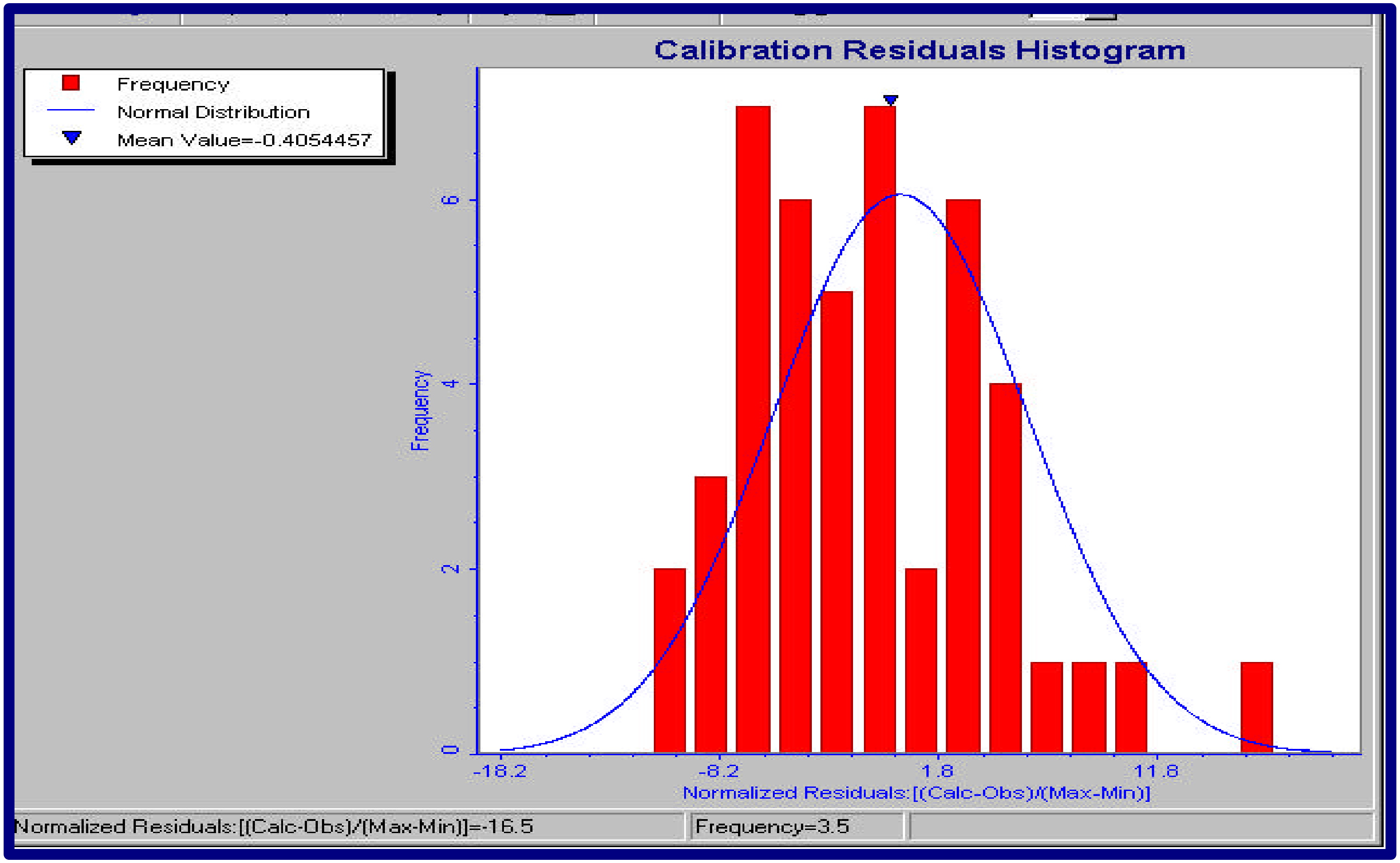

Normalized Residuals:[(Calc-Obs)/(Max-Min)]=-16.5

Frequency=3.5

**Figure 5.7** Histogram of calibrated residuals of the difference in calculated versus observed heads in the White Limestone aquifer of the Rio Cobre and Rio Minho-Milk river basins.

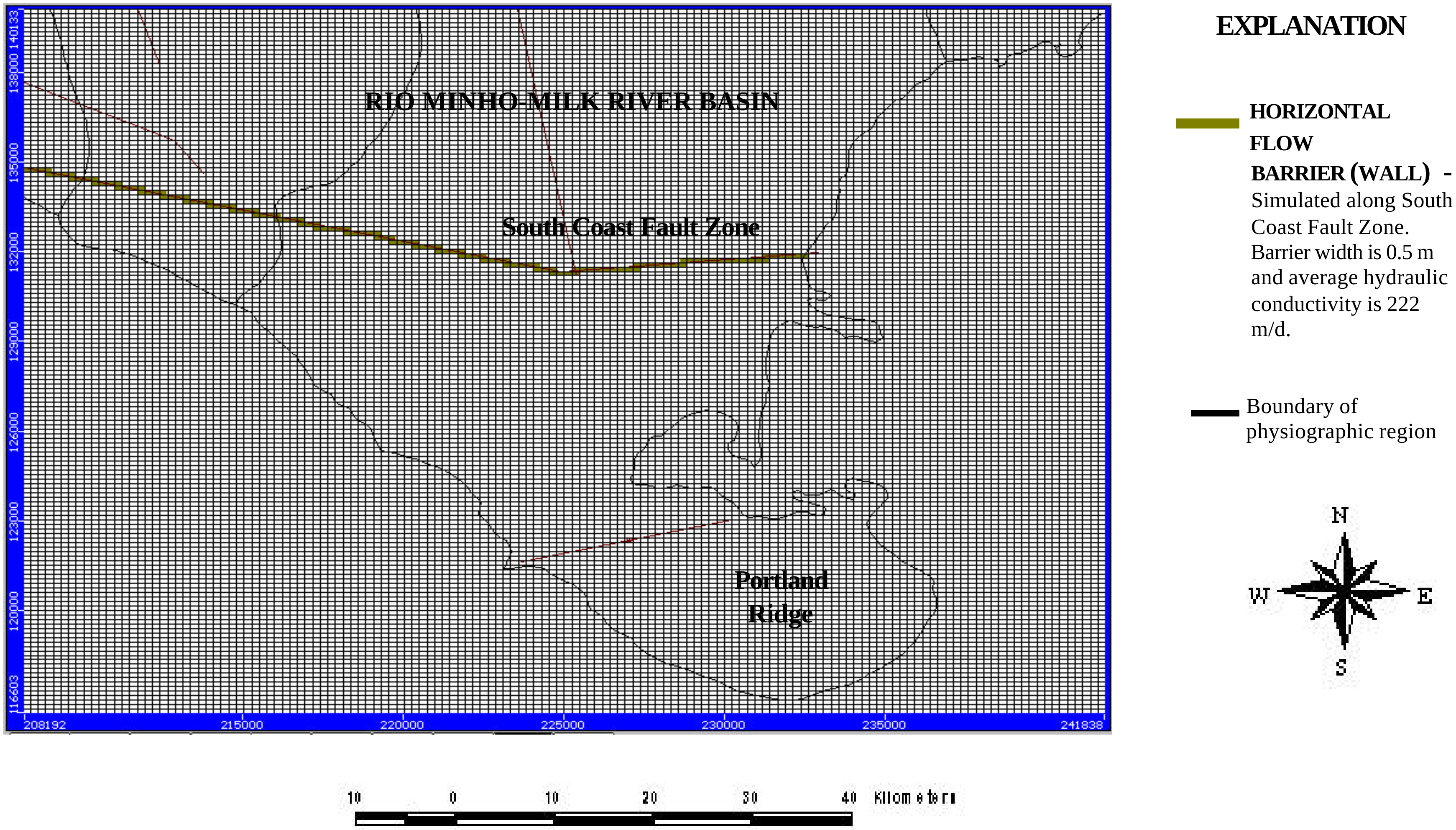

**Figure 5.8** Map showing a section of the South Coast Fault where a horizontal-flow boundary was simulated.

the horizontal flow of ground-water allowing these features to be modeled without the need to reduce grid spacing with an excessive number of cells. These features are approximated as series of horizontal flow barriers conceptually situated on the boundaries between adjacent cells in the finite-difference grid. The fundamental assumption regarding of the HFB Package is that the width of the barrier is negligibly small in comparison to the horizontal dimension of the cells in the grid. The barrier hydraulic conductivity divided by barrier width, though not explicitly considered in the package, represents barrier width. The branch conductance in the row direction between the two cells can be determined as shown by McDonald and Harbaugh (1988, chap. 5, p. 6 Eq. 38, and p.7, fig 25):

$$\frac{1}{CR_{i,j,+1/2,k}} = \frac{1}{\dfrac{TR_{i,j,k}DELC}{\dfrac{DELR_{j}}{2}}} + \frac{1}{TDW_{i,j+1/2,k}DELC_{i}} + \frac{1}{\dfrac{TR_{i,j+1/2,k}DELC_{i}}{\dfrac{DELR_{j+1}}{2}}} \qquad (14)$$

where

| | |
|---|---|
| $CR_{i,\,j+1/2,k}$ | is the branch conductance in the row direction between nodes $_{i,j,k}$ and $_{i,j+1,k}$ $[L^{2}T^{-1}]$ |
| $TRJ_{i,j,k}$ | is the transmissivity in the row direction of cell $_{i,j,k}$ $[L^{2}T^{-1}]$ |
| $TRJ,_{i,j+1,k}$ | is the transmissivity in the row direction of cell $_{i,j+1,k}$ $[L^{2}T^{-1}]$ |
| $DELR_{j}$ | is the grid width in row direction of column [L] |
| $DELR_{j+1}$ | is the grid width in the row direction of column $_{j+1}$ [L] |
| $DELC_{i}$ | is the grid width in the column direction of row $_{i}$ [L]; and |

$TDW_{i,j+1/2,k}$ is the barrier transmissivity divided by the width of the barrier between cell $_{i,j,k}$ and cell $_{i,j+1,k}$ [LT-1]

A detailed report of the documentation of the mathematical and numerical implementation of the HFB package is contained in the USGS Open-File Report 92-477, “Documentation of a Computer Program to Simulate Horizontal-Flow Barriers Using U.S. Geological Survey’s Modular Three-Dimensional Finite-Difference Groundwater Flow Model (Hsieh and Freckleton, 1993).

## SIMULATION RESULTS

The model was most responsive to the general-head boundary assigned to the upper boundary. This was the first significant calibration strategy for the model development. There is however, a discrepancy between the amount of inflow expected to occur through the boundary ($2.8 \times 10^5 m^3/d$) and the actual inflow of $1.162 \times 10^6$ $m^3/d$ calculated by model. The amount of inflow expected to occur through the boundary is based on volume of recharge calculated for the region between the topographic divide (Central Inlier) and the northern boundary of the study area. It is evident that the upland subsurface inflow across the boundary is a second source of recharge to the study area. The discrepancy in flow through the upper boundary may be due to the hydraulic conductivity values used to calibrate the model. Simulated values may be high and not characteristic of the aquifer, even though the calibrated values are lower than those estimated from specific-capacity tests. These tests were conducted for a very short duration; hence, it is likely that only near surface highly permeable karst regions in the basins are affecting the tests. Therefore, higher transmissivity values could have been used than actually exist at depth within the aquifers of the study area.

Hydraulic conductivity values computed from WRAJ specific capacity data are much higher than those used to calibrate the model (Table 13). The values used to calibrate the model in this study range from a fraction of those computed from WRAJ data to an order of magnitude lower. This is an indication that the values provided by WRAJ data are too high and perhaps result from insufficient time spent conducting pumping tests. Zone 5 is characterized by a high contrast in hydraulic conductivity compared to the other surrounding zones including the hydraulic conductivity of the overlying alluvium (110m/d). Zone 5 represents a highly permeable, Tertiary carbonate platform in the White Limestone aquifer of the lower Rio Minho-Milk River basin. If the hydraulic conductivity value of this zone was decreased below 480 m/d during calibration, then significant increase in the RMSE was observed. The Tertiary carbonate platform is also transected by numerous reverse faults including the South Coast fault. It would be particularly interesting to investigate the role played by these faults in conjunction with the South Coast fault in a future hydrologic investigation. The possibility does exist that they may be impacting the current flow regime of both basins.

The simulation of the HFB along the South Coast fault with a subsequent decrease in the width of the fault barrier from 1m to 0.5m or lowering the hydraulic conductivity from 444 to 222 m/d resulted in an overall improvement in the development and calibration of the model. During calibration, an improvement of 4 –10 m in matching the heads was accomplished by reducing the barrier hydraulic conductivity by one half. A gentler hydraulic gradient and a more agreeable match between the calculated and observed heads in lower Rio Minho-Milk River basin replaced the steep hydraulic gradient that formed earlier along the area closest to the fault. An experiment was conducted, in which the fault was not simulated, in order to see its effect on model development and calibration. The results were similar to the scenario in which cells were simulated with a high, average hydraulic conductivity value of 222 m/d in both directions along the fault. This key observation suggests that the simulation of the horizontal-flow barrier does inhibit horizontal flow across the fault, but there is no inhibition of flow in the vertical direction of the fault.

The water table slopes in a general northwest-southeast direction that coincides with the major fault trend in the basin. The Tertiary carbonate platform facilitates a steep water table gradient in the southwest region of the study area, and a gentle water table surface over the immediate area of the lower Rio Minho-Milk River basin (Figure 5.7). It may be inferred from this modeling study that the South Coast Fault works in conjunction with the tertiary carbonate platform in controlling the water table gradient and flow regime in the Rio Cobre and Rio Minho-Milk river basins being simulated as one basin. This was the most significant calibration strategy used in the overall development of the model.

Hydraulic heads from several well observation points failed to calibrate within reasonable differences between calibrated heads and observed heads. A few examples of these are Nutshell Core Hole, Fattening Pasture, and Clifton School Core Hole (Figure 5.6). The calculation of the percentage error of the residuals (i.e. the margin of error divided by the calculated error x 100) clearly reveals the limitation of the data collected from areas in the study region (Tables 14-15). The percentage error of the residuals is low (1-8%) for observation points in the White Limestone aquifer of the upper Rio Cobre basin (e.g. Hyde, Venecia, West Prospect, Garden Bush, Tulloch, and Palm) and the upper Rio Minho-Milk River basin (Arcadia, Porus, Moore, Rhymesbury Diary, and Rhymesbury Explorer 5A). The percentage error of the residuals for observation points in the alluvial aquifer (that lies in the lower half of the study region and the coastal plains) seemed high (15-43%) compared to those observed in the unconfined White Limestone aquifer. The lack of calibration of some observed heads in the alluvial aquifer confirms that water level data are being not recorded accurately. Reliable estimates of long-term average hydraulic heads would have been suitable for the modeling effort if were determined from monitoring the wells in this aquifer on a regular basis. The difficulty arising from the lack of calibration of observed heads in these wells may also be due to datum reference errors observed in some places. Care ought to be exercised in collecting water level data and determining datum reference points.

The model demonstrated slight sensitivity to the initial streambed vertical hydraulic conductivity value of 0.08344 m/d. Sensitivity analysis was performed during

**Table 14**. Simulated and measured 1997 heads in the alluvial aquifer of the Rio Cobre and Rio Minho-Milk River Basins, Jamaica, West Indies.

| No | Layer | Well Location | Column | Row | Measured or estimated Head (m) | Calibrated Head (m) | Margin of Error | Percent Error $PE = \frac{ME}{H_c} * 100$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Ashley Hall | 152 | 301 | 13.19 | 16.209 | 3.019 | 18.62 |
| 2 | 1 | Bog 1K | 166 | 308 | 12.52 | 12.844 | .324 | 2.52 |
| 3 | 1 | Bog 4 | 167 | 309 | 10.75 | 9.422 | -1.328 | 14.09 |
| 4 | 1 | Bullards CH 1 | 141 | 239 | 33.96 | 29.036 | -4.924 | 16.95 |
| 5 | 1 | Campeachie | 299 | 230 | 20.47 | 25.778 | 5.308 | 20.59 |
| 6 | 1 | Chesterfield | 161 | 329 | 35.58 | 29.437 | 6.143 | 20.86 |
| 7 | 1 | Clifton School CH | 125 | 282 | 16.59 | 23.121 | 6.531 | 28.24 |
| 8 | 1 | Content Village Explorer | 147 | 233 | 33.84 | 29.546 | -5.384 | 18.22 |
| 9 | 1 | Cookson 1 | 314 | 216 | 19.33 | 27.199 | 7.869 | 28.93 |
| 10 | 1 | Denbeigh Farm 2 | 151 | 222 | 41.16 | 34.761 | -6.399 | 18.4 |
| 11 | 1 | Exeter 3 | 139 | 315 | 6.22 | 10.838 | 4.618 | 42.60 |
| 12 | 1 | Fattening Pasture | 161 | 223 | 42.07 | 30.556 | -11.514 | 37.68 |
| 13 | 1 | Gimme-me-bit | 134 | 284 | 14.3 | 23.066 | 8.796 | 38.13 |
| 14 | 1 | Greenwich 2 | 152 | 346 | 2.39 | 1.943 | -0.447 | 23 |
| 15 | 1 | Knights | 145 | 335 | 3.83 | 3.148 | 0.692 | 21.98 |
| 16 | 1 | Mitchell Town | 182 | 335 | 2.78 | 3.325 | .545 | 16.39 |
| 17 | 1 | Morelands 2 | 178 | 323 | 8.71 | 7.744 | -0.966 | 12.47 |
| 18 | 1 | Needham 3 | 155 | 309 | 10.48 | 14.265 | 3.785 | 26.53 |
| 19 | 1 | Parnassus CH1 | 159 | 246 | 34 | 26.984 | -7.016 | 26 |
| 20 | 1 | Parnassus CH2 | 159 | 247 | 33.72 | 26.725 | -6.995 | 26.17 |
| 21 | 1 | Rhymesbury CH2 | 141 | 240 | 21 | 26.476 | 5.476 | 20.68 |
| 22 | 1 | Rhymesbury Diary | 131 | 251 | 26 | 28.254 | 2.254 | 7.97 |
| 23 | 1 | Rhymesbury Expl 5A | 139 | 248 | 29 | 27.565 | -1.435 | 5.2 |

**Table 14.** Simulated and measured 1997 heads in the alluvial aquifer of the Rio Cobre and Rio Minho-Milk River Basins, Jamaica, West Indies.

| No | Layer | Well Location | Column | Row | Measured or estimated Head (m) | Calibrated Head (m) | Margin of Error | Percent Error $PE = \frac{ME}{H_c} * 100$ |
|---|---|---|---|---|---|---|---|---|
| 24 | 1 | Rocky Point | 158 | 357 | 0.89 | 0.949 | 0.059 | 6.21 |
| 25 | 1 | Rowington 3 | 134 | 275 | 15.44 | 24.198 | 8.758 | 36.19 |
| 26 | 1 | Sedge Pond | 132 | 298 | 13.13 | 18.283 | 5.153 | 28.18 |
| 27 | 1 | Vernamfield Expl 1A | 143 | 272 | 20.36 | 24.218 | 3.858 | 15.93 |
| 28 | 1 | Vizzard Run 6 | 147 | 318 | 6.54 | 10.899 | 4.618 | 42.37 |
| 29 | 1 | York Pen 1 | 151 | 231 | 37.88 | 28.987 | -8.893 | 30.67 |

**Table 15**. Simulated and measured 1997 heads in the White Limestone aquifer Rio Cobre and Rio Minho-Milk River Basins, Jamaica, West Indies.

| **No** | **Layer** | **Well Location** | **Column** | **Row** | **Measured or estimated Head (m)** | **Calibrated Head (m)** | **Margin of Error** | **Percent Error** $PE = \frac{ME}{H_c} * 100$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Arcadia (Porus) | 89 | 179 | 108.56 | 104.951 | -3.609 | 3.43 |
| 2 | 1 | Ashley Hall | 152 | 301 | 13.19 | 16.209 | 3.019 | 18.62 |
| 3 | 1 | Bullards CH1 | 141 | 239 | 33.96 | 29.036 | -4.924 | 16.95 |
| 4 | 1 | Garden Bush 2 | 281 | 114 | 78 | 81.971 | 3.972 | 4.84 |
| 5 | 1 | Hyde | 260 | 100 | 88 | 89.857 | 1.857 | 2.06 |
| 6 | 1 | Moore CH | 181 | 171 | 41.63 | 44.056 | 2.426 | 5.5 |
| 7 | 1 | Naseberry Grove | 261 | 176 | 52 | 59.967 | 7.967 | 13.28 |
| 8 | 1 | Nutshell | 248 | 47 | 133 | 114.672 | -18.328 | 15.98 |
| 9 | 1 | Palm | 261 | 52 | 116 | 110.481 | -5.519 | 4.99 |
| 10 | 1 | Porus 1 | 86 | 166 | 111 | 108.371 | -2.629 | 2.42 |
| 11 | 1 | Rhymesbury 2a | 135 | 255 | 32 | 28.449 | -3.551 | 12.48 |
| 12 | 1 | Rhymesbury Diary | 131 | 251 | 26 | 28.254 | 2.254 | 7.97 |
| 13 | 1 | Rhymesbury Expl 5A | 139 | 248 | 27 | 27.565 | -1.435 | 5.20 |
| 14 | 1 | Tulloch Marsden | 284 | 105 | 88 | 83.058 | -4.942 | 5.95 |
| 15 | 1 | Venecia | 265 | 101 | 86 | 88.857 | 1.568 | 1.76 |
| 16 | 1 | West Prospect | 290 | 97 | 91 | 87.341 | -3.659 | 4.187 |

calibration, until the streambed hydraulic conductivity values for the White Limestone and the alluvium aquifers were gradually lowered to an acceptable final calibrated value of 0.0563 m/d. The final calibrated streambed hydraulic conductivity is assumed to reflect the hydrogeologic properties of the streambed materials. The final values of streambed vertical hydraulic conductivity values are probably low in the modeling study, because the streambed material consists of very fine sand, clay and some detrital volcanic sediments. Final calibrated streambed hydraulic conductivity values are compared to the initial estimate in Table 16.

## HYDROLOGIC BUDGET

### Zone Budgets

The ground-water budget for steady-state simulation of flow in the Rio Cobre and Rio Minho-Milk river basins gives an accounting of recharge to the basin, discharge from the basin, and flow between hydrogeologic units in the basin (MODFLOW - Zonebudget, 1990). The continuity equation establishes that inflows are equal to outflows. One of the main benefits of using MODFLOW is that mass balance calculations provide a very useful way to examine the source of water provided to a system of hydrologic stresses like recharge and discharge.

The main objectives of this study were the estimation of ground-water flow budget estimation and determination of aquifer-flow directions. Nine budget zones were assigned throughout the Rio Cobre and Rio Minho-Milk river basins using

**Table 16**. Initial estimates and calibrated values for streambed vertical hydraulic conductivity used in the model analysis of the Rio Cobre and Rio Minho-Milk river basins, Jamaica, West Indies.

| Underlying hydrogeologic unit | Streambed Hydraulic Conductivity (meters per day) | |
|---|---|---|
| | Initial estimate | Calibrated value |
| White Limestone | 0.08344 | 0.0563 |
| Alluvium | 0.08344 | 0.0563 |

Zonebudget (MODFLOW) to determine the overall hydrologic budget for the region (Figure 5.9). These zones included smaller zones where discharge may be taking place such as in the swamps near the coast and where the aquifers are hydraulically connected to the sea.

The ground-water budget for the water year 1988 is illustrated in Figure 4.10 and is summarized in Table 17. Water budget inflows include recharge from precipitation and recharge via the general head boundary. Water budget outflows include: 1) net recharge from precipitation (2.54 x $10^6 m^3$/d, 2) subsurface inflow along the upper boundary (1.16 x $10^6 m^3$/d), and a minimal amount of aquifer recharge by the streams (4.69 x 10 $m^3$/d). Water budget outflows calculated in this modeling are presented in Table 18 and Figure 5.10 and include: 1) submarine discharge from along the coastal boundary, 1.98 x $10^6 m^3$/d, 2) river leakage stream discharge (1.70 x $10^6 m^3$/d) and a small discharge through the northern boundary of the upper Rio Minho-Milk River basin (2.06 x. $10^4$ $m^3$/d). The total calibrated ground-water flow was (3.70 x $10^6$ $m^3$/d) (Table 18).

Calculations of leakage from streambed sediments (Zonebudget, 1990) were compared with the known stream discharges recorded from reaches in the Rio Cobre, Rio Minho and Milk Rivers to determine which streams were considered gaining streams or losing streams. If the rate of river leakage for a zone exceeded the total combined discharges for reaches in a particular zone, then the stream is considered a losing stream. The Rio Minho is considered a losing stream in its upper reaches where the river leakage

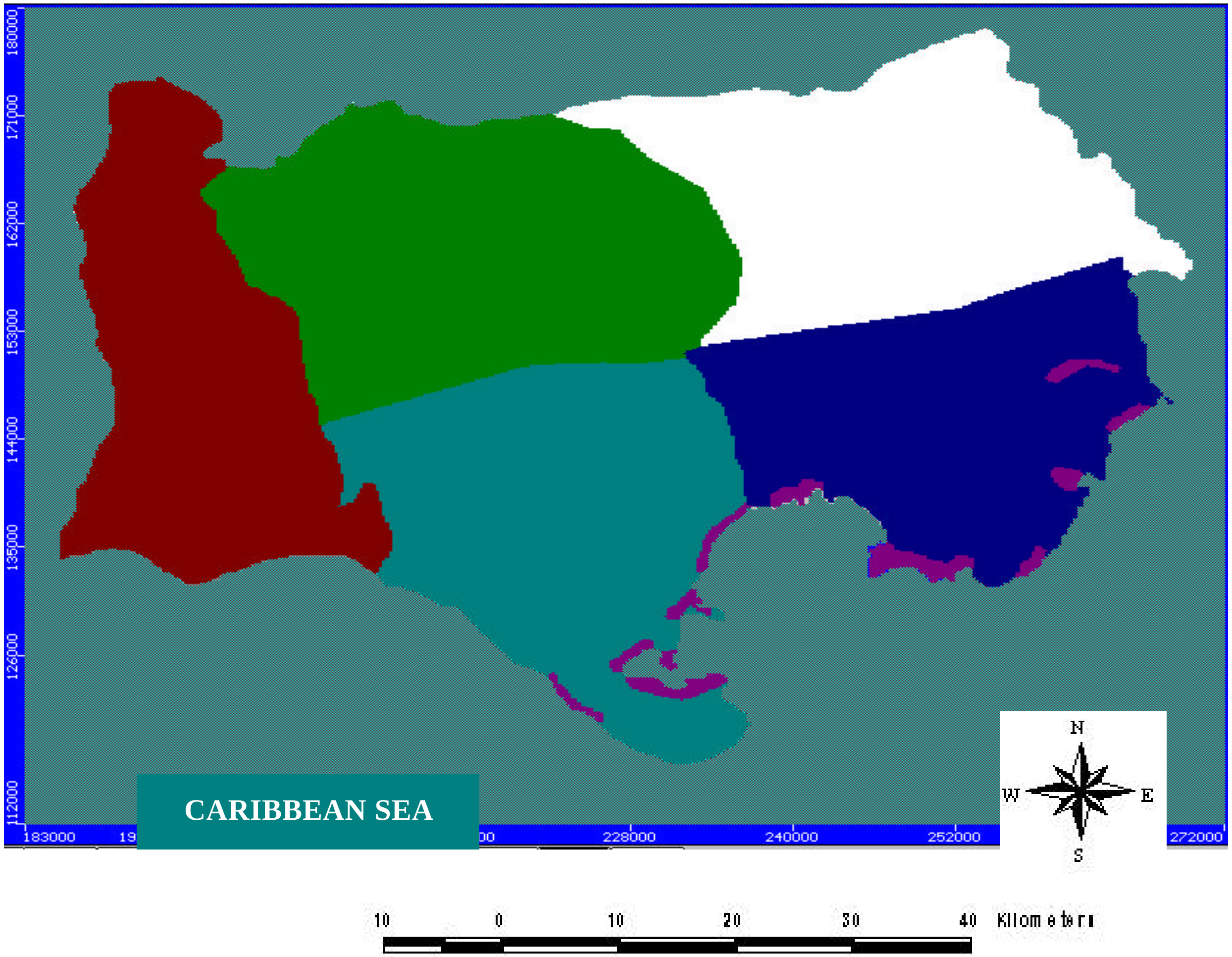

**Table 5.9** Assigned zones in ZONEBUDGET used to calculate the hydrologic budget of the Rio Cobre and Rio Minho-Milk river basins.

## EXPLANATION

### ZONE BUDGET

- ☐ 1. Upper RCB
- ■ 2. Lower RCB
- 🟩 3. Upper RMMB
- ■ 4. Lower RMMB
- 🟥 5. Manchester Highlands
- 🟪 6. Swamps
- ■ 8. Interface at MH (RMMB)
- ■ 9. Interface at Old Harbor
- 🟦 10. Interface at Bernard Lodge

**Table 17.** WRAJ-estimated ground-water budget for the Rio Cobre and Rio Minho-Milk river basins in $m^3$/d, Jamaica, West Indies (WRAJ, 1990).

| | **WATER RESOURCES AUTHORITY OF JAMAICA 1990** |
|---|---|
| RECHARGE: | |
| | ($m^3$/d) |
| Precipitation | 3,503,000,000 |
| Net recharge from precipitation | 926,000,000 |
| Water released from storage | 0 |
| TOTAL RECHARGE | 4,429,000,000 |
| DISCHARGE: | |
| Evapotranspiration | 3,091,000,000 |
| Water taken into aquifer storage | 0 |
| Surface water runoff | 412,000,000 |
| Ground – water recharge (Exploitable surface) | 926,000,000 |
| TOTAL DISCHARGE | 4,429,000,000 |

**Table 18.** Modeled ground-water budget for the Rio Cobre and Rio Minho-Milk river basins [Modeled values in $m^3/d$].

| | THIS STUDY (2000) |
|---|---|
| RECHARGE: | |
| | ($m^3/d$) |
| Net recharge from precipitation | 2,542,104 |
| Irrigation | ? |
| Streams | 4.69 |
| Subsurface inflow along northern boundary | 1,162,286 |
| Inflow along coastline | 4112.31 |
| TOTAL RECHARGE | 3,708,507 |
| DISCHARGE: | |
| Subsurface outflow along northern boundary | 20,060 |
| River leakage | 1,704,473 |
| Submarine (Caribbean Sea) | 1,983,974 |
| TOTAL DISCHARGE | 3,708,507 |

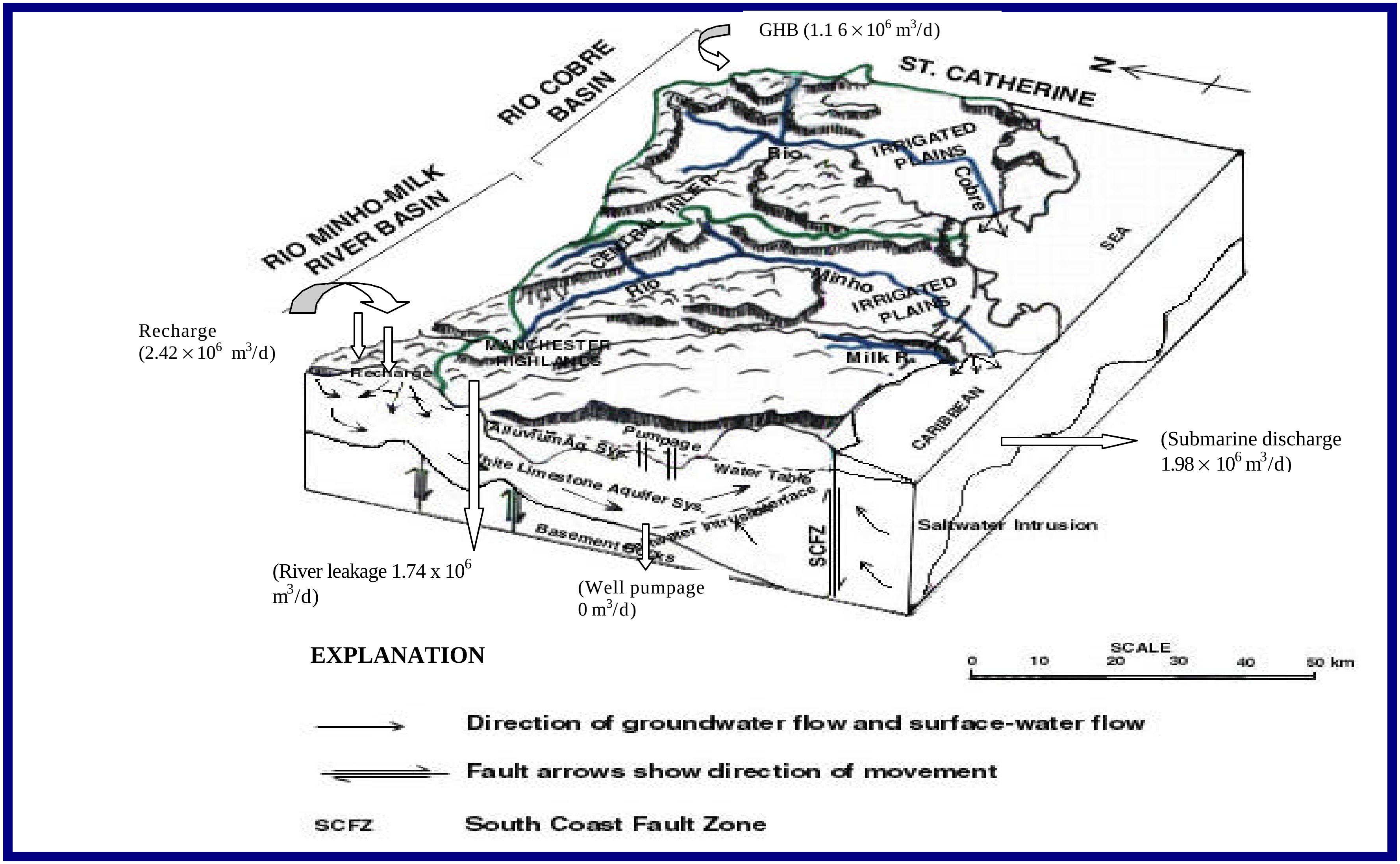

**Figure 5.10** Modeled ground-water budget

from that zone is 9.67 x $10^5$ $m^3$/d whereas the combined discharge is 7.00 x $10^5 m^3$/d. This can be expected because the streambed sediments are not necessarily thick, but consist of highly weathered volcanic sediments and clay from weathered crystalline rocks exposed in upland region. All other rivers reaches are recognized as gaining streams.

An important objective of this modeling study was to determine if submarine discharge was occurring from coastal aquifers that are hydraulically connected to the Caribbean Sea. Submarine discharge was calculated based on WRAJ data from three areas: the White Limestone aquifer at Manchester Highlands, the alluvium aquifer Bernard Lodge and Old Harbor (Table 8). The submarine discharge calculated from WRAJ data (4.72 x $10^5 m^3$/d) does not agree with the submarine discharge calculated by the model (1.983 x $10^6 m^3$/d).

## Sensitivity Analysis

The overall performance of a ground-water model may be better analyzed through a sensitivity analysis of its aquifer parameters. The process of model development and sensitivity analysis allows the ground-water investigator to better understand the system's response to changing hydrologic parameters. Sensitivity analyses were used during model calibration to refine initial estimates of input parameters and after model calibration to determine which input parameters had the largest effect on simulated head values. The model is considered sensitive to an input parameter when small changes in the value of that parameter result in large changes in simulated head values. Conversely, if large changes in the value of an input parameter result in little or no change simulated in the simulated head, then the model is not sensitive to that parameter, and the model is not useful for refining the initial estimate of the parameter. If the model is sensitive to an input parameter, additional data on that variable can help improve calibration. Increments and decrements of 10 percent were applied to hydraulic conductivity and rainfall recharge. Sensitivity analysis was applied to the streambed vertical hydraulic conductivity and the general-head boundary conductance values during calibration.

Sensitivity analyses conducted for recharge, horizontal hydraulic conductivity, and conductance assigned along the general-head boundary verify a satisfactory level of calibration with a root mean squared error of 5.82. An incremental increase of 10% in the boundary hydraulic conductivity causes an automatic increase in the root mean squared error (RMSE), a decrease in the amount of flow through the general-head boundary, and increased net recharge in the model. The effect is the same if net recharge to the area is increased by 10%. The lowest value of RMSE achieved in any sensitivity analysis of hydraulic input parameters for the model in this study is 5.82. Increments and decrements of 10% to any one hydraulic parameter improve neither model calibration nor development. The model sensitivity to these changes may also be caused from hydraulic conductivity values that may be too high. Sensitivity analyses of these parameters indicate simulated heads are mostly sensitive to changes in hydraulic conductivity and aquifer recharge and least sensitive to streambed vertical hydraulic conductivity (Table 19 and Figures 5.11-5.14).