# FINAL REPORT
# DEP Contract No. SP621

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## INTRODUCTION

Researchers from the Pennsylvania State University and Florida State University entered into a contractual arrangement with the Florida Department of Environmental Protection to develop a technique to estimate the loading of injected wastewater nutrients on surface waters of the Florida Keys. The scope of work stated:

The Contractor shall make an assessment of the loading of injected wastewater-derived P and N on surface waters of the Florida Keys, based on:

1) knowledge of the position, rate and water- quality of wastewater discharges to the subsurface to be provided by Florida DEP and placed in the PSU GIS database;

2) estimates of subsurface flow rates and directions (FSU) based on previous published work.

3) determination of travel times based on the information above (FSU-PSU)

4) an empirical relationship, to be developed by us (PSU-FSU colleagues) that relates the proportional loss of biologically available N and P as a function of time spent in the subsurface.

5) an estimate of flushing times and exchange rates for canals and nearshore waters (from the literature - PSU).

The final product shall be a spatial model of nutrient loadings on surface waters (canals and nearshore waters) based on existing information concerning injection rates. The model will be implemented in a GIS environment that will allow full spatial analysis of relationships between injection well location and surface water discharge sites. The Contractor will be responsible for all GIS development.

The model will have the flexibility to allow multiple scenarios in the analysis of present and future wastewater disposal methods (e.g., centralized vs. dispersed injection). The model will make specific predictions of water quality in canals and nearshore waters. Model output results will be presented in an interactive visual display environment, accessible with a standard Web browser, that will allow users to investigate a library of model simulations developed using a multiple input parameters. This approach will be particularly effective for visualizing the impacts of time- dependent (e.g., seasonal) loading patterns.

This approach will also allow users to evaluate potential sampling and analysis locations for monitoring the water quality of surface discharges.

The Contractor shall present the final report, including the GIS layers and simulations, by June 30, 2003 to the Florida DEP and EPA program contacts.

The Final Report of this project follows. The report focuses on the methods used and the uncertainties inherent in these estimates, because the web-based tool we provided is self-explanatory, and it was not our goal to explore the implications of our estimates or make recommendations for remediation. We went beyond the scope of work in terms of the groundwater modeling. However, an analysis of the wastewater injection data did not reveal the anticipated "seasonal" cycle in injection rate that we thought would result from changes in the number of people in the Keys between summer and winter. Thus, we did not pursue time-dependent tools (animations). At the end of this report we also include a correspondence from Gus Rios, FDEP, regarding modifications to the initial software tool submitted, and include detailed responses to his queries.

## METHODS

### Groundwater Modeling

Numerical modeling of subsurface wastewater plumes was completed for all 254 injection wells permitted by the Florida Department of Environmental Protection using a commercially available 3-dimensional finite element modeling software package called FEFLOW. Model domains were taken from a shoreline GIS layer acquired from the Monroe County, FL GIS department.

Island boundaries were treated as open flow boundaries with specified tidal fluctuations driving exchange with normal salinity (36,000 mg/L) groundwaters outside the model domain. Florida Bay tides were specified as having a 0.1 m amplitude, while Atlantic Ocean tides were specified as having 0.5 m amplitude with a -0.1 m mean displacement, reflective of previously recorded values for Key Largo (Reich et al., 2002) but certainly not an accurate representation of tidal fluctuations in the Florida Keys for specific sites. Transitional zones and inland waterways were given an intermediate tidal cycle of 0.3 m amplitude with a -0.05 m mean displacement. All tidal signals reflected an idealized semidiurnal cycle with a 12 hour period.

Subsurface flow reflected both the head driven flow resulting from rapidly changing differential tidal boundary conditions and density driven flow resulting from low salinity wastewater mixing with the saltwater aquifer. The unstable nature of such advection-dominated models under rapidly changing boundary conditions required the application of a full-upwind differencing numerical scheme, which may introduce extra numerical dispersion. Some models show the anticipated "wakes" of positive salinity fluctuations behind rapid flows of low-salinity wastewater. All models were run for one full year.

In cases where small adjacent keys are separated by shallow bodies of water, such keys were grouped together as one hydraulic unit for the purpose of modeling. Canals were included in models where they were expected to have a significant effect on flow regimes and could be simulated with reasonable accuracy. Injection wells were modeled at 18 m (60 ft), and model domains extended down to a stratigraphically defined no-flow boundary at 36 meters (120 feet; Enos and Perkins, 1977).

## Estimation of Nutrient Loading

The delivery rate of wastewater nutrients to surface waters (coastal waters or canals) is dependent upon a variety of factors, including the wastewater injection rate, the nutrient concentration of the wastewater, the pathlength and time spent in the subsurface, and the reactivity of the material in the groundwater environment. Previous studies by the Florida State and Penn State groups have documented significant removal of phosphate from wastewater plumes through interaction with the limestone substrate, a process that seems to be best related to the distance traveled before discharge to surface waters. In contrast, nitrate (the dominant form of nitrogen in injected wastewater in the Keys) removal is best related to the time spent in the subsurface.

The modeling we have done has taken these factors into consideration in the estimation of nitrogen and phosphorus loading on surface waters. The necessary variables were estimated as follows:

1) **Pathlength**: The 3-dimensional groundwater model results were used as visual guides to establish flow directions and the nearest point of intersection between wastewater plumes and coastal waters (including canals). This less-than-optimal approach was necessitated by the amount of time available for the modeling; none of the models were run sufficiently long to establish a steady-state plume.
2) **Travel time**: Once pathlengths were established, travel times were determined

based on the quotient of the pathlength and the estimated groundwater velocity. Average groundwater velocities were taken from previous field tracer studies conducted at the Keys Marine Laboratory on Long Key (Kump, unpublished data), Key Largo (Reich et al., 2002), and Key Colony Beach (see FSU report).

3) **Reactivity**: The FSU report details the analysis of the reactivity of phosphate and nitrate in the subsurface. The only modification was to the phosphate-distance relationship. Instead of a simple linear relationship, we felt that the observations better support an exponential relationship, where phosphate concentrations decrease exponentially with distance, achieving a minimum value of 0.2 ppm in a steady-state wastewater plume. The equations used were:

   P(out, mg/L) = P(in, mg/L) exp (-0.042*distance(m)) or 0.2 ppm, whichever is larger;

   N(out, mg/L) = N(in, mg/L)-0.042*travel time (days)

   (note that it is coincidental that the two parameters in the two equations are identical)

   where the concentrations labeled "out" are the concentrations at the point of surface-water discharge and those labeled "in" are the average wastewater concentrations for the period of observation (2001-2002).

Loadings were then calculated from the product of these concentrations and the volumetric wastewater injection rate. This calculation involves the simplifying assumption that the wastewater injected ultimately is discharged to surface waters. Our numerical modeling indicates that wastewater rises to the surface and moves toward points of discharge. The largest treatment plants generate large, low salinity plumes for which this approximation is appropriate. Wastewater from the smaller facilities mixes with saline groundwater, and may not rise buoyantly to the surface as quickly. In such cases, the loading estimates are upper limits.

## GIS Data

Locations and associated wastewater characterization data for permitted wastewater injection facilities were acquired from the Florida Department of Environmental Protection. The Monroe County GIS staff provided a shoreline boundary file of the Florida Keys. Two additional datasets, wastewater flow paths and affected shore segments, were created from the hydrologic modeling output.

*Facility locations*

Nine permitted wastewater facility records were dropped from the database because they did not contain complete information. Because the FEFLOW program does not handle wells in close proximity to model boundaries, eleven facility locations within 5 m of the shoreline were moved inland (5-10 m) to enable modeling.

*Shoreline Boundary*

In order to maintain reasonable model dimensions and run times, the shoreline boundary file was generalized to a tolerance of 5 m. Generalization reduces the complexity of lines by removing extraneous vertices within the search tolerance. As a result, a maximum of 5 m of positional error was introduced to the shoreline boundary. The benefits of increased model efficiency greatly outweigh the relatively small cost of the positional error.

*Wastewater Flow Paths*

Wastewater flow paths characterize the primary flow from each injection well to the nearest coastal water body (including canals). The lengths of these paths are the basis of both the pathlength and travel time variables previously mentioned.

*Affected Shore Segments*

The affected shore segments represent the approximate intersections of the wastewater plumes with the shoreline. For each affected shore segment, the nitrate and phosphate surface water loadings of contributing wells (i.e. flow paths intersect segment) were summed. However, the highlighted segments are meant as visual cues only, and the actual length of the segment has no bearing on loading calculations.

*Estimate Of Horizontal Positional Error*

The quantitative positional error of the shoreline boundary data is unknown; however, qualitatively the data overlaid well with other datasets for the area. If we assume that the data were produced to National Map Accuracy Standards from 1:24:000 scale source material, the minimum positional error would be approximately 12 m. However, such error applies only to "well-defined" points such as road intersections, building corners, or property markers. Considering that shorelines are not composed of many "well-defined" points, we expect the positional error to be greater than 12m.

Furthermore, quantitative positional accuracy of the permitted facility locations was not provided with the data. Given that the data were acquired with GPS units according to the FDEP Locational Data Standards, we assume the horizontal positional accuracy to be approximately 2-5 m. It is also important to note that these locations represent a point within the permitted facility and not the positions of constituent injection wells.

When evaluating the lengths of flowpaths or the position of wells relative to the shoreline boundary, consider the cumulative positional error of all data. Given the positional error estimates discussed in the previous paragraphs, the minimum positional error for such a comparison is approximately 30 m.

## LIMITATIONS OF THE METHOD

A number of limitations of the method have been discussed above, including errors inherent in the GIS approach. In addition:

1) The groundwater modeling we performed was inadequate to allow a highly confident determination of travel direction for the wastewater plume, because only in a few cases did we include canals as boundaries to the model domain. The selection of paths was guided by the modeling performed, but several "judgement calls" were made. In most cases, flow was directed to the nearest surface water body (canal, shoreline), except where the modeling clearly indicated flow away from this water body. A much more thorough (and presently quite tedious) modeling study would need to be performed to significantly improve this situation. Such simulations will still be limited by the small amount of information on tidal variations on the Bay, ocean, and channel sides of the Keys and the virtual absence of tidal data for the canals.

2) The reactivity functions used to determine the degree of reduction of phosphorus and nitrogen contents of the wastewater plume were based on field observations from one site only, Key Colony Beach (KCB; research completed previously with support from the EPA). Questions arise as to the appropriateness of extrapolating results from this site to the Keys in general, in particular because the limestone bedrock (the Key Largo Limestone) is capped by ~6m of unconsolidated mud, an atypical situation in the Keys. Our monitoring of KCB groundwater chemistry was restricted to wells installed in the Key Largo Limestone, though, so we suspect that the general relationships we determined at KCB should apply to sites throughout the Keys. The overlying mud may be promoting some additional denitrification, however; diffusion of electron donors (dissolved organic matter or hydrogen sulfide) from the overlying mud to the bedrock layer could be occurring.

3) **Because of these limitations, our product should not be considered a site-specific tool. Rather it should be used for regional planning purposes only.**

## MODIFICATIONS AFTER SUBMISSION OF SOFTWARE

Beginning on the next page we include a memo sent to Penn State investigators by Gus Rios, FDEP, with questions and requests for modifications to the software submitted on June 10, 2003, along with our responses to those requests marked in italics:

FLORIDA DEPARTMENT OF ENVIRONMENTAL PROTECTION

# INTEROFFICE MEMORANDUM South District

To: Dr. Lee Kump, Pennsylvania State U.

From: Gus Rios, FDEP Marathon

Date: June 18, 2003

Subject: Injection Well Loading Model - June 11, 2003 Draft.

During our June 13, 2003, teleconference Nancy Brooking and I had the opportunity to discuss the draft model with you and other members of your team. We had a very productive discussion and we identified some areas that need further attention.

1. On the "Start Tool" screen, please change the first sentence: **"over 250 permitted injection wells..."** to **"over 250 FDEP-permitted wastewater treatment plants, with injection well systems, discharge..."**

   *Done.*

2. The on-line tool you sent with your June 10 electronic mail includes a function that allows you to view a list of the facilities (wells) that contribute loading to a coastal segment when you click on the highlighted segment. This is a very useful function because it allows you to view and print a list of facilities that contribute to the loading in that particular segment. However, the final product provided in the CD (dated June 11, 2003) does not include this function. This function should be included in the final product. Also, in the June 10 on-line tool, when you click the coastal segment on the western end of Marathon the model shows loading contributions from two Key Largo facilities: Cross Key and Manatee Bay Club. The only facility that belongs in the westernmost coastal segment of Marathon is Hawk's Nest Condo. Please check and correct these discrepancies.

*Done. We are including a new CD with this mailing.*

3. Nancy pointed out that labeling the coastal segments and providing a reference table, listing the coastal segments and the contributing wells, would improve the model by making it user-friendlier.

*We have no way of logically labeling coastal segments. In reference to navigating to facilities by means of a reference table, this does not fall under the scope of the present project. The tool was designed to be navigated geographically rather than by facility. We could add a "find by" (ID, name, etc.) tool, but this would require additional development work.*

4. Nancy identified several facilities (see attached spreadsheet) where the distances from the injection wells to surface waters need to be checked for accuracy. For instance, the Turek Building facility, in Tavernier, is adjacent to a canal but the model shows a distance to SW of 144.6 m. Please check the attached list as discussed and make any necessary corrections. As you indicated during our teleconference, it may be that the GIS database used does not include some smaller canals and basins.

*We have reviewed the routing decisions and have re-routed 6 segments that logically discharge to nearby canals, including the Tudek building.*

5. Some of the terms used in the data tables may need clarification. For example, "flow-averaged wastewater concentration". Are these the (TN and TP) average values reported for the period comprising January 2001 and December 2002? Also, I am not clear on the meaning of the term: "Average concentration at surface water discharge site". Does this represent the actual concentration of TN or TP expected in the wastewater plume as it reaches surface waters? If this is the case, I am concerned that some of these concentrations may be overestimated for wastewater discharges with low flows (smaller package plants) since you would expect greater groundwater dilution in some of these cases. We may need to reconsider using these concentrations, unless you feel the model will be able to predict these concentrations at the surface water discharge point with a reasonable level of confidence. I feel more comfortable with the loading values in terms of lb/day. Please provide some comments to address these issues.

*Done.*

6. We would like to see a final report provided as part of the final product. A final report is one of the deliverables included in the November 11, 2002 Scope of Work. The report should include the "Methods" already provided with the CD as well as additional information addressing the assumptions made during development of the model and its limitations (including any GIS limitations that may affect the estimation of flow paths and the length of these paths to surface

waters). Since a lot of the data used to determine plume travel times was generated at the Key Colony Beach site, it would be useful to include a section addressing any differences in the KCB fill substrate and whether the KCB data can be successfully extrapolated to other areas of the Keys.

*These concerns are addressed in the present document.*

7. I am excited about the possible applications of this model in predicting loading from injection wells to surface waters. An obvious next step would be to use this type model to complement, and even fine tune, the loading analyses that will be performed with the Florida Keys Carrying Capacity Study. How difficult would it be to change or update the effluent concentrations values, or add new injection well sites, in order to use our model to predict loading conditions that may exist in the future? This may include predicting any loading reductions resulting from future treatment upgrades or additional loading from new development. And, assuming that this model can be used to run different loading scenarios, does the CD (final product) provide the tools and information that FDEP will need to accomplish this task (assuming our GIS folks will be available to work on this)?

*The current tool requires a significant amount of manual data entry and processing. We are including the Excel spreadsheet that allows anyone to enter new wastewater input parameters and calculate the surface water loads for existing flowpaths. However, transferring this updated information into the graphical tool requires knowledge of Flash application programming. Automating maintenance and update would require additional funding.*

8. The scope of work mentions that the web browser will be "effective for visualizing the impacts of time-dependent (e.g. seasonal) loading patterns". Please explain how this model could be used to address seasonal loading patterns.

*We were surprised to find that there was no discernible temporal (seasonal) pattern in the wastewater injection volumes or nutrient loadings for the facilities. Thus, we abandoned this aspect of the work in favor of attributes of the visualization tool that weren't part of the original scope of work..*

Finally I would like to commend you and your colleagues at PSU and FSU for taking over this project and accomplishing so much in such a short period of time. I also appreciate your willingness to work with us to make sure that the final product will be a useful tool that could be used to address important water quality issues in the Keys. Please do not hesitate to contact Nancy Brooking, or me at (305) 289-2310, if there are any questions.

CC: Gordon Romeis, FDEP Fort Myers

Vacher, H. L., Wightman, M. J., and Stewart, M. T., 1992. Hydrology of Meteoric Diagenesis: Effect of Pleistocene Stratigraphy on Freshwater Lenses of Big Pine Key, Florida. Quaternary Coasts of the United States: Marine and Lacustrine Systems, SEPM Special Publication No. 46. pp. 213-219. (Reference 3, Table 1)