USE OF INDICES IN EVALUATING FLORIDA'S GROUND-WATER QUALITY

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Abstract

In the late 1990s, Florida redesigned its statewide surface- and ground-water quality monitoring networks, based on random sampling. There was a desire to develop water quality indices for each water resource that state, in defendable but simplistic terms, the overall quality of water in an individual sample and an entire basin. Currently, indices have only been developed for ground water. The Ground-Water Quality Criteria Index is based on whether one or more sampled analytes exceeds a Florida Guidance Concentration Level (GCL) in a sample. Each GCL is based on known or suspected human health hazards. The logic is that if *only one* such chemical exceeds its GCL, then the water cannot fully support its designated use. For ground water the use is drinking water. The Basin Resource Index is based on the proportion of ground-water samples from an area that have at least one analyte to exceed a GCL. The redesigned network commenced operations in 2000 and sampled approximately 25% of the state. It was found that 89% (± 5%) of the wells in the sampled portion of Florida meet standards. For the first time Florida has a key indicator that can be used to estimate the overall quality of its ground water with known confidence intervals.

Introduction

In the mid 1990s, the Florida Department of Environmental Protection (FDEP) decided to modify and integrate statewide ground-water and surface-water quality monitoring networks. The primary impetus of this change in monitoring design was to assist in reporting the status of the quality of the waters to FDEP management, the U.S. Environmental Protection Agency (EPA), state and local governmental agencies, the legislature, and private citizens. The design of the integrated network (Status Network) enhances FDEP's ability to rigorously assess the overall quality of Florida's water resources.

There is also a need to be able to answer broad, non-specific questions, such as "how good is the water quality" or "has water quality changed", without bias. Furthermore, there is a need for water-resource managers to be able to broadly communicate the status of ground-water quality, such as by stating that "95% of the ground water is unimpaired" or that "there has been a statistically significant overall improvement in water quality since the management program was begun". The ground-water quality indices addressed in this paper were developed to assist in meeting these needs.

Ground-water indices were developed specifically to assist in interpreting ground-water data generated by the Status Network. Surface-water indices are currently being developed. The integrated network monitors two sampling strata for ground-water quality: (1) confined aquifers, and (2) unconfined aquifers and springs. These two sampling strata were selected on the basis of apparent aquifer vulnerability.

This paper discusses indicators that FDEP has developed and is using to report the conditions of Florida's ground-water quality. The two indicators address the overall ground-water quality from an individual well basis (Ground Water Quality Criteria Index) and the overall ground-water quality of a region or basin (Basin Resource Index). It is envisioned that the indices, or modifications of them, can be used in other monitoring programs as well as for ground water.

The Status Network

In order to understand the operation and design of the Status Network, it is important to describe the relationship among Florida's five water management districts (WMDs) and FDEP. FDEP is responsible for the quality of Florida's water resources, while Florida's five WMDs are responsible for managing its quantity. FDEP and the WMDs work together cooperatively.

FDEP functions as the administrator of the Status Network, determines the network's goals and strategies, and sets program priorities. Whenever possible the WMDs assist the department in operating and maintaining the network. They collect the water samples for the network, using FDEP sampling protocols. Other , local governmental agencies also cooperate with both FDEP and the WMDs in the operation and maintenance of the network. Because of shared interests in water quality and maintaining the resource, the state, regional, and local agencies have pooled human resources and enabled a large monitoring program to exist that far exceeds the resources of any one agency. As a result, it is possible to collect statistically significant numbers of samples and develop regional assessments of ground-water quality.

The Status Network (Summers et al., 1998) relies heavily on the design of the EPA's Environmental Mapping and Assessment Program (EMAP; Messer et al., 1991 and Whittier and Paulsen, 1992). Both EMAP and Florida's Status Network are heavily influenced by the

principles of sampling theory (Scheaffer et al., 1996), particularly the use of random sampling designs. The Status Network answers broad-based assessment questions from a basin-wide to statewide scale. Other FDEP networks and programs address site-specific water-quality issues. The overall purpose of the Status Network is to evaluate the regional status of ground-water quality. The Network commenced operations in 2000.

In order to limit the sizes of target populations, Florida was subdivided into 20 separate "Reporting Units" (RUs) ranging in approximate size from 3800 to 19700 km^2 (1470 to 7600 mi^2). The boundaries of each RU coincide with one or more US Geological Survey-defined surface-water drainage basins. Even though the RUs are based on surface-water drainage, their boundaries were selected in order to coincide with unconfined, ground-water basins whenever possible.

Each of the five WMDs is divided into four RUs (Figure 1). Each year, one RU within each WMD is sampled, providing a comprehensive, statewide assessment over a four-year period. Not including quality assurance samples, approximately thirty randomly selected wells are sampled in each RU for each of the two ground-water resources. Thus, for any given year, about 300 ground-water samples are collected (150 from confined aquifers and 150 from unconfined aquifers and springs).

Seasonal variability is minimized by sampling at specific times of the year (index periods) that were chosen to coincide with periods when the sampled analytes typically have the highest concentrations (i.e., when ground-water levels are typically the lowest). In order to address seasonal variability issues, FDEP also maintains a separate, temporal variability, ground-water-quality monitoring network.

The parent population of the sample set is water from wells and springs that tap the potable ground waters of the state. The list frame (list of wells from which sample sites are randomly selected) is made up of different types of wells (e.g. public supply, domestic supply, monitor, irrigation, and industrial supply). Every effort was made to include as many wells as possible in the frame and to make sure the frame is partitioned proportionally by well type. In order to avoid over populating the list frame with monitoring well data from permitted facilities that may have localized water-quality issues, only background wells at these facilities are included in the list frame.

Therefore, a regional water-quality problem that derives from overlapping plumes in heavily industrialized sites will be detected, but individual contamination sites whose waste plumes are limited to their permitted zone of compliance are not likely to be included in the sample. This strategy increases the ability of obtaining access to monitored facilities and prevents overpopulation with compliance monitoring wells.

Ground Water Quality Criteria Indices

There are two Ground Water Quality Criteria Indices (GWQCIs): one for health and one for aesthetics. They provide a rigorous method for evaluating water samples taken from individual wells. In Florida, ground-water-quality standards protect the designated use of aquifers (Rule 62-520, Florida Administrative Code, 1996), and they are used as the basis for the GWQCIs. Because most of Florida's drinking water is taken from aquifers, Florida applies drinking water standards to all aquifer systems. Primary numeric standards have been established for selected analytes in order to protect public health, natural systems, and the designated uses of the ground water. These standards include drinking water Maximum Contaminant Levels

(MCLs), which closely parallel Federal Primary Water Quality Standards, and Guidance Concentration Levels (GCLs; Baker, 1994), which are based on health criteria adopted by the state. The GCLs are used as screening tools for interpreting the narrative minimum criteria in Florida statutes. Secondary numeric standards are established to protect the aesthetic nature of ground water (e.g. color, taste, and odor considerations). These also closely parallel Federal Secondary Water-Quality Standards.

While Florida's ground water is categorized into several designated use classes, the overwhelming majority of ground water used in Florida is designated for potable use. Thus, the index is only applied to aquifers with a potable use designation, and the GWQCI is a measure of water quality for an individual ground water sample drawn from an individual well or spring.

Florida has over 80 water-quality analytes with primary or secondary MCLs or GCLs. Because of a lack of sufficient funding, only a fraction are included on the Status Network analyte list. Thus, analytes with MCLs were included on the list (Table 1) only after consideration of their historic regional prevalence in ground water in Florida and the cost of analysis. Available resources limit the number of analytes, so only analytes known to be of regional concern in Florida are included. The GWQCIs can be modified to include other analytes as resources or needs change, however.

If one or more analytes in an individual ground-water sample is found to exceed a primary MCL or health-based GCL, the sample is considered to represent water that has an unacceptable risk for use as drinking water, and action is recommended. Analytes with primary MCLs that are currently being monitored include sodium (Na), fluoride (F), nitrate plus nitrite as nitrogen (nitrate). Total coliform bacteria are also monitored through use of fecal coliform bacteria (FeCol) as a surrogate. The primary MCL is for total coliform bacteria, and the threshold is four colonies per 100 ml. However, if the concentration of FeCol exceeds four colonies/100 ml, then the total coliform bacteria must also exceed four. Thus, fecal, rather than total, coliform bacteria is on the list because its source can be more readily identified (warm-blooded animals; American Public Health Association, 1992).

If one or more analytes in an individual ground water sample is found to exceed a secondary MCL or aesthetic based GCL, the sample is considered to represent a concern for drinking-water quality. For the Status Network, chloride (Cl), sulfate ($S0_4$), total dissolved solids (TDS), and F are on the analyte list and have secondary MCLs. The secondary MCL for fluoride is a lower concentration than its primary standard.

Table 2 displays the indices, their bases, and the resulting outcome categories. For the GWQCI(health) index the *Action* (A) outcome includes several possibilities. If the sample is from a public supply well, FDEP contacts the facility owner and corrective action is taken. If the sample is from a domestic supply well, the Florida Department of Health (FDOH) is notified. FDOH re-samples the well. If the problem is verified by re-sampling, the owner is supplied information with possible options to rectify the problem. If the well is not a public or domestic supply well (e.g. a monitoring well or irrigation well), a letter explaining the situation is mailed to the owner of the well. Included in the letter is a contact so that the well owner can obtain additional information, if desired.

For the GWQCI(aesthetics) index, no direct action is taken if a well is categorized as having water quality of *Concern* (C). However, a letter is mailed to each well owner explaining the situation, including a contact name. The well owner can contact FDEP if further information is desired.

The N label for either index (Table 2) represents that there is no basis for action or concern based with respect to the analyte suite. Since a limited number of possible analytes is measured from a given sample, an N label means simply that there is not enough evidence to warrant concern. Note that assigning an index score of N to a water sample does not preclude the possibility of contamination by other chemicals.

Comparative analysis of well samples on the basis of their GWQCI results should only be attempted when GWQCIs are based on a standard analyte list. Additionally, analytical methods should be standardized, since different methods can limit direct comparison of results.

Finally, it should be noted that FDEP does not change either an A or a C classification until the well or spring has been re-sampled. This policy assists FDEP in conducting necessary follow-up actions and setting priorities for sampling.

Basin Resource Indices

Basin Resource Indices (BRIs) summarize overall ground-water quality on a basin-wide or regional scale. It is FDEP's intent to utilize the BRI to summarize the results of testing at RU, WMD, and statewide scales. Each BRI is determined by the percentage of random samples categorized as being either N (No Basis for Action or Concern), or that received an A or C GWQCI score.

As with the GWQCIs, there are two BRIs: one for human health and one for aesthetics. If greater than 10% of the random ground-water samples from a region are classified according to the GWQCI as either A or C**,** then ground water from the target aquifer in the entire region is categorized for Action or Concern, as demonstrated in Table 3.

An index must be able to discriminate on the basis of the intended criteria. If the threshold (i.e., 10%) is either too small or too large, an overwhelming percentage of sampled wells will be classified into one of the two categories and the usefulness of the index is minimized. In order to address this issue, FDEP evaluated historical ground-water quality data collected from a statewide ground-water monitoring network that was in use from 1986-1999 (Background Network; Maddox et al., 1992). With the exception of FeCol, the analyte list of the Background Network included those analytes necessary to determine both the GWQCIs and BRIs. Since FeCol data were lacking, data from the Background Network were used to generate "quasi" BRIs that include all analytes other than FeCol (Table 1).

The historical data revealed that the percentage of wells categorized as N for the quasi-BRIs ranged from 65 to 100 percent per RU. In other words, the percentage of wells classified as being either A or C ranged from zero to 35 percent. For more than three-fourths of the RUs of the state, the percentage of wells classified as N ranged between 80 and 100 percent. Based on these data, FDEP decided to adopt a threshold of 10 percent. This means that for 30 samples, three or less must not be "impaired" in order for the RU to receive a BRI of N.

Recall that each GWQCI has two categories (A or N for health; C or N for aesthetics) and that the samples are collected randomly. If it is assumed that (1) the result of each outcome (A or N; C or N) is independent of the other samples, (2) the actual proportion of A or C wells throughout the entire basin remains constant during a sample collection index period, and (3) the number of samples collected in the basin is predetermined, then the resulting distribution of the GWQCIs is binomial (Triola, 1998). Assumption (1) may not hold if the samples are located a short distance from each other. However, during the first year of sampling no two wells (out of

281 sampled) were closer than three kilometers (~ two miles) from each other. Because the sampling index period is only three months in duration, and since the number of samples to collect (30) was determined during the design phase of the network, it is believed that the binomial theory is valid for BRI applications.

Since the distribution is binomial, the error of the estimate of the proportions (uncertainty) of a category (Triola, 1998) is

$$E = Z_{a/2} \sqrt{(\hat{p}\hat{q})/n} \quad (1)$$

where,

$Z_{a/2}$ = two-tailed Z-score from a normal probability distribution table,
$\hat{p}$ = estimated proportion of wells in the sample set that are not impaired (number of samples with a score of N),
$\hat{q}$ = 1- p (proportion of samples that received a score of A or C, depending on the GWQCI),
E = error of the estimate of the proportion ($\hat{p}$),
n = number of samples, and
a = significance level.

The equation can be rearranged to:

$$n = [(Z_{a/2})^2)(\hat{p}\hat{q})]/E^2. \quad (2)$$

The number of samples required to achieve a given error rate can be calculated from equation (2). For example, let a = 0.05 (confidence level = 0.95). If 10 percent of the GWQCI(health) samples in a basin are categorized as A and 40 random samples are collected, then the resulting uncertainty is ± 9% (equation 1). If the sample size is decreased to 20, the uncertainty increases to ±13%, and if the sample size is decreased to 10, the uncertainty increases to ±19%. The FDEP decided that the uncertainty is too large if the sample size is less than 20. Therefore, the FDEP does not calculate BRIs in RUs with less than 20 samples.

The thresholds between the BRI categories and the boundaries of the study areas must remain constant when comparing basins or monitoring basin resource quality through time. Changing thresholds and boundaries will potentially result in confusing interpretative results over time.

Not all analytes are suitable for GWQCI or BRI use. Both color and pH are included in the Status Network analyte list. However, neither analyte is used to calculate aesthetic GWQCIs and BRIs because they result in poor discrimination power. During the evaluation of historical data, it was discovered that use of color, which has a secondary MCL of 15 Pt-Co units, in the GWQCI(aesthetic) results in BRI(aesthetic) indices being classified as C for unconfined ground water for all 20 RUs and C for confined ground water for 17 of the 20 RUs. The analyte pH has upper and lower secondary MCLs of 8.5 and 6.5 pH units, respectively. Because of the lower MCL, use of pH in the GWQCI(aesthetic) results in the BRI(aesthetic) indices for all sand aquifers in Florida being classified as C. Because color and pH do not have discriminatory power, they are poor indicators. Therefore, neither analyte is used in development of GWQCI(aesthetic) or BRI(aesthetic) indices. It should be emphasized that, based on secondary

MCLs, both color and pH are of concern in the unconfined sand aquifer throughout Florida. However, these naturally occurring conditions are not manageable and, therefore, they are not reported.

Use of Indices in Evaluating Florida's Ground-Water Quality

During the year 2000 and 2001, 10 of the 20 RUs (two within each WMD), or about 50% of the state were sampled. The 10 RUs are illustrated in Figure 1. The sampled RUs were: Northwest Florida WMD RU A and B (NWA and NWB), Suwannee River WMD RU A and B (SRA and SRB), St. Johns River WMD RU D and A, (SJD and SJA), Southwest Florida WMD RU B and C (SWB and SWC), and South Florida WMD RU A and D (SFA and SFD).

GWQCIs

GWQCI summary statistics for the sampled wells are displayed in Table 4. A total of 273 confined wells were sampled. For the GWQCI(Health), the number of Primary MCL violations is 32 in 31 different wells in the sampled RUs. The best estimate of all confined aquifer wells that contain impaired water in the 10 sampled RUs is 11%. Using equation (1) and a 95% confidence interval (CI), the uncertainty with this estimate is ± 4%. Thus, the estimate of impacted confined aquifer wells in the 10 RUs is between 7 and 15%.

For the GWQCI(Aesthetics), the number of Secondary MCL violations is 111 in 53 different wells. Thus from the 273 sampled wells, it is estimated that 19% of all confined aquifer wells within the sampled RUs are impacted. The uncertainty associated with this estimate is 5% (14 to 24%).

A total of 300 unconfined wells and springs were sampled in 2000 and 2001. With respect to the GWQCI(Health), 37 Primary MCL violations were observed in 37 different wells. The estimated proportion of impaired wells is, therefore, 12% ± 4% (8 to 16%). With respect to the GWQCI(Aesthetics), there were 45 Secondary violations in 29 wells. The estimated proportion of impacted wells is 10% with an uncertainty of ± 4% (6 to 14%).

The GWQCI can be an extremely useful tool for the FDEP in estimating the overall "health" of the ground-water in wells. The estimates of the proportions of impacted in 10 of the 20 Florida RUs range between 10 and 19%, while uncertainty of the estimates vary between three and five percent. This represents the first time in the existence of FDEP that such a statement can be made.

BRIs

Figure 2 presents an example of the results of the BRI(health) determinations for the 10 RUs sampled in 2000 and 2001 for unconfined aquifers and springs. Note that instead of discussing the percentage of wells that have one or more MCL violation, the BRIs emphasize the proportion of wells that are not impaired for each RU. Analogous BRI maps were also generated for unconfined aquifers and springs for aesthetics and for confined aquifers for both health and aesthetics. However, because of space limitations, they were not included in this paper. The maps are available from the authors.

Figure 2 displays the name of the sampled RU, the percentage of sampled wells within each RU labeled as N, and, for the RUs labeled as A, the analytes of concern. Note that the percentage of wells labeled N represent the projected proportion of non-impacted wells within the

RU. Of the 10 sampled RUs, SRB, SWB, SWC, and SFA are labeled A. The major analyte of concern for SRB is FeCol. For SWB the analytes of concern are FeCol and Na. For SWC the analyte of concern is Na, while in SFA, the analytes of concern are NO_3 and Na.

The source of sodium (Na) (Maddox et al., 1992,) is from saline water located in a transition zone of along Florida's coasts (SWB and SWC) and at depth (SFA). Heavy pumping can exacerbate the problem.

The major sources of nitrate (NO_3) are believed to be from animal wastes and from inorganic fertilizers (Maddox et al., 1992). A major portion of Florida's citrus agriculture is located in SFA.

The ultimate source of fecal coliform bacteria (FeCol) is from warm blooded animals (American Public Health Association, 1992). However, their fate and transport in ground water is not totally understood at this time. The two most probable pathways to the sampled wells are from septic tanks located near the wells and from bacteria that find their way into wells for land surface via the annular space between the well casings and the aquifer material. Because of the lack of detailed understanding of the FECol problem, FDEP is initiating follow-up studies to determine: (1) the severity of the problem within the SRB and SWB and (2) the fate FECol in Florida's ground water.

The BRIs are extremely useful to FDEP. For example, the BRI allows Department officials to ascertain the status of the regional ground-water "health" of a RU from a quick inspection of Figure 2. Also, both the proportion of wells with impaired water and BRIs can be tracked over time. Tracking the GWQCI and BRI scores over time results in an ability to answer a number of important management outcome questions, such as (1) have the proportions of non-impaired wells in a RU changed significantly since the last time it was sampled and (2) has the BRI of the RU changed significantly since the last time it was sampled? One and two-sided tests of significance for are available to answer questions such as these for binomial distributions (Triola, 1998). Contingency tables and chi-square tests can be also be used to track the changes in proportions over time (Mendenhall et al, 1981).

Summary and Discussion

Florida recently redesigned and integrated its ground- and surface-water quality monitoring networks to form a new monitoring network known as the Status Network. The driving force for the redesign was to better enable FDEP to assess the overall quality of its water resources. With regard to ground water, the network monitors two resources: (1) confined aquifers and (2) unconfined aquifers and springs. Florida is divided into 20 RUs (four within each WMD; Figure 1). Each RU ranges in size range from 3800 to 19700 km^2 (1470 to 7600 mi^2). Each year, approximately 30 randomly selected ground-water samples are collected from each resource in each RU.

FDEP recently developed two indices to assist in the assessments. The GWQCI indicates the overall ground-water quality of a sample from an individual sample, well, or spring. The BRI indicates the overall ground-water quality of a basin or region.

There are two GWQCIs. One addresses health concerns and the other addresses aesthetic concerns. There are also two BRIs. Again, one addresses health and the other aesthetics.

The Status Network is designed so that the results of the GWQCIs and BRIs each have a binomial distribution. Statistical tools (Triola, 1996) are available that allow FDEP to establish confidence intervals as to the proportions of wells and proportions of basins that are not impaired. For example, during the first two year of operations, FDEP sampled 50% of Florida's RUs. Regarding health criteria, at a 95% confidence level, for unconfined aquifers and springs, it is estimated that 88% of the wells and springs within the 10 RUs are categorized as N (no basis for action or concern), with an uncertainty level equal to ± 4%. For confined aquifers, the estimate is 89% ± 4%. Regarding aesthetic criteria, for unconfined aquifers, the estimate is 81% ± 5%, and for confined aquifers the estimate is 90% ± 4%.

The indices are independent of scale. For this reason, the indices can be used for a variety of sampling projects designed to assess regions of differing sizes.

To date the indices have proven to be useful to FDEP. Use of the indices has improved FDEP's ability to make statements regarding the status of Florida's ground-water quality. In the future, FDEP plans to initiate additional sampling programs and use the indices to assist in interpreting the conditions of Florida's ground-water resource.

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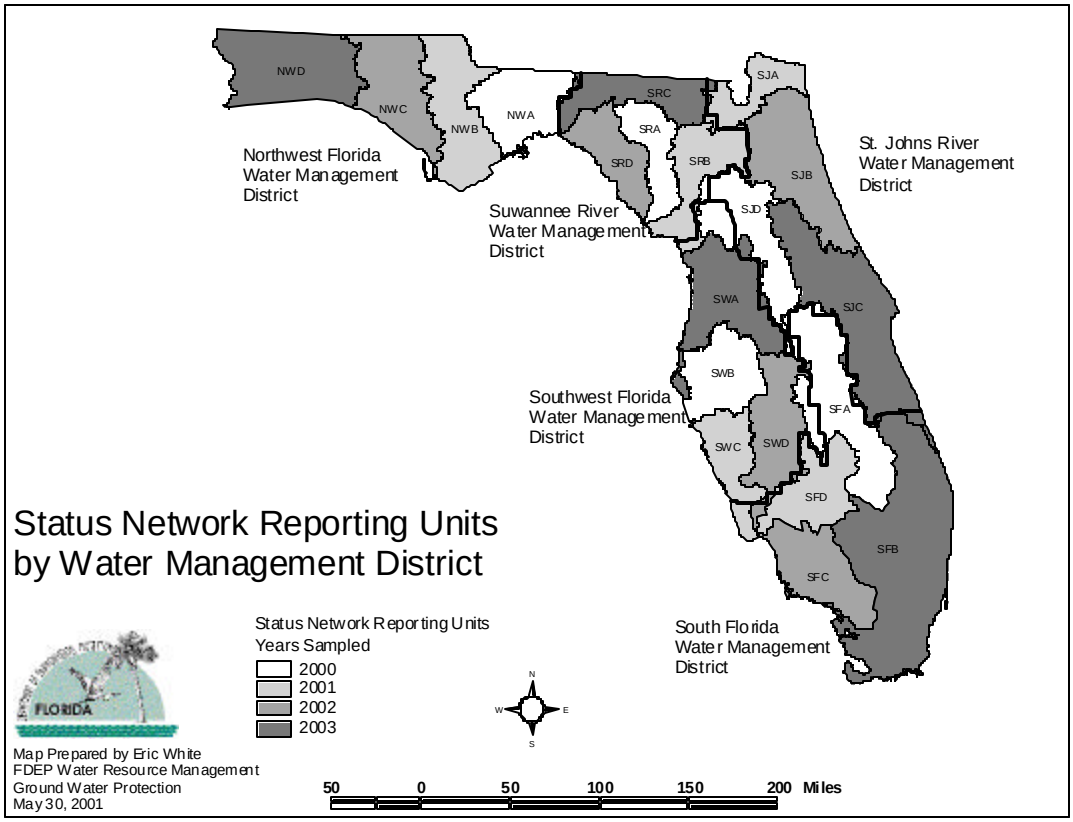
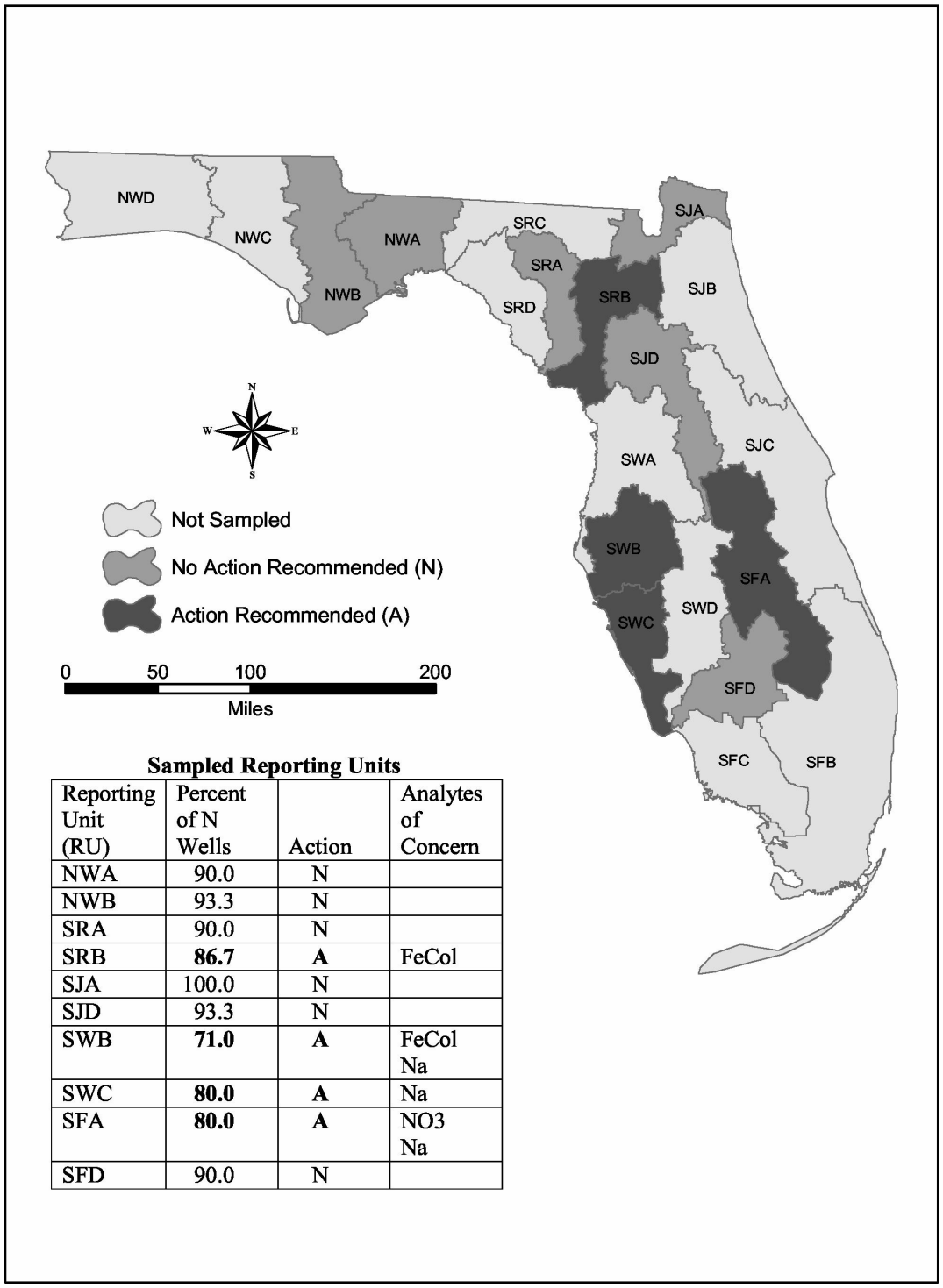


Figure 1. - Status Network Reporting Units and Florida's five water management districts.



Sampled Reporting Units

Reporting Unit (RU)	Percent of N Wells	Action	Analytes of Concern
NWA	90.0	N	
NWB	93.3	N	
SRA	90.0	N	
SRB	**86.7**	**A**	FeCol
SJA	100.0	N	
SJD	93.3	N	
SWB	**71.0**	**A**	FeCol Na
SWC	**80.0**	**A**	Na
SFA	**80.0**	**A**	NO3 Na
SFD	90.0	N	

Figure 2. – Results of Status Network 2000 and 2001
Basin Resource Index – [BRI(Health)]
Unconfined Aquifers and Springs

Table 1. - Status Network Analyte List

INDICATOR	MCL Threshold		Dissolved or Total
	Primary	Secondary	
Calcium			D
Magnesium			D
Sodium	160		D
Potassium			D
Chloride		250	D
Sulfate		250	D
Fluoride	4	2	D
Alkalinity			D
Nitrate + Nitrite	10		D
Ammonia			D
Kjeldahl Nitrogen			D
Phosphorous			D
Orthophosphate			D
Organic Carbon			T
Dissolved Solids		500	T
Suspended Solids			T
Turbidity			T
Color		15	T
Total Coliform	4		T
Fecal Coliform	4**		T
E. Coli			T
Enterococci			T
Water Temperature			N/A
pH		< 6.5, > 8.5	N/A
Specific Conductance/Conductivity			N/A
Dissolved Oxygen			N/A

T - total sample
D - filtered sample
N/A - Not Applicable
**4 - used as surrogate for Total Coliform

Table 2. - Ground Water Quality Criteria Indices

INDEX	***Does an ANALYTE EXCEED a:***		***CATEGORY***
GWQCI (health)	Primary MCL or Health-Based GCL?	YES NO	A - Action Recommended N – No Basis for Action or Concern
GWQCI (aesthetics)	Secondary MCL or Aesthetic-Based CL?	YES NO	C – Concern N – No Basis for Action or Concern

Table 3. - Basin Resource Indices

INDEX	***Are:***		***CATEGORY***
BRI (health)	> 10 % of wells in region categorized as **A?**	YES NO	A - Action Recommended N - No Basis for Action or Concern
BRI (aesthetics)	> 10% of wells in region categorized as **C?**	YES NO	C – Concern N - No Basis for Action or Concern

Table 4. - Summary of the Year 2000 and 2001 GWQCIs in 10 Florida Reporting Units

	Confined Ground Water		**Unconfined Ground Water**	
	Health	**Aesthetics**	**Health**	**Aesthetics**
MCL Violations	32	111	37	45
Impaired Wells	31	53	37	29
Sampled Wells	273	273	300	300
Impaired Wells in (%)	11	19	12	10
Error (E) in %	± 4	± 5	± 4	± 4
CI in %	7 – 15	14 – 24	8 – 16	6 – 14