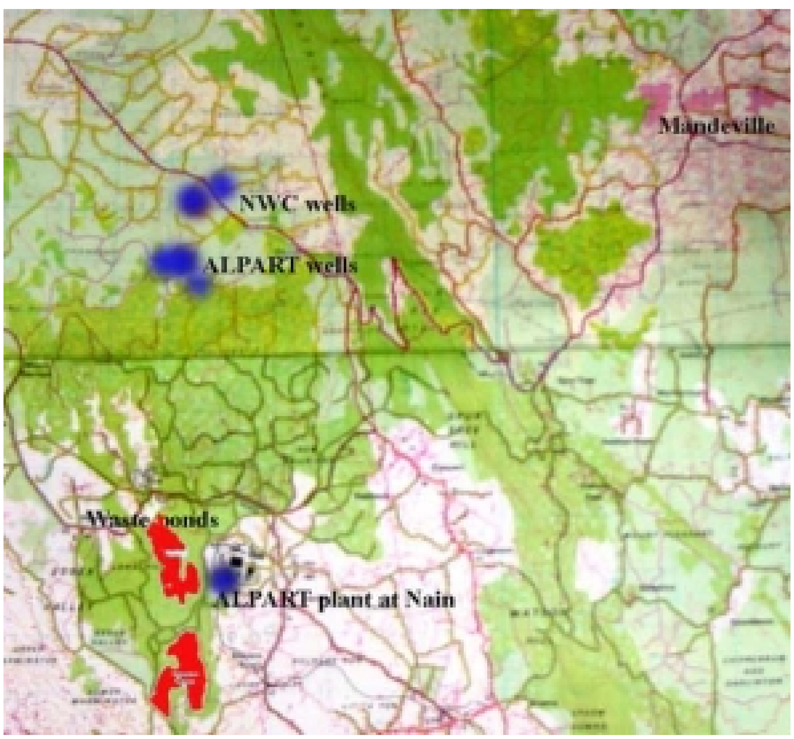
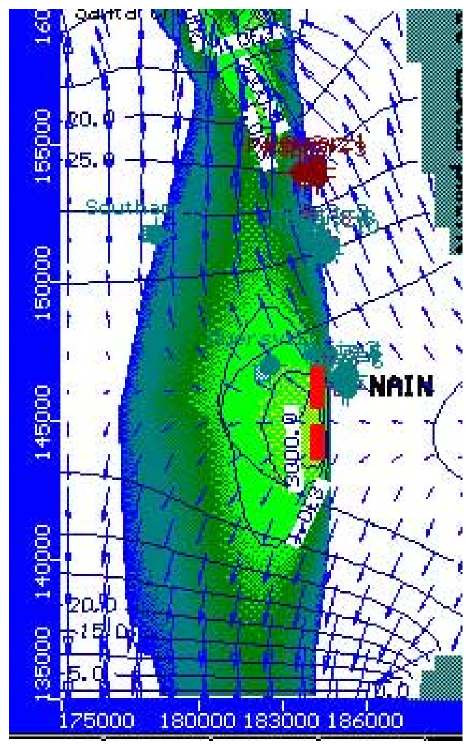
“Mapping Vulnerability of Jamaican Aquifers”
University of the West Indies Research Project

Mathematical Model of the Essex Valley St. Elizabeth Parish



Major wells groups (NWC to Mandeville and ALPART to Nain)



Sodium plume if and when ALPART stops operations

by: Dr. Jasminko Karanjac
Hydrogeologist & Sr. Research Fellow at UWI

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Mathematical Model of the Essex Valley, St. Elizabeth Parish

EXECUTIVE SUMMARY

Refining bauxite into alumina uses a so-called Bayer process in which bauxite is ground, slurried with a solution of caustic soda (sodium hydroxide, NaOH), and impurities are removed. Excess sodium (Na) and impurities, called red mud (with heavy metals, such as Cd, Fe, Mn, Ti, As, Zn, Pb, etc.), are deposited into waste ponds. If such waste pond is not properly constructed and/or is constructed on top of karstic limestone, it will leak and contaminate the ground water in limestone aquifers underneath.

This is the case of the alumina production at Nain in the St. Elizabeth Parish. The photograph of the processing plant is reproduced in Figure 1. The following are the facts (Figure 2):

- *Aluminum Partners of Jamaica (ALPART) pumps the water north of the Nain bauxite plant and at the plant itself and uses this water in the production of alumina at Nain and for domestic purposes at the plant..*
- *The industrial processing water is discharged into two waste ponds nearby the plant.*
- *National Water Commission (NWC) pumps water from the Pepper-Goshen wells and supplies the town of Mandeville and its surrounding area.*
- *Waste ponds leak and Na (and eventually some heavy metals) travel with the ground water flow from the waste pond towards ALPART's wells at Pepper and eventually toward NWC wells at Pepper-Goshen.*

The mathematical model of the Essex Valley is made to have a means to predict what may happen should ALPART stop the production (as it did in the second half of 1980's). It is expected that if ALPART wells were not pumping, the contamination from waste ponds would have endangered the water supply wells (NWC) at Pepper. It is for the model to confirm and quantify this expectation.

The model simulated a scenario of abstractions and discharge/release of sodium that appears to be close to what was happening between 1970 and 2000. The model output did match the sodium concentrations in several strategically located wells. The model continued with simulating some hypothetical scenarios. The most appealing one is the scenario with ALPART stopping operations and bringing to an end all abstractions and discharges of industrial waste waters.

The conclusions of that scenario are as follows. If and when the industrial use of ground water ceases, this could be taken as an opportunity to increase withdrawals from the Pepper-Goshen area for domestic water supply. The ground water system can sustain such a high production from such a small area.

The concentration of sodium at the Pepper-Goshen wells would be less than about 300 ppm because of the dilution effect of waters filling the cone of depression. Near the end of the simulated (ten years after industrial operation would stop) pumping period, there would be a decrease in the Na content. This is explained by dilution and by reduced inflow of contaminated-with-sodium ground water from the south.

It appears that such a scenario would not have adverse effects on the ground water system. The concentration of sodium in the drinking water of about 300 ppm (a maximum in one well, P-2, closer to the Goshen area) could be reduced by blending this water with the water from two more eastern wells at Pepper (P-1 and P-3). These two wells do not exhibit higher sodium content than 50 ppm.

The modelling work must be improved. The following improvements may be considered to make this model a more viable prediction tool:

- *Modify the boundaries to result with the ground water contours more curved toward the New Forrest and Alligator Pond. A well at New Forrest in the model remains outside the simulated Na plume. In the field, the opposite was observed and confirmed. The plume should also spread more toward the southeastern corner of the modelled area.*
- *Input as accurate as possible pumping rates and schedules for the entire period of simulation (starting with early 1970's). Include the cessation of abstraction in the second half of 1980's when the plant stopped operations. Acquire correct and complete data from ALPART and consult some earlier reports.*
- *Obtain more information on chemical analyses of "red mud". Modify the input of sodium (concentrations and locations). Enter the modified "red mud" discharging practices in the last four or so years. Inspect the ponds and notice the sites of sinkholes and places where the liquid waste may enter the subsurface. Use this in the model.*
- *Since sodium was simulated as a conservative substance, test the model using nonconservative behaviour of sodium including dispersion.*
- *Learn more about actual abstractions at Pepper-Goshen (by N.W.C.) and plans for future supplies of Mandeville and surrounding areas.*

Repeat the modelling using improved data in consultation with ALPART, WRA and N.W.C.

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1. Introduction

Refining bauxite into alumina uses a so-called Bayer process in which bauxite is ground, slurried with a solution of caustic soda (sodium hydroxide, NaOH), and impurities are removed. Excess sodium (Na) and impurities, called red mud (with heavy metals, such as Cd, Fe, Mn, Ti, As, Zn, Pb, etc.), are deposited into waste ponds. If such waste pond is not properly constructed and/or is constructed on top of karstic limestone, it will leak and contaminate the ground water in limestone aquifers underneath.

This is the case of the alumina production at Nain in the St. Elizabeth Parish. The photograph of the processing plant is shown in Figure 1. The following are the facts (Figure 2):

- Aluminum Partners of Jamaica (ALPART) pumps the water north of the Nain bauxite plant and at the plant itself and uses this water in the production of alumina at Nain and for domestic purposes at the plant. The wells in the vicinity of the plant at Nain were completed in 1967, and at Pepper in 1974.
- The industrial processing water is discharged into two waste ponds nearby the plant.
- National Water Commission (NWC) pumps water from the Pepper-Goshen wells and supplies the town of Mandeville and its surrounding area.
- Waste ponds leak and Na (and eventually some heavy metals) travel with the ground water flow from the waste pond towards ALPART's wells at Pepper and eventually toward NWC wells at Pepper-Goshen.

The pollution from waste ponds is already a well-documented fact. Figure 3 presents the distribution of sodium in 1999 and highlights the extension of the sodium pollution. Individual wells show a sharp increase of Na after the bauxite-alumina operations started (Figure 4). They also display a decrease of Na content after operations stop (second half of 1980's). This is the case of wells either at the Nain plant or at ALPART wells near Pepper.

Another example is shown for well BR-031 in Figure 5 at New Forrest. This is a location more south towards Alligator Pond. It also displays a sharp increase in Na. The increase in sodium implies that the contamination from Nain waste ponds has come that far south. There is also an increase in the Cl content coming from seawater intrusion.

ALPART wells at Pepper also display an increase in Na content. At the site of the well at ALPART 9 (Pepper 5), Figure 6, Na is used as a tracer to point at pollution reaching the well. The production started in 1969/70, and sodium-enriched water arrived some 5 km north after 5 years.

The mathematical model of the Essex Valley is made to have a means to predict what may happen should ALPART stop the production (as it did in late 1980's). It is expected that if ALPART wells were not pumping, the contamination from waste ponds would have endangered the water supply wells (NWC) at Pepper. It is for the model to confirm and quantify this expectation.

The modelling results are also uploaded to the Internet. The URL at http://www.geocities.com/briver2000 contains the ground water information system (GWIS) for the whole Black River Basin, all currently available data processed, interpreted and displayed in an easy to retrieve format, and the Essex Valley ground water flow and fate of sodium model. The web site contains discussion of geology and hydrogeology, lithology of every drilled or dug well that was entered into the data base and GWIS, chemical analyses, abstraction graphs, time series of sodium, pH values, and chloride, hydrographs at water level monitoring sites, etc.

The model is of preliminary nature. Its conclusions are valid but it may need refinements, especially in recreating piezometric maps in the last 20 or so years. Using the actual pumping volumes and schedules from all ALPART wells in the period under simulation (since the operations started), including the periods without operation and pumping, may correct some of results and modify conclusions. The more precise calibration of sodium in monitoring wells over the last 20 years may also modify the input of sodium as simulated in this model.

2. Model

2.1 Modelled Area Grid Size

The location of the modelled area and coverage by the model is shown in Figure 7. The model grid is represented with:

- 36 columns, each 500 m wide, from X coordinate 175,000 through 193,000
- 70 rows, each 500 m wide, from Y coordinate 135,000 through 170,000.

2.2 Model Boundaries

- South: the coast, Head=0 m, constant.
- North: no-flow across, H=variable, not assigned.
- East: no-flow across the line that represents the Spur Tree Escarpment. This is to say that the recharge on the Escarpment does not contribute ground water to the Essex Valley aquifer. This is a conservative assumption and not necessarily absolutely correct.
- West: no-flow across the column 1, being represented by Santa Cruz mountain acting as a ground water divide. This would imply that the recharge from columns one, two, etc. would contribute water to the Essex Valley aquifer. The recharge on a hypothetic column west of the column 1 would contribute to the western part of the Santa Cruz mountain aquifer (and would flow toward Pedro Plains).

- Several cells north of Santa Cruz and within the Upper Morasse are declared as constant-head cells with H set at 6 m (AMSL). Ground surface in the Upper Morasse is at elevations between 8 and 10 m.
- Although the modelled area is partly within the Manchester Parish (eastern part), the ground water flow within the Essex Valley is entirely within the St. Elizabeth Parish.

2.3 Hydraulic Conductivity and Storativity

The hydraulic conductivity in x and y directions is taken as 20 m/day in all of the model area except in the Essex Valley Fault system where it is made 30 m/day. Reports indicate that this fault system acts as a preferential way for ground water flow, being more karstified than the rest of limestone. The fault system extends from the waste ponds (Figure 8) to the north and south. Its northern extension coincides with pathlines starting between Myersville and Nain north of the north pond. The ponds are within the fault system.

2.4 Recharge to Limestone Aquifer

- The recharge from infiltrated rainfall is equal to 250 mm/year in the most of the model area, except north of Santa Cruz in a portion of the Upper Morasse where it is reduced to 200 mm/day or eliminated altogether.
- The rationale for this is the following. Average annual rainfall is 57 inches (1450 mm), and the recharge coefficient of 17% is of correct order of magnitude or an underestimate. Considering the karstic nature of the terrain and lack of a thick and extensive soil cover, the order of magnitude of the recharge coefficient would be between 15 and 25%. Earlier authors have proposed recharge coefficients between 0.25 of rainfall (Newberry, 1969) and 0.29 (Wiebe, 1974).
- The Upper Morasse is the final recipient of the ground water flowing through the Essex Valley aquifer to the north and northwest. From there, the water either evaporates or transpires supporting the growth of swamp-kind of vegetation or feeds tributaries of the Black River system. Assigning the recharge to the Upper Morasse and evaporation in the same time would not change the outcome of the simulation. Only the water balance would be different.

2.5 Evapotranspiration from Aquifer

- Maximum rate of evapotranspiration is assigned at 2000 mm/year, with the extinction depth set at 2 m below ground surface. The model does have the ground surface elevations assigned to each cell according to real topography.
- The extinction depth is interpreted in the following way. When the elevation of the water table is beneath the surface elevation less the 2 m (extinction depth), evapotranspiration from the water table is curtailed. When the water table is at or above the ground surface, evaporation loss from the water table occurs at the maximum rate (2,000 mm/year, in this model).

2.6 Abstraction from Limestone Aquifer

The ground water information system that was recently established for the Black River Basin has the following cumulative volumes for major groups of wells within the Essex Valley:

Table 1

Locality	**No. of wells**	**Q in 1994**	**Q in 1995**	**Q in 1996**	**Q in 1997**	**Q in 1998**	**Q in 1999**
Nain	5	7.8/4.7	4.9/3.0	3.4/2.1	9.5/5.7	5.9/3.5	8.1/4.9
Alpart-Pepper	4	8.5/5.1	5.7/3.4	5.3/3.2	10.7/6.4	9.2/5.5	10.7/6.4
NWC-Pepper	3	6.0/3.6	5.7/3.4	5.0/3.0	6.1/3.7	5.8/3.5	4.8/2.9

Q is the total abstraction volume from one of well groups in one year. The first number is million cubic metres (MCM); the second number is million imperial gallons per day (migd).

It appears that all abstractions are underreported. In 1982, it was reported[1] that “actual abstraction from the Nain-Pepper section of the Valley is about 13 migd” not including the NWC Pepper wells. The abstractions (pumping) used in the simulation are:

NWC at Pepper: 18,000 m^3/day (4.0 migd)
Alpart at Pepper: 28,800 m^3/day (6.3 migd)
Alpart at Nain: 27,400 m^3/day (6.0 migd)

The heads (equipotentials) in the model were calibrated using the above abstractions and 250 mm/yr recharge rates from rainfall. Higher abstraction rates would demand a recharge coefficient greater than 17%, or recharge rates higher than 250 mm/yr.

For comparison, shown are also daily abstractions as entered into the GWIS of the Black River basin. There are many missing months and data appear to be incomplete, so that the reported volumes are evidently underestimated.

- N.W.C. abstracts from Pepper-Goshen area and supplies Mandeville with about 33.5 MCM in the period from 1994 through 1999, at an average daily rate of 15,310 cubic metres (Figure 9).
- ALPART's abstraction at Pepper (for domestic use at the plant) in the same period is reported at about 50.0 MCM, or an average daily rate of 22,836 cubic metres (Figure 10).
- ALPART's abstraction at Nain (for industrial use) displays the total volume about 39.6 MCM or an average daily rate of 18,096 cubic metres in the 6-year period (Figure 11).

[1] Re-appraisal of the water resources of the Essex Valley sub-catchment, Upper Black River Basin, Jamaica. By: Hydrology Consultants Ltd., 1982.

3. Software Used for Modelling

- The **Visual Modflow** package from Waterloo Hydrogeologic Inc. was used for the simulation of the Essex Valley aquifer. It is a proven standard for 3-D ground water flow and contaminant transport modelling using MODFLOW, MODPATH and MT3D. These packages are integrated with an intuitive and powerful graphical interface.
- Most of graphics presented here is directly obtained from Visual Modflow. The rest is obtained using **Ground Water for Windows (GWW)** as a post-processor, with data exported from Visual Modflow runs and imported into the GWW.

4. Phases of Modelling

Phase One: simulating ground water flow using the parameters and boundaries as described above. The maps in Figure 8 and an expanded (zoomed in) section in Figure 12, showing the flow pattern from the ponds northwards, were obtained by assuming no-pumping conditions from either producer (ALPART at Nain, ALPART at Pepper, NWC at Pepper-Goshen, etc.). The map simply shows the directions of flow and elevations of water table in the simulated aquifer. Such a distribution of heads could have been a valid representation some 30 years ago when the abstraction from limestone aquifer was in its infancy.

Phase Two: simulating ground water flow in present days by adding the abstraction from wells at Nain (ALPART's bauxite plant), at Pepper (ALPART's industrial wells supplying the water to the bauxite plant at Nain), at Pepper-Goshen (NWC wells supplying Mandeville) and other individual wells at Myersville, Southampton, etc.

The distribution of equipotentials as shown in Figure 13 from Phase Two is used in contaminant (sodium) transport modelling phases.

Phase Three: simulating contaminant transport or fate of sodium (Na) under the real conditions. This is, five wells at the Nain plant (Nain 1,3,4,5,6) pump a cumulative total of 27,400 m^3/day (6.0 million IGPD or migd) throughout the period of 20 years; four wells at ALPART's well field south of Pepper pump a total of 28,800 m^3/day (6.3 migd) also throughout the period of simulation of 20 years; and three N.W.C. wells at Pepper-Goshen pump a cumulative total of 18,000 m^3/day (4 migd) in the last ten years of the simulation.

Phase Four: hypothetic scenario of ALPART's wells stopped pumping and the only abstraction coming from N.W.C. wells (3 wells, each pumping at 6,000 m^3/day) throughout a period of ten years. The purpose of this simulation is to predict what may happen should ALPART's wells stop intercepting the contaminant plume (in other words, stopped doing their "scavenging" work).

Phase Five: hypothetic scenario with N.W.C. wells at Pepper-Goshen pumping at total of 18,000 m^3/day throughout a ten year period (between 11th and 20th year, with the first ten years being idle or nonexistent), and then at about 10 migd rate in the remaining 10 years (45,000 m^3/day). This appears to be the reported water demand for Mandeville. In the same time, the ALPART's wells stopped pumping after 20 years of continuous operation. Waste ponds stopped contributing Na after 20 years.

5. Simulating Transport of Sodium

Sodium in this model is treated as a conservative substance. In other words, the only process of importance is advection. Sodium travels with ground water and is neither sorbed, retarded, nor decayed. It is only diluted. There is a different conclusion from a master thesis on *"Nonconservative Behaviour of Sodium"* by Taraszki (University of South Florida, Tampa, 1993). The author comes to a conclusion that "chemical reactions possibly responsible for sodium fixation include precipitation of sodium carbonates and gibbsite and sorption of sodium onto aluminum species. Trona and dawsonite are the most likely sodium carbonates to form upon evaporation in South Pond. Sodium will co-precipitate with gibbsite, and amorphous aluminum species and gibbsite crystals may also provide sorption sites for sodium."

The code used for simulation is **MT3D**, and upstream finite difference is the advection method selected.

6. Results

6.1 Phase Three (Real Case)

Sodium is being introduced at concentrations of 4,000-4,500 ppm (4 to 4.5 g/l) at 5 model cells, and at 12,000 ppm (12 g/l) in one model cell. The total area occupied by ponds is 1.75 sq.km. The recharge of wastewater into the aquifer from ponds is 2000 mm/yr. The total annual recharge of wastewater from ponds is equal to 2 m/yr * 1.75 * 1,000,000 m^2 = 3.5 million cubic metres (MCM/yr). The total mass of sodium being introduced annually into aquifer is about 17,500 t/yr.

The extension of the Na plume after 5, 10, 15, and 20 years is presented in Figure 14. It is shown that the plume (at concentration of 50 ppm) reaches the ALPART wells at Pepper after some 10-12 years. It never reaches the NWC wells at Pepper-Goshen. Rather than continuing to the north, the plume is being intercepted by ALPART's wells at both Pepper and Nain. Actual deviation from the background concentration of sodium of some 10 ppm was noticed much earlier.

Pathlines as shown in Figure 15 indicate that most of the contaminant from the pond will end in ALPART's wells at Nain. A smaller portion will bypass the Nain wells and will terminate in ALPART's wells at Pepper.

The time evolution of the sodium content is shown in three points.

- At the Nain site (Figure 16), the Na content becomes elevated almost instantly after the plant started working. Near the end of the 20-year period, the Na content is almost steady above 1300 ppm. This model output may be compared with the actual Na content in the well BR-073/Nain-3 in which the Na content in December 1999 was 1320 ppm (Figure 4).

- At the ALPART's site at Pepper (Figure 17), the Na content becomes elevated after 6 years in ALPART 8 and after 9 years in ALPART 9. The model output may be compared with actually observed in the field at BR-079/ALPART 9 (Figure 6) and at BR-078/ALPART 8 (Figure 18). In both wells, the real rise starts in 1989 and continues at an average rate of 3 to 4 ppm in each year until the end of 1999. This was a consequence of ALPART's plant at Nain stopping its operation in late 1980's due to economic constraints on aluminum production. With reduced or eliminated inflow of red mud and sodium carried with it, the ground water reacted by dilution and rebound. The content of sodium was reduced to background values of less than 10 ppm. Yet with resumed operations, the sodium quickly filled in the aquifer and monitoring wells started showing increase above the 10-ppm threshold.
- The mass balance (input into and output from the ground water system) is as follows (as an average daily rate in the first ten years of simulation; migd = million imperial gallons per day):

Input:	Recharge = 305,000 m^3/day (67 migd)
	From storage = 5,000 m^3/day
Output:	Evapotranspiration = 150,000 m^3/day (33 migd)
	Wells = 56,000 m^3/day (12 migd)
	Constant head boundary cells = 104,000 (23 migd)

6.2 Phase Four (Hypothetical Case of Pumping from N.W.C. Wells Only)

Only NWC wells (3) are pumping at 6,000 m^3/day each. They start pumping ten years after the Nain bauxite plant became operational. In other words, the limestone aquifer between the ponds and the Pepper-Goshen area is already enriched with sodium. The model should answer just how much the release of sodium in ponds would affect the quality of drinking water in NWC wells.

Figure 19 shows the plume after 20 years. It appears that the NWC wells at Pepper-Goshen would remain at the periphery of the plume. The plume would spread mostly in the western direction from the ponds, and would reach the Upper Morasse area, which is the discharge area for the ground water system north of the ponds. As shown in one of concentration with time diagrams (Figure 20), the concentration at one of NWC wells would reach a maximum of only 100 ppm.

6.3 Phase Four: Conclusions

If the geology and hydrogeology of the Essex Valley are correctly translated into this model, then there will be not much danger to the NWC wells at Pepper-Goshen from ALPART stopping altogether its production. NWC wells appear not to be in the direct path of ground water flow.

6.4 Phase Five: Hypothetical Case of Abstracting 10 Million IGPD at Pepper-Goshen

It was reported that the actual water demand for the Mandeville area was about 10 million Imperial gallons per day (migd). This is equivalent to about 45,000 m^3/day. In this phase, a hypothetical scenario is tested. Three wells at Pepper-Goshen are pumping in the additional 10 years (beyond what was tested in phase four) about 15,000 m^3/day each. Thus the total abstraction in the year 21-30 was about 10 migd or 45,000 m^3/day. In the same period (after the year 20), the ALPART's wells stopped abstraction altogether. The model simulated also the end of the sodium input at ponds to zero after the year 20.

The results are shown as a map (Figure 21) with heads and velocity vectors and as another map (Figure 22) with heads and Na plume after 30 years of simulation.

The drawdown at the Pepper-Goshen sites is acceptable. Water levels are still high, at about 17 m (AMSL). The plume did cover the abstraction sites, with a maximum of less than 300 ppm (Figure 23).

6.5 Phase Five: Conclusions

The redistribution of pumping from the Nain area to the Pepper-Goshen area would not create an additional depression. In other words, if and when the industrial use of ground water ceases, this could be taken as an opportunity to increase withdrawals from the Pepper-Goshen area for domestic water supply. The ground water system can sustain such a high production from such a small area.

The concentration of sodium at the Pepper-Goshen wells would be less than about 300 ppm (Figure 22) because of the dilution effect of waters filling the cone of depression. Near the end of the pumping period, there would be a decrease in the Na content. This is explained by dilution and by reduced inflow of contaminated-with-sodium ground water from the south.

It appears that such a scenario would not have adverse effects on the ground water system. The concentration of sodium in the drinking water of about 300 ppm (a maximum in one well, P-2, closer to the Goshen area) could be reduced by blending this water with the water from two more eastern wells at Pepper (P-1 and P-3). These two wells do not exhibit higher sodium content than 50 ppm. It is probably the current practice of NWC to transmit the water from all three wells in the same pipeline to the treatment plant.

7. Improvements to the Model

The following improvements may be considered to make this model a more viable predictable tool:

- Modify the boundaries to result with the ground water contours more curved toward the New Forrest and Alligator Pond. The well at New Forrest 2 (Figure 5) remains outside the simulated Na plume. In the field, the opposite was observed and confirmed. The plume should also spread more toward the southeastern corner of the modelled area. This can be accomplished by reassigning boundary conditions and recharge in that part of the model.
- Input as accurate as possible pumping rates and schedules for the entire period of simulation (starting with early 1970’s). Include the cessation of abstraction in the second half of 1980’s

when the plant stopped operations. Acquire correct and complete data from ALPART and consult some earlier reports (by Geraghty & Miller, e.g.).

- Obtain more information on chemical analyses of “red mud”. Modify the input of sodium (concentrations and locations). Inspect the ponds and notice the sites of sinkholes and places where the mud may enter the subsurface. Use this in the model.
- Since sodium was simulated as a conservative substance, test the model using nonconservative behaviour of sodium including dispersion.
- Learn more about the actual abstractions at Pepper-Goshen (by N.W.C.) and plans for future supplies of Mandeville and surrounding areas.

Repeat the modelling using improved data and in consultation with ALPART and N.W.C.