stability in the Azerbaijan Republic by facilitating the development of a blueprint for safe and sustainable water supplies. At present, there is no integrated strategy for water resource or catchment management in the country. This must change and time is of the essence. The most difficult problem that Azerbaijan and many similar countries face is the selection of management strategies that can best utilize and protect the existing fresh water resources while simultaneously limiting environmental damage. These strategies cannot be developed without a full understanding of the hydrologic system including a quantitative knowledge of key system components (hydrometeorology, surface water, groundwater, and chemistry), their interdependence, and how the system has changed with time. In response to these concerns, the primary purposes of the project are:

- To assess existing ground and surface water reserves and their state of degradation through the establishment of an advanced database linked to GIS and computer-based analytical tools.
- To conduct catchment water budget analyses and determine the extent to which these water budgets have been altered through urbanisation and leakage from water distribution systems.
- To develop regional groundwater flow system models of the Absheron peninsula, linked to GIS, which can be used for resource and environmental management decision-making.
- To identify a range of alternative water resource management scenarios, likely involving integrated “conjunctive” use of ground and surface water supplies and “recharge management”, through which long-term sustainability of urban water resources can be achieved.
- To identify options for urban waste water management including the potential for re-using wastewater using artificial recharge technologies.

4. APPROACH

To effectively manage, exploit and protect Azerbaijan’s water resources, management tools are required that can quantitatively represent the hydrologic system in its current state of operation and reliably predict the outcome of various alternative water management scenarios. Currently, the tools that best meet these requirements are computer generated hydrologic models.

4.1. GIS (Geographical Information System)

The success of any model depends on the quantity and quality of data used to create and calibrate the model. Therefore, as a first step, Microsoft Access, a highly versatile and widely used relational database system, has been adopted to maintain temporal data, and ESRI ArcView, a globally popular GIS (Geographical Information System) system is being used to maintain spatial data. The two databases are linked with the GeoDatabase feature of ArcView. The design has been kept flexible to enable easy expansion of the databases as new types of data become available. To date, much of the work has involved validation and database entry of a large urban and rural water dataset that was collected under the previous Soviet regime and exists in hard-copy form in the archives of the Azerbaijan National Academy of Sciences (ANAS) and the Water Problems Institute (WPI). Key data include basic geological and hydrogeological information, oil and water well drilling records, meteorological records, land use and population data, stream flows, groundwater levels, and ground and surface water quality data. All the available existing data need to be assembled and checked for consistency and reliability. An important first task is to convert this valuable dataset, as it exists for the Absheron Peninsula, into a form that is suitable for analysis using modern computational techniques.

4.2. Visual MODFLOW Pro

GIS is a powerful tool that can be used directly to aid decision-making through computer-aided "querying" processes. However, it can also be used interactively with a range of analytical tools including numerical models of the groundwater flow system, thereby providing the ultimate in informed decision-making. For the current study, groundwater flow models are being constructed and calibrated using Visual MODFLOW Pro version 4.1, a popular implementation of the U.S. Geological Survey's 3-dimensional, finite difference code developed and distributed by Waterloo Hydrogeologic. Visual MODFLOW Pro has an easy-to-use graphical user interface that facilitates data entry and provides many options for the presentation of results. It has become the industry-standard for applications in 3D groundwater flow and contaminant transport modeling. Development of the models is well advanced and is being supported by an exhaustive program of field work focusing on the quality and quantity of both ground and surface waters, the rates of degradation, water resource sustainability and the potential for finding new water supplies.

4.3. Field Data Collection

Prior to full project implementation, ground and surface water monitoring programs were very limited in extent. For example, surface-water flow and groundwater head measurements were generally conducted manually at intervals varying from three times per month to once a year. In addition, water-quality monitoring was largely limited to laboratory pH and major ion components (calcium, magnesium, sodium, bicarbonate, chloride and sulphate) - parameters that can provide an indication of the salinity and hydrochemical character of the water but are insufficient for "forensic" determination of contaminant sources. During the study, pressure transducers and data loggers have been installed at carefully selected sites to provide short-interval data regarded as essential for calibrating the system response models and understanding the periodicity and magnitude of aquifer recharge events. Plans are also underway to install a network of electrical conductivity sensors attached to dataloggers, and extend the range of analyzed parameters to include diagnostic minor ions (fluoride, iodide and bromide), together with field pH, redox potential, nitrate and selected organics.

4.4. Catchment Water Balances

Successful calibration and implementation of the groundwater flow models requires a good understanding of catchment water balances or "water budgets". Records exist for precipitation (inflow) and stream flows (outflow) but prior to the project, there had been no systematic attempt to refine water balances to the level required for effective water resource management. Evaporation and transpiration losses were not well known, and thus aquifer recharge rates were equally lacking. Some knowledge of aquifer recharge rates had been derived from measured river flows, but the reliability of these data is open to question. While, rigorously conducted water budget analyses for all catchments in the Absheron Peninsula are beyond the scope and budget of the project, much is being gained by focusing on two selected catchments, one rural and one encompassing the heavily urbanised Baku area. Recharge estimates are being made using soil moisture balance techniques operated on no more than a daily basis, and water table responses to recharge are being monitored in selected boreholes and used to identify “rapid recharge”, a form of recharge in which precipitation manages to circumvent the soil zone in urban areas to enter the water table, usually due to movement along pipes or between cobblestones. Also important in urban areas is aquifer recharge that results from water leaking from pressurized distribution networks, canals and from damaged sewers. It is suggested that distribution network losses are about 50% in Baku, one of the largest values in the world. The exact figure has enormous implications, not only for the water budget calculation but for establishing resource management priorities. Refinement of this estimate by locating areas of major leakage has become an important project task and will be accomplished through water balance calculations and groundwater modeling.

5. CONCLUSION

With support from NATO, a research project is well advanced that aims to promote economic and social stability in the Azerbaijan Republic through the development of a blueprint for safe and sustainable water supplies. Work focuses on the heavily populated city of Baku, the nation’s capital and an area seriously threatened by dwindling supplies of potable water and inadequate wastewater management. A major component of the project is the development and calibration of 3-D transient groundwater flow models of the region which are linked to a GIS database and computer-based analytical tools. These models are based on Waterloo Hydrogeologic’s version of the MODFLOW finite difference model code and are recognized as the key to effective resource and environmental management decision-making in the region. Work is well advanced and model development and calibration is well supported by a comprehensive field data collection program. When calibrated and tested, the models will be used to explore alternative water management strategies for the region. These strategies will likely involve integrated “conjunctive” use of ground and surface water supplies and “recharge management” technologies. The models will also be used to identify options for urban waste water management including the potential for re-using wastewater as a supplement to natural aquifer recharge.

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