Title: Evaluation of the declining groundwater levels of the coastal aquifers of Guyana

Topic: Groundwater Management and Modelling

Abstract

Groundwater abstractions globally are increasing resulting in degradation of groundwater quantities and qualities. In Guyana 90% of the population lives along the coast which accounts for approximately 10% of the total land mass. Groundwater is the main source of domestic consumption and as such results in an elevated pressure on this resource and reported decline in groundwater levels. The aim of this project is to establish the cause of decline in groundwater levels, and whether this is attributed to a change in climate, specifically rainfall within the recharge area, or increased abstraction rate. Rainfall and groundwater level data were analysed using R^2 trend analysis while recharge was calculated using a simple recharge equation and evaporation data derived from the ERA-40 reanalysis data set and use of the Thornthwaite equation. The impacts of recharge and abstraction are evaluated using Groundwater Modelling Software MODFLOW. It was accepted that the aquifer was connected to the rivers within the basin as well as the Atlantic Ocean. The high variability in rainfall over this region and the reported continuous decline in groundwater levels suggest there may be an additional reason for this decline. Current abstraction rates in comparison to the storage capacity of the recharge area did not suggest that there should be decline in groundwater sources. While abstraction rates continue to increase it is the proximity of wells that raises alarms as these can be found within a thin strip along the coast and banks of rivers. In addition to this, with connectivity to the

ocean and extensive cones of depression, the possibility of saline intrusion increases and poses a threat to this precious resource.

Key Words

Groundwater modelling; Guyana; Groundwater decline; Recharge; Abstraction

Introduction

Freshwater accounts for only 2.5% of all the water on the Earth and is further divided into groundwater sources, rivers, lakes, and snow cover (WWAP, 2009). The United Nations estimate that 70% of the world's freshwater is stored in ice caps and snow covers, less than 1% in lakes and rivers and the remainder in subsurface as groundwater (UN Water, 2013). Freshwater, specifically groundwater, is not equally distributed spatially or temporally (WWAP, 2009). The WWAP Report (2009) stresses the relevance of pressures exerted on groundwater systems as demand, such as abstraction, increases. An estimated 23% of the world's populations live within 1,000 km of the coast and within an area less than 100 m above sea level (IPCC, 2007). In Guyana, approximately 90% of the population lives along the coast (Beaie, 2007) which is approximately 10% of the land mass which is 2 m below sea level (Mercado, 1997). Although population growth has been relatively stable within the past 40 years an increasing number of housing schemes, 300 in 15 years, infer an increase in demand for water. This is highlighted by the approximately 20 m decline in the water table level along the coastal region of Guyana over the last 80 years (USACE, 1998).

The coastal aquifers were first drilled in 1781 penetrating the 'Upper Sands' with yields of 458 m^3 d^{-1} but was abandoned due to salinisation. The 'A Sands' were later penetrated in 1913 with a yield of 1,636 m^3 d^{-1} which increased to 347,382 m^3 d^{-1} in

2012. This study investigates the impacts of climate change, via a change in precipitation, and an increase in abstraction rates on the coastal aquifers of Guyana.

Methods

The study aims to identify the possible causes for declining groundwater levels within the coastal aquifers of Guyana over a 40 year period from 1970 to 2010. To ass the functionality of this aquifer the Groundwater Modelling Software (GMS) MODFLOW (Modular Three-Dimensional Finite-Difference Groundwater Flow Model) was used. Rainfall analysis was completed on data derived from the European Centre for Medium Range Weather Forecasting (ECMWF). The ECMWF Re-Analysis-40 and Interim (ERA-40 and ERA-Interim respectively) were used. A comparison of estimated recharge values from a study done in 1993 by Sir William Halcrow & Partners and using the ERA-40 data was also undertaken. Abstraction and water level data were obtained from the Guyana Water Incorporated (GWI) and reviewed for changes over time where possible.

Conceptual model: The conceptual model created was based on literature available on the stratigraphic and geographic features of the aquifer basin. The hydrogeological model was developed using Groundwater Modelling Software (GMS) MODFLOW 3D finite differences model which incorporated the SIP (strongly implicit procedure) and SSOR (slice successive over-relaxation) solution techniques (Anderson & Woessner, 1992) which solve simultaneous equations of parameters through iterations by using Guassian elimination methods and control when the model solution reached is adequate (Winston, 2013). No-flow boundaries were allowed south, southwest, and west of the aquifer basin while specified-head boundary was assigned to the north, to the Atlantic Ocean, and to rivers within the basin, but was turned on and off to test connectivity between the aquifer and ocean and rivers. Discharge was identified as specified flow over polygons covering the distribution area along the coast. Hydrogeological parameters used were derived from previous studies particularly Worts Jr. (1963) including hydraulic conductivity (75 m d^{-1}) and recharge (0.0027 m d^{-1}). Borehole data, based on stratigraphic descriptions of the aquifer, were used to create cross-sections and a 3Dsolid using Inverse Distance Weighting (IDW) interpolation. A 6 layer, 40 rows, and 80 columns 3D finite difference grid model was used.

Rainfall: Rainfall data was retrieved from the ECMWF which are derived from historical observations, such as from radioscondes, pilot balloons, surface observations, and satellite data, and analysis models (Bovolo, et al., 2012). To cover the 40 year period (1971-2010) two versions of the reanalysis models data were utilised, ERA-40 and ERA-Interim. The ERA-40 data covers the period September 1957 to August 2002 and utilises ECMWF dynamical model version cycle 23R4 (CY23R4) with 60 vertical levels and a horizontal resolution of T159 (~125 km) and employs a three dimensional variational data assimilation (decker 2012). ERA-Intermin covers the period January 1979 to April 2012 and utilises the ECMWF forecasting model version cycle 31r1 (CY31r1) with a horizontal resolution of T213 (~80 km) and employs a four-dimensional variational data assimilation (decker 2012). The data was aggregated from daily to monthly, seasonal, and annual and were analysed using R^2 trend analysis.

Water Level: Water level data was collected from GWI and processed to generate the specified flow polygons used in the groundwater model.

Recharge: Recharge was evaluated using a combination of methods as a result of the limited and poor quality of the data available for the area. Recharge estimated by Sir

William Halcrow & Partners (1993) for a 65 year period (1890-1955) was used as a baseline. The simplest of recharge calculations, precipitation minus potential evaporation and runoff, was employed using evaporation data from the ERA-40 reanalyses data set and calculated potential evaporation using the Thornthwaite equation. The Thornthwaite equation was used to calculate potential evaporation using the ERA-40 reanalysis air temperature data and an average 30 day month.

$\mathrm{PET} = 1.6\mathrm{L_d}\left(\frac{10\mathrm{T}}{I}\right)^{a}$, where; $\mathrm{L_d}$ is daylight time; T is monthly mean air temperature; a is $(6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 + 0.01791I + 0.49239$; and I is $\sum_{j=1}^{12}\left(\frac{T_j}{5}\right)^{1.514}$. To ensure a better comparison the same assumptions of Halcrow's study were employed, specifically that 80% of rainfall was available for recharge. These results were inputted to the 3D model and results compared.

Abstraction: Abstraction data were aggregated from various sources including raw data and annual reports from the GWI and previous studies on the coastal aquifer basin. This required conversion of units from Imperial gallons per day (Igal d^{-1}) and litres per day (L d^{-1}). The change in abstraction over time was addressed using data from historical accounts and current abstraction rates provided by the GWI.

Quality Control and Sensitivity Analysis: Water level and abstraction data were gathered in the form of raw data from reports from the GWI. The order of dates and units of measurement were not consistent and as a result the data was cleaned to allow uniformity base done verified information. The combined data sets were treated for duplication, missing data, and anomalies.

A 'one-at-a-time' sensitivity analysis was done to test the reactions of the model to 25% and 50% changes in recharge and hydraulic conductivity. During the tests discharge was not activated allowing for a comparison to the reported initial groundwater levels. This was done to test the significance of the hydrogeological parameters and shows how critical these values are and their reliability within the model (Brassigton, 2007). Several grid sizes were also tested to evaluate the impact of this on the produced water level and the most realistic and appropriate was selected.

Results

Conceptual model: Several attempts were made to make the model as representative of the aquifer system as possible, however, as a result of the interpolation by MODFLOW and limited information, the ‘B Sands’ aquifer was almost completely isolated from this system. The model did not converge when connectivity to rivers was turned off. Connectivity to the Ocean resulted in water levels ranging between 2 m below sea level (bsl) and 4.5 m above sea level (asl) reflecting the initial heads reports by Worts Jr. (1963) which range between -0.02 m bsl and 3.64 m asl.

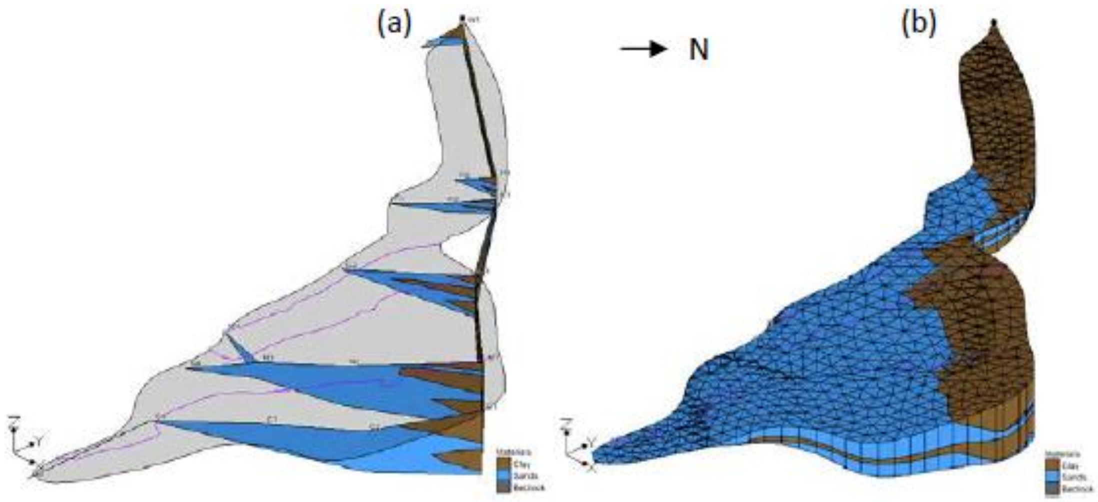

Figure 1: (a) Cross-sections created based on borehole data for the coastal aquifer of Guyana and (b) the interpolated 3D solid using GMS MODFLOW

Climate: The ERA-Interim trend line mimicked that of the average line while hte ERA-40 trend line was slightly inclined indicating an increasing trend with a R^2 value of 0.0505. The ERA-Interim trend line had a R^2 value of 0.0076. ERA-40 and ERA-Interim data sets along the coast varied in their annual average rainfall with ERA-40 having the higher average. The annual average varied by more than twice as much for the ERA-Interim data set (395 mm) than the ERA-40 (183 mm).

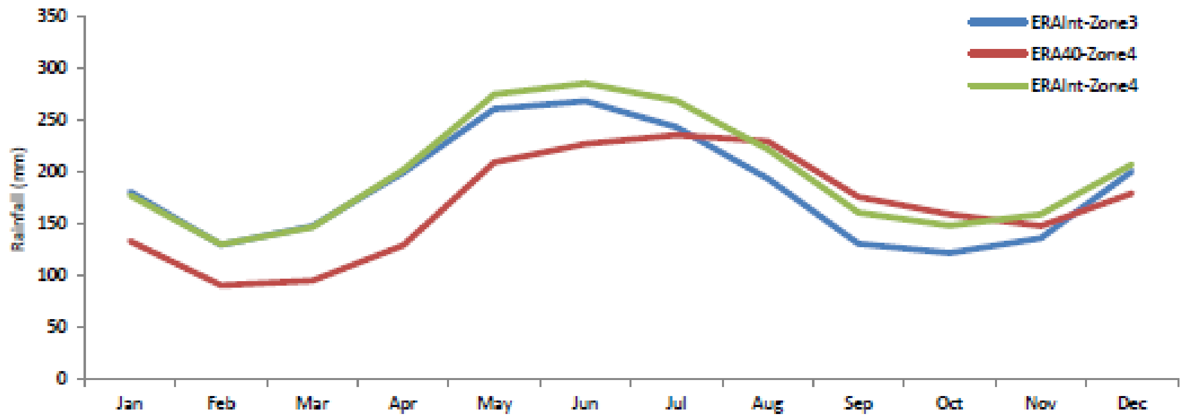

Figure 2: Average monthly rainfall for ERA-40 and ERA-Interim for the recharge area

Over the recharge area the ERA-40 had a similar patter when compared to the ERA-Interim data sets. The ERA-Interim data trend line followed the average rainfall mark with a R^2 value of 0.0059 while the ERA-40 trend line indicated an increasing pattern with an R^2 value of 0.1037. As with the coastal area, the ERA-Interim data suggests that there is little to no change in the trend while the ERA-40 data suggests there is an increasing in the total amount of rainfall for the period. The R^2 value for these is low and as such may be influenced by the high variability of the data sets. The ERA-40 data set covering the period 1971-2002 suggests an overall increase in rainfall, however, the ERA-Interim data set, covering the period 1979 - 2010 did not replicate this. It instead suggests no trend, based on the R^2 values between 0.0008 and 0.022. The ERA-40 data sets had R^2 values between 0.0009 and 0.1037 indicating a higher coverage of the variability but not significant enough to accept the trend as absolute. The data was analysed based on the two sets of dry and wet seasons experienced in Guyana. The data sets appear to follow a similar pattern but were highly inconsistent with average amounts. There was a slight difference between the annual average and the trend line for the ERA-Interim data set for the area covered. Annual average rainfall for the period 1970 to 2010 indicates a decrease in comparison to the period 1890 to 1955. Monthly averages were, in general, similar for the ERA-40 and ERA-interim data sets with the ERA-40 data set having a lower average than ERA-Interim. The ERA-40 data appears to be generally lower during the wet seasons and higher during the dry seasons in comparison to ERA-Interim.

Groundwater level: Data available was very sporadic and few within the 40 year period. There was variation in groundwater levels along the coast with Georgetown having the deepest static level and the shallowest range to the northeast at Berbice. This indicates a lowering at the centre, in Georgetown, and an eventual rise towards the boundaries of the aquifer.

Recharge: The ERA-40 re-analysis evaporation data indicated there was an average of 78 mm $year^{-1}$ evaporation over the south-eastern quadrant which covers the White Sand Series. This is significantly lower than the recorded average evaporation reported by Halcrow (1993) of 1,132 mm $year^{-1}$. The ERA-40 data set suggests a lower average annual rainfall, 27% less than Halcrow's, combined with the low evaporation rates resulted in a higher recharge rate by more than 300 mm $year^{-1}$. With the high uncertainty of the ERA-40 evaporation data set, potential evaporation was calculated using the Thornthwaite equation, to draw a comparison of the two. There was a positive relationship between the recharge rates and groundwater levels. The outputs of the model with Halcrow's and the ERA-40 estimation of recharge, 0.0027 and 0.0036 m d^{-1} respectively, is representative of the elevation within the recharge area. The third estimation using Thornthwaite equation did not represent this and may be attributed to the underestimation enforced by the equation.

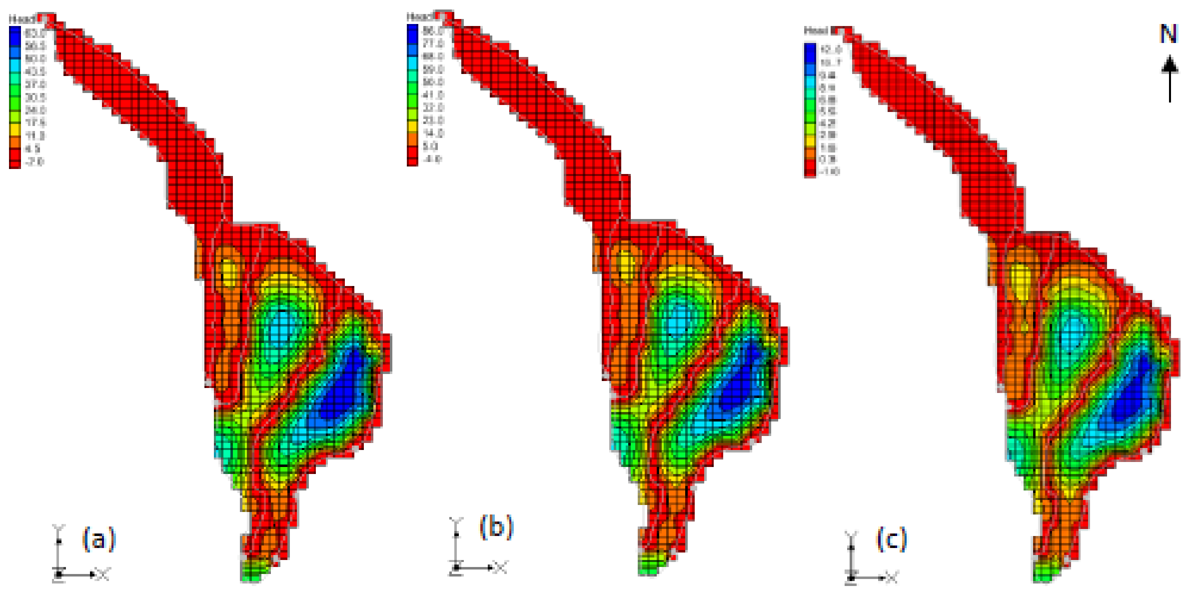

Figure 3: Model output with the estimated recharge rates (m d^{-1}): (a) R=0.0027 (b) R=0.0036 (c) R=0.0005

Abstraction: An abstraction rate of 74.69 MCM $year^{-1}$ (Million Cubic Metre per year) was reported in 1972 (Bassier and Porter 1972) which was followed by a decrease in total abstraction almost 50% to 36.5 MCM $year^{-1}$ in 1992 (Sir Wiliam Halcrow). In 2010 abstraction increase by almost 200% from the 1992 value to 106.6 MCM $year^{-1}$. The per capita consumption along the coast has increased from 103.99 m^3 $year^{-1}$ in 2004 to 157.91 and 187.84 m^3 $year^{-1}$ per capita in 2010 and 2012 respectively.

Sensitivity analysis: There was a positive relationship between changes in recharge, -50% to 50%, and the resulting groundwater levels projected by the model. Changes to the hydraulic conductivity resulted in an inverse relationship on an exponential curve illustrating the relationship between hydraulic conductivity and groundwater levels. The model represented the natural relationship between hydraulic conductivity and recharge and groundwater and as such can be accepted as reliable.

Discussions

Conceptual model: The model did not converge when connectivity to the rivers was turned off indicating that they model was not able to find a solution and therefore the aquifer must be connected to the rivers. When run with connectivity to the ocean, the groundwater levels along the coast were similar to those identified by Worts Jr. (1963) unlike when it was without connectivity which resulted in unrealistic figures suggesting that the aquifer system is connected to the ocean.

Climate: Although a similar pattern between the ERA-40 and ERA-Interim data sets was observed the Interim data seems to suggest that there was little to no change in the total amount of annual rainfall, however, the high variability of the data should be noted as a possible reason for this. There was greater correlation between the two data sets for the primary dry (FMA) season with the ERA-40 data indicating an increase in rainfall during this period. An increase in rainfall during this period would suggest an increase in potential recharge to the aquifer. A visible variation was present in the other three seasons. The primary rainy season (MJJ) both data sets had similar monthly averages for the season but the ERA-40 trend line indicated an increase in rainfall for this period. Unlike with the dry season, an increase in rainfall during the wet season results in an increase in runoff but given the high infiltration rates of sand this is likely to increase the recharge rate of the aquifer. Monthly data followed a similar pattern to the annual and seasonal data. ERA-40 had an exaggerated trend compared to the ERA-Interim. The impacts of this on groundwater levels is not easily visible given that the aquifers act as a resilient buffer during droughts and fluctuations in rainfall in comparison to surface water storage sources. Groundwater level data was very sporadic and few and did not allow for adequate statistical analysis. In addition to this, there is no standard operating procedure for the collection of data and as such this adds a level of uncertainty to the data collected. Groundwater levels varied along the coast depending on the distribution of people. This may be a direct reflection of increased abstraction within these areas and the potential influence of the cones of depression on each other where well distribution is dense.

Recharge: Very few studies have been done to estimate the potential and actual evaporation experienced more recently in Guyana. The ERA-40 data set suggests a higher recharge by more than 300 mm year^{-1} and reflects the low evaporation rates even with the low average rainfall. With the high uncertainty of the ERA-40 evaporation data set, potential evaporation was calculated using the Thornthwaite equation, to draw a comparison of the two. Air temperature data used in the Thornthwaite equation were taken from the ERA-40 data set and the assumption of 80% effective rainfall. This resulted in a significantly lower potential recharge for the aquifer by more than 80%. The particularly low value for evaporation may be attributed to humidity bias experienced by the ERA-40 model as a result of the infrared radiance bias combined with the low background error in temperature and thus low evaporation rates in the tropics.

Abstraction: It would be expected that given the apparent decline in groundwater levels, and its relationship with abstraction, that as abstraction continues to increase there is likely to be a continued decline in groundwater levels. Sporadic and poor data sets did not allow for a robust review. Bassier and Potter (1972) predicted that abstraction would exceed 300 MCM year^{-1} by the year 2000, however, it is estimated to be half of this, disregarding the 1972 figure which produces a more realistic pattern. Unusual groundwater levels were produced by the model when abstraction was activated particularly for the hilly region of the White Sand Series, however, along the coast the value ranged between 100 m bsl to 40 m asl which, given the current records, may be plausible.

Conclusions

The model created in this study aided in confirming the relationship between the aquifer and the rivers and Atlantic Ocean. Change in rainfall patterns and potential recharge to the aquifers can have devastating effects but may go unrecognised given the delayed response of groundwater systems. This does not appear to be the case with the coastal aquifers of Guyana as rainfall is highly variable and groundwater levels have been reportedly continuously declining. However, it may be plausible, given the pronounced uncertainty in the groundwater level data available it is quite difficult to dismiss this notion. The lowest depth of groundwater level is experienced within the capital city, Georgetown, and decrease further away towards the boundaries of the aquifer. It is believed that this may be the result of multiple interactions between the cones of depressions within the aquifer specifically within the Georgetown area. This is of particular concern when considering the close proximity of the wells along the coast.

With an inevitable increase in abstraction over time, this was result in a further falsified decline in groundwater levels. The poor quality and limited data available in this study does not permit for a conclusive attribute to be assigned the reason for the reported decline. As a result, it is particularly important that actual recharge, abstraction rates, and groundwater levels be compiled to establish the true head and possible true rate of decline.

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