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MODELING AQUIFER RECHARGE WITH GIS

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Abstract: A series of six recharge maps, covering the entire area within the South Florida Water Management District, was developed using ESRI's ARC/INFO geographic information system (GIS) software (Version 6.1.1) on a Sun SparcStation 20, SunOS 4.1.3c UNIX platform, and printed on a Canon Laser Printer. This paper demonstrates the step-by-step GIS modeling methodology used for this project. Recharge rates and excess precipitation were determined principally from data sets extracted from existing numerical ground-water flow models developed at the District, and standardized to reflect long-term average annual precipitation trends. ASCII data were preprocessed and transformed into point coverages. Other coverages were digitized from existing maps. All coverages were converted into raster grids by kriging, and combined through map algebra to create new information. The results were converted to polygon coverages, and reclassed for viewing in ArcView, and for map display through ArcPlot. The six recharge maps appear as plates in SFWMD Technical Publication 95-02 (DRE 327), "Mapping recharge (infiltration/leakage) throughout the South Florida Water Management District" by Phil Fairbank and Susan Hohner.

INTRODUCTION

As the population of South Florida grows, increased water needs require management of ground-water resources to meet present and future demands. As of 1994, regional use exceeded 900 million gallons of water per day (SFWMD, 1994) while human activities and urbanization contribute to water quality degradation and reduction of available recharge surfaces within aquifer systems. In order to effectively manage ground-water resources, Florida has adopted legislation focusing on the identification, delineation, and protection of ground-water recharge areas. Section 373.0395 of the Florida Statutes (FS) requires the water management districts (WMD's) to inventory "prime" recharge areas, while Section 373.0397, FS, requires the mapping of the boundaries of these areas for both the Biscayne aquifer and the Floridan Aquifer systems. These and other statutory requirements led to the publication of SFWMD Technical Publication 95-02 (DRE 327), "Mapping recharge (infiltration/leakage) throughout the South Florida Water Management District" by Phil Fairbank and Susan Hohner (1995). The data sources and calculations used in modeling were discussed in this earlier publication. This paper describes how the mapping was accomplished through building a Geographic Information System (GIS). The purpose of the current paper is to review the GIS methodology used, without repeating the details of the ground-water modeling originally discussed.

ESTIMATING RECHARGE AND EXCESS PRECIPITATION

Fairbank and Hohner (1995) includes six maps as plates. These are:

a) Biscayne Aquifer and Surficial Aquifer System, Potential Precipitation Recharge and Excess Precipitation for the Lower East Coast Planning Region: Palm Beach, Broward and Dade Counties;
b) Surficial Aquifer System, Potential Precipitation Recharge and Excess Precipitation for the Upper East Coast Planning Region: St. Lucie and Martin Counties;
c) Surficial Aquifer System, Potential Precipitation Recharge and Excess Precipitation for the Lower West Coast Planning Region: Collier, Hendry and Lee Counties;
d) Lower Tamiami Aquifer, Potential Recharge/Discharge for the Lower West Coast Planning Region: Collier, Hendry and Lee Counties;
e) Sandstone Aquifer, Potential Recharge/Discharge for the Lower West Coast Planning Region: Collier, Hendry and Lee Counties; and
f) Upper Floridan Aquifer, Potential Recharge/Discharge and Excess Precipitation for the Kissimmee Basin Planning Region: Charlotte, Glades, Highlands, Okeechobee, Orange, Osceola and Polk Counties within SFWMD boundaries.

Information displayed includes:

a) Potential Precipitation Recharge (for unconfined systems);
b) Potential Recharge/Discharge (for semi-confined and confined systems); and
c) Excess Precipitation.

Precipitation recharge is defined as the amount of water derived from rainfall that infiltrates the ground surface, moving through the soil to the water table, thereby increasing ground-water storage. Potential Precipitation Recharge (R_p) in unconfined systems was calculated as rainfall minus runoff minus unsaturated evapotranspiration losses. However, in South Florida, unsaturated ET loss is considered negligible as compared to saturated ET loss and, therefore, was not accounted for in the calculations.

$$R_p = P_n - Q_d - ET_u \qquad (1)$$

where

P_n is the average net precipitation depth not lost to interception or depressional storage,
Q_d is the average depth of water lost to surface drainage, and
ET_u is the average actual evapotranspiration depth from the unsaturated zone.

Leakage is defined as the amount of ground water moving into or out of a confined aquifer through adjacent semi-permeable confining media, thus resulting in the recharge (gain) or discharge (loss) of water to the aquifer system. Potential Recharge/Discharge (R_l) was calculated as the hydraulic pressure differences existing between the semi-confined or confined system and the overlying water table, multiplied by the modeled leakance estimates from the upper confining media separating these aquifer systems.

$$R_l = H \times L_k \qquad (2)$$

where

H represents the hydraulic pressure difference existing between the water-bearing unit directly above the aquifer and the aquifer itself, and
L_k represents the leakance as a ratio of vertical hydraulic conductivity of the aquifer confining bed to the thickness of the confining bed.

Excess precipitation varies spatially, reflecting precipitation trends. Defined as the difference between long-term average annual rainfall and actual evapotranspiration estimates, it represents the amount of residual water potentially available for urban and/or rural supply, assuming runoff as an available component. Average excess precipitation (P_e) was calculated as Rainfall minus Actual Evapotranspiration.

$$P_e = P - AET$$

where
P represents average annual rainfall, and
AET represents average annual actual evapotranspiration losses.

For further discussion of the factors influencing recharge, details on standardizing the data to long-term averages and the calculations used, and a listing of the regional modeling studies which provided numerical data sets used in this project, the reader is referred to Fairbank and Hohner (1995).

GIS METHODOLOGY

The modeling and map generation in Fairbank and Hohner (1995) was done using Environmental Systems Research Institute's (ESRI) ARC/INFO geographic information system (GIS) software (Version 6.1.1) on a Sun SparcStation 20, SunOS 4.1.3c UNIX platform, and printed on a Canon Laser Printer.

Potential Precipitation Recharge for unconfined systems

Numerical ground-water flow model results in the form of ASCII recharge matrix array files were available for Broward, Collier, Dade, Hendry, Lee, Martin, Palm Beach and St. Lucie county models. These were each preprocessed, using SUN Fortran 77, into Arc/Info Generate Files and converted to Triangulated Irregular Networks (TINs) using the CREATETIN command. TINs are used to model 3-dimensional surfaces, but in this case served as a transitional step. The TINs were converted to Point Coverages with TINARC. Each of these county recharge coverages encompasses a rectangular model area extending beyond the political boundary of the county. Each was therefore clipped down to the county boundary and combined into regional point coverages with APPEND. These regional models include the Lower East Coast (Broward, Dade and Palm Beach), the Lower West Coast (Collier, Hendry and Lee) and The Upper East Coast (Martin and St. Lucie). Points representing NODATA were edited out of the coverages using Arc/Edit.

While each of the county models originally conformed to its own regularly spaced array, these arrays were in a variety of sizes, ranging from 1000 to 5280 feet in width. To convert the three newly appended regional model coverages into regularly spaced arrays, they were converted to GRIDs through a LINEAR KRIG. A grid cell spacing of 500 foot width and height was chosen in order to produce "smooth" boundaries in the output maps. These GRIDs were then converted into Polygon Coverages with GRIDPOLY. Descriptive statistics were tabulated and the coverages reclassed into class ranges for map display.

Potential Recharge/Discharge for semi-confined and confined systems

Lower Tamiami and Sandstone Aquifers

Potential recharge/discharge matrix array files were not available from numerical ground-water flow models as in the case of recharge for unconfined systems. For the Lower Tamiami and Sandstone Aquifers, this had to be calculated as the hydraulic pressure differences existing between the semi-confined or confined system and the overlying water table, multiplied by the modeled leakance estimates from the upper confining media separating these aquifer systems.

Spreadsheet listings of potentiometric head data at well locations for each county were preprocessed into input files for use with the Arc/Info GENERATE and INFO IMPORT commands, to create Point Coverages for each county, which included data for the Lower Tamiami, Sandstone and Surficial Aquifers. These county coverages were divided out into separate coverages for each aquifer, using SELECT in Arc/Edit, and then combined with APPEND into three regional coverages, one for each aquifer. The coverages were converted to 500 foot GRIDs with a LINEAR KRIG. In the case of the Lower Tamiami and Sandstone Aquifers, a Mask was used to removed those portions of the GRIDs that were extrapolated beyond the boundaries of the aquifers.

Arc/Info GRID analysis is accomplished through the use of Map Algebra. Map Algebra GRID operators perform mathematical computations within and between GRIDs. A simple example is the Addition Operator. When two GRIDs are added together, the corresponding GRID cell values are added together, and the output for each cell equals the value of the sum (Figure 1).

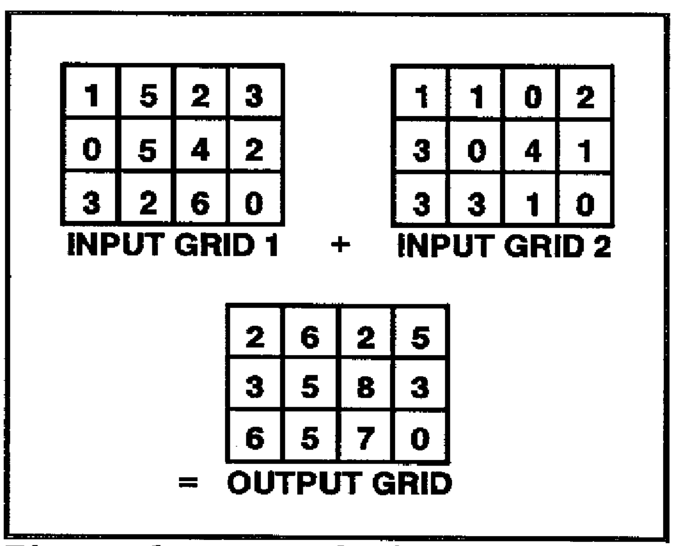

Figure 1. Map Algebra Addition

Hydraulic pressure differences for the Lower Tamiami and Sandstone Aquifers were calculated using Map Algebra. The Surficial GRID minus the Lower Tamiami GRID produced the hydraulic pressure differences GRID for the Lower Tamiami Aquifer. Creation of the hydraulic pressure differences GRID for the Sandstone Aquifer required an extra step. The Sandstone Aquifer is overlaid by the Lower Tamiami. However, the Lower Tamiami does not extend as far to the Northwest as the Sandstone. That portion of the Sandstone is overlaid directly by the Surficial. Therefore a single "overlying" GRID was created, using the Lower Tamiami pressures where existing, or the Surficial pressures otherwise. Then the Sandstone GRID was subtracted from the "overlying" GRID, resulting in the hydraulic pressure differences GRID for the Sandstone Aquifer.

Leakance, or Vertical Conductance, was available as matrix array files. These were converted into Coverages and GRIDs using the same process as described above for Potential Precipitation Recharge for unconfined systems. The final step in calculating potential recharge/discharge was to multiply the hydraulic pressure differences and the leakance. This was done in Map Algebra by multiplying the GRIDs. The resulting recharge grids were then converted into Polygon Coverages with GRIDPOLY. Descriptive statistics were tabulated and the coverages reclassed into class ranges for map display.

Floridan Aquifer

Data files were not available for the Floridan Aquifer. Instead, existing hardcopy choropleth maps in Bush and Johnston (1988) were digitized to create two Polygon Coverages showing estimated predevelopment recharge/discharge of the 1930's, and estimated changes due to recent (1980) pumpage. These coverages were converted to 500 foot GRIDs with the POLYGRID command. In Map Algebra, the predevelopment estimates were adjusted with the change estimates by adding the two GRIDs, resulting in an updated recharge/discharge GRID. The GRID was converted into a Polygon Coverage with GRIDPOLY. Descriptive statistics were tabulated and the coverages reclassed into class ranges for map display for the Kissimmee Basin region.

Excess Precipitation

As in the case of Floridan Aquifer Recharge/Discharge, data files were not available for excess precipitation, and hardcopy maps were used. A rainfall Line Coverage was digitized from an isohyet map in MacVicar (1981). The Line Coverage vertices were transformed into a TIN with ARCTIN, from a TIN to a Point Coverage with TINARC, and finally to a 500 foot GRID with a LINEAR KRIG. An evapotranspiration Polygon Coverage was digitized from a choropleth map in Bush and Johnston (1988) and converted to a 500 foot GRID with POLYGRID. Average excess precipitation is calculated as rainfall minus actual evapotranspiration. Therefore, in Map Algebra, the evapotranspiration GRID was subtracted from the rainfall GRID, resulting in an average excess precipitation GRID. This GRID was converted into a Polygon Coverage with GRIDPOLY. Copies for each of the four areas of interest (Kissimmee Basin, Lower East Coast, Lower West Coast and Upper East Coast) were clipped to their respective areas. Descriptive statistics were tabulated and the coverages reclassed into class ranges for map display.

CONCLUSIONS

The maps compiled in Fairbank and Hohner (1995) were an initial attempt at quantitatively mapping recharge at a regional level, based on large-scale data. This project demonstrates that, through the use of GIS, various forms of data including matrix data, spreadsheet data, and hardcopy maps, could be brought together into a single format, namely GRID. Computational analysis of the GRIDs was accomplished through Map Algebra to model new spatial and statistical information, which could then be output in hardcopy map form.

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