Groundwater is a vital natural resource, and its discharge provides a significant amount of both water and nutrients to lakes, rivers, and coastal areas. Many different methods, ranging from chemical tracers to physical methods and hydrological models, have been used to study this parameter. Quantifying discharge using many of these techniques can be difficult, however, as this flux is heterogeneous and diffuse. GIS (Geographic Information Systems) can be used both independently of and concurrently with each of these techniques, and the system is greatly useful in the examination of groundwater discharge. Its incorporation along with physical methods greatly improves the accuracy of these surveys. GIS groundwater applications cover a wide range of uses, and can be as simple as providing locations and maps of groundwater reservoirs and recharge areas. Conversely, GIS can be integrated into complex models used to evaluate and quantify groundwater flow to coastal regions, lakes, and rivers. By providing the tools to help evaluate and analyze groundwater flow and recharge, GIS significantly aids in the study and management of groundwater resources.

Kolm (1996) provides a standard procedure for using GIS to study groundwater systems, and this method can be incorporated to various degrees in many types of groundwater discharge studies. Kolm’s procedure can be broken down into four basic steps: data capture, data editing and preprocessing, numerical modeling, and spatial structuring and visualization. In general, data regarding surface, subsurface geology, and hydrogeologic characteristics can be collected in the field or obtained from existing GIS datasets. This data can then be incorporated into the study’s primary database and can be used to create a series of increasingly complex models simulating the study area’s hydrologic system. Throughout the entire research process, GIS can be used in many ways, including for data management, integration, analysis, and display. Beyond this, GIS may be used in model design and operation, as well as for the visualization of results (Kolm, 1996). This basic procedure has been employed in studies over many areas, ranging from and analysis of the Death Valley Basin in California (Turner & Kolm, 1992) to a small case study near Cheyenne, Wyoming (Talbot & Kolm, 1993).

In addition to this standard procedure, there are many examples of GIS use in the creation and use of groundwater discharge models. These models can operate over multiple dimensions and vary greatly in complexity. GIS can be useful here by providing spatial data for multiple parameters over large areas.
Such large-scale data was necessary for a study conducted by Arnold, et al (2000), who modeled recharge and discharge in the Upper Mississippi River basin, an area covering 491,700 km². In order to properly model groundwater flow here, detailed data regarding watersheds, soil, land use, and geology was needed for this large basin. GIS provided this information, through datasets such as STATSGO and 8-digit HUCs. Similar models are also created and employed for much smaller areas, such as southern Rhode Island’s coastal ponds (Masterson, et al, 2007) and deep lakes in western Greece (Zacharias, et al, 2003). Although the scope of these models may be different than that of Arnold et al’s study, similar datasets are necessary. GIS provides high quality local data for these small-scale models much like it does regional data for the larger models. For both large and small regions, GIS-based models are able to evaluate and quantify discharge where physical measurements and chemical methods may be too difficult, expensive, or imprecise.

In qualitative studies, GIS can also be extremely useful. In most regions, groundwater discharge tends to be cooler than a basin’s surrounding water during the summer and warmer than this water in winter months. These temperature anomalies can be measured in many ways, including physical measurements in the field, airborne thermal imaging, and Landsat TM analysis. Data from these surveys can then be displayed using a multitude of GIS software packages and incorporated in various ways. Some studies merely use these maps to illustrate areas where groundwater input is high (Tcherepanov, et al, 2005), while others go one step further and use the data as a marker for locations to conduct physical measurements of groundwater flow (Mulligan & Charette, 2006).

Although GIS is already extensively employed in groundwater studies, this usage could easily be extended. One way GIS could be further integrated into groundwater modeling in the future would be to link groundwater discharge and chemical characteristics to various watershed parameters. By doing this, the study of groundwater flow and discharge could yield practical results for town and coastal planning. Although some groundwater studies integrate both planning and scientific data (Batelaan, et al, 2003), such relations are rare in the literature. The current GIS database contains a wealth of data, notably including land use, vegetation, soils, and geologic layers. Within a watershed, each of these datasets can be matched to trends in groundwater nutrient and pollutant concentrations, as well as various discharge characteristics. For example, attempts could be made to correlate groundwater nutrient discharge with developed land or farmed acreage in a groundwater recharge area. GIS technology, along with traditional physical and chemical groundwater studies, could help identify critical areas affecting groundwater and guide policy to protect this resource.

The future of GIS in groundwater studies is bright. As new, more detailed GIS datasets are created, and processor speed increases, groundwater models based on GIS data can become increasingly more complex and accurate. In addition, GIS is already employed in many intercomparison-style studies, where modeled discharge can be compared to that measured physically or through
chemical tracers (Mulligan, et al, 2006). As GIS becomes progressively more pervasive, future studies will likely add to this trend, and further comparative exercises will improve upon the accuracy of groundwater discharge estimates. Because of its great utility, GIS should be linked with groundwater studies well into the future.

**Annotated Bibliography**


Here, two separate models were used to estimate groundwater recharge and discharge in the upper Mississippi River basin, an area draining 491,700 km². The first of these models, designated “SWAT”, operates using a GIS-based interface. To improve the quality and speed of this model, the large region analyzed in this study was broken down using 8-digit HUC data provided by the USGS. Furthermore, GIS-based soil (STATSGO) and land use data was utilized to derive individual hydrologic response units (HRUs), which are areas of roughly homogeneous hydrologic parameters (in terms of drainage, etc.). Discharge calculated using this method correlated fairly well with measured data over a twenty-year span. A weakness to this model is that it is quite complex and requires a myriad of parameters to accurately estimate groundwater flow; subsequent models developed within the last seven years may have become more simple and easy to use. Although it is largely well written, large parts of the paper are filled with methodological data and jargon. Unfortunately, much of this may be entirely necessary due to the size and complexity of the SWAT model used here.


In this study, the authors develop a methodology to evaluate the importance and sensitivity of and various groundwater recharge and discharge areas in the Grote-Nete Basin, Belgium. Moreover, impacts from future development in the basin are simulated. In order to develop this model, hydrologic, vegetation, and land-use data were integrated in a GIS environment, allowing for areas critical to groundwater recharge and discharge to be delineated. This paper is quite thorough, as the authors rigorously discuss the many parameters necessary to successfully operate the model. Notably, and importantly, the authors highlight the practical importance of their work, as the model results can be applied to future land-use planning.

In this paper, the author provides a multi-step approach for using GIS to illustrate and characterize groundwater systems. The procedures for both data collection in the field and analysis in the laboratory are thoroughly explained, and the utility of GIS in studying groundwater is highlighted. The author does an excellent job of specifically explaining an effective procedure for GIS based groundwater study. However, the author does not describe a real-world example of this process, although some such studies are listed. Such an in-depth case study would radically improve the paper and demonstrate the efficacy of the method.


In this study, the authors created and utilized a groundwater flow model to calculate the groundwater input to and accurately delineate the watersheds of Southern Rhode Island’s coastal ponds. The authors provide a rigorous description of the area’s geology and hydrology, as these factors are key components of the physical model used in the study. RIGIS and USGS data was employed extensively in this study, and the model was rasterized and discretized based on USGS 1:24,000 base map data for the area. The study’s model was based on the USGS MODFLOW program. Notably, this study also employed geochemical tracers to study groundwater flow to these ponds, allowing for a comparison between these two (physical and chemical) methods. Overall, this paper is well presented, but at some points is overly weighed down with technical data. Moreover, although the authors discuss the importance of groundwater in delivering nutrients and pollutants to these coastal ponds, nutrient (i.e. nitrate and phosphate) fluxes are never calculated. Future studies could conduct this calculation to improve upon the existing data. Moreover, GIS could be used in such a study to link land use data to these nutrient fluxes.


Here, the authors use multiple physical and chemical techniques to quantify groundwater discharge into Waquoit Bay, Cape Cod, Massachusetts. In one of these techniques, GIS was utilized along with airborne thermal imaging to indicate the locations and magnitude of this discharge. GIS data was also used to help determine and illustrate the area’s water table conditions. The results from this analysis provided locations for physical measurements of groundwater discharge; normally this flux is heterogeneous and diffuse, and therefore is
difficult to accurately measure using physical methods. A large positive of this study was the use and comparison of multiple techniques in groundwater discharge investigation. These complimenting methods allow for greater accuracy and simplicity of this parameter.


In this study, the authors use a combination of remote sensing, physical measurements, and GIS technology to analyze groundwater discharge in multiple lakes in the Nebraska Sand Hills. Summer cold temperature anomalies, measured in the field, were inferred to be groundwater discharge zones. These measurements were correlated with seasonal Landsat TM data, which revealed warm anomalies in similar locations during the winter. The data was integrated using ERDAS and other GIS-based models. Although this study revealed the locations of groundwater discharge in these ponds, it failed to quantify this parameter. A large improvement to the study could involve using physical methods at the identified discharge zones to measure the discharge into these lakes.


Here, the authors use multiple techniques and measurements to calculate the groundwater discharge into Lake Trichonis, located in Western Greece. In particular, a digital terrain model was combined with GIS technology and physical measurements to yield the lake’s water storage. This storage was combined with estimated rainfall, runoff, and outflow data to determine the groundwater discharge. For deep lakes, where physical measurements of groundwater discharge are exceedingly difficult and costly, studies such as this are vital, and are some of the only ways to measure discharge. The water budgets incorporated into the model used here are rigorous, which indicates the final result should have a high degree of accuracy.

Additional References
