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OPTICAL BRIGHTENER SCREENING FOR SEWAGE CONTAMINATION OF WATER TABLE AQUIFERS IN SOUTHEASTERN MINNESOTA, USA

Ronald C. Spong[1], Steffan R. Fay[2] and E. Calvin Alexander, Jr.[2]

ABSTRACT

Novel screening methods for detecting optical brighteners, fluorescent organic blue dyes principally used in laundry detergents for whitening fabrics, have been developed for the monitoring of water table aquifers impacted by septic systems. Four rural residential communities characterized by private water supply and sewage systems were selected in southeastern Minnesota. Developments were chosen with a variety of saturated and unsaturated zone materials and thicknesses, water table and well depths, and topographic and cultural settings. Sampling sites were enrolled if wells were completed above regional aquitards. Sanitary surveys of sampling sites were completed with attention to drinking water usage and waste/wastewater disposal practices to uncover sources of cross-contamination. Water supplies were sampled and analyzed to determine aquifer sources, sanitary quality and natural backgrounds and anthropomorphic contributions of physicochemical and microbiological parameters of interest (e.g., nitrate, chloride and coliform bacteria). Filter holders containing untreated cotton, activated carbon and polysulfone/polyethersulfone membrane filters were installed as immersion-type detectors in toilet reservoirs. Syringe filter capsules comprised of polyethersulfone membranes were utilized for direct sampling. Exposure times ranged from minutes to months, and exposed filter media were analyzed in solid phase utilizing a scanning spectrofluorophotometer. Spectral data were computer-processed to objectively match peaks with the spectra obtained from pure fluorescent dyes and laundry detergent formulations. Detections were positive if matched peaks at 440 nm appeared above background fluorescence. Water supply test data and site survey information indicative of septic system contamination were moderately correlated with positive optical brightener detections.

KEY WORDS

Fluorescent whitening agents (FWA) or optical brighteners; groundwater contamination; septic systems or on-site sewage systems; and water table aquifers.

INTRODUCTION

Septic systems and other waste and wastewater disposal practices account for a significant share of the nonpoint source pollution that directly and indirectly impacts the burgeoning rural and urban unsewered communities in Minnesota which are largely dependent on groundwater resources for drinking water supplies (MPCA, 1989). Many quantitative contaminants, such as nitrate which has a natural background concentration less than 1.0 mg N/L in regional groundwaters, have potentially several sources. Therefore, it is difficult to assign responsibility for the impacts, target timely and effective remediation and facilitate land use planning and education to prevent and mitigate the pollution. This is especially true in agricultural settings where, for example, nitrogen from fertilizers and livestock operations is practically indistinguishable from septic system nitrogen.

Traditional sanitary indicators of drinking water supplies, such as coliform bacteria and nitrate, are ambiguous, especially if test results are variable, at or below background levels or negative. Straining, adsorption and competition limit fecal bacteria migration and survival, and reducing or denitrifying conditions either slow nitrogen oxidation to nitrate or reverse it (Bitton and Gerba, 1984). Negative sanitary tests alone do not prove that a water supply is safe for human consumption without more extensive testing. Other quantitative pollution parameters indicative of septic system contamination, including electrical or specific conductance and chloride, give similar equivocal results. Therefore, septic system-specific, qualitative contaminants (i.e., with no natural background concentrations in groundwaters), such as surfactants (MBAS - methylene blue active substances, etc.) and optical brighteners, also known as fluorescent whitening agents (FWA), have been investigated as septic system indicators.

Synthethic optical brighteners were developed in the 1930's by organic chemists after Krais in 1929 isolated aesculin (a glucosidal derivative of coumarin) from horse chestnuts which temporarily brightened linen (Zahradnik, 1982). Following World War II, additional optical brighteners, derived from DASC (diaminostilbene/cyanuric chloride), DSBP (distyrylbiphenyl) and other aromatic hydrocarbons, were synthesized and found widespread commercial application. Use in detergent compounds for whitening fabrics, especially cotton, accounts for approximately 80 percent of the optical brighteners produced annually in the United States.

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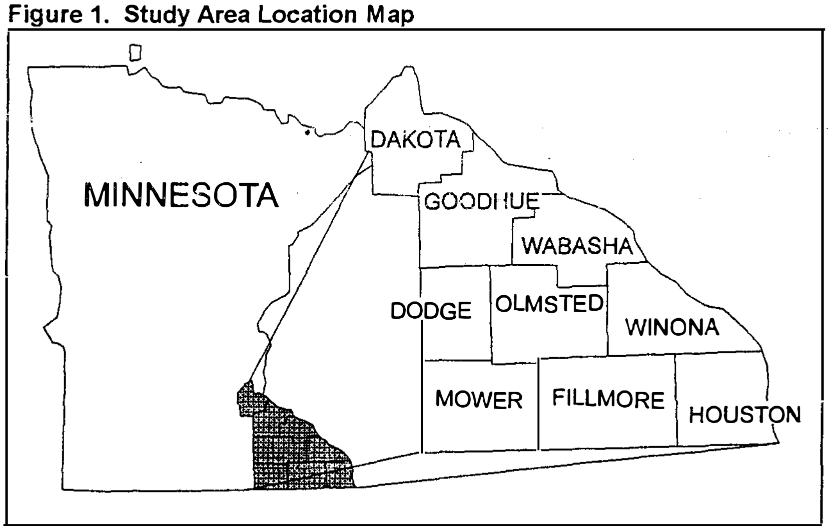
Optical brighteners comprise between 0.1 and 2 percent by weight of modern laundry product formulations (average range of 0.2-0.5 percent). In Minnesota, non-commercial phosphate detergents were banned in 1970 to slow the progressive eutrophication of the State's valuable recreational surface water resources. Synthetic detergent compounds, such as linear alkyl sulfonates, were substituted but first met with dissatisfaction because of "dingy", "dull" looking, washed clothing. Manufacturers responded by adding higher concentrations of optical brighteners to enhance the appearance. Consequently, optical brighteners have been discharged to septic systems for 25 years and have been detected in surface and ground waters in southeastern Minnesota (Spong, 1993).

Since the mid-1970's, interest in optical brighteners or fluorescent whitening agents (FWA) as passive tracers of septic system contamination of groundwaters has been pursued by researchers with varied results. Kerfoot and Brainard (1978) recommended optical brighteners as indicators of septic system pollution which eventually led to the commercial development of instruments known as "Septic Leachate Detectors" or "Septic Snoopers". The instruments combined a filter fluorometer with a specific conductivity meter and were used in Clean Water Act-funded lake pollution and restoration studies in the late 1970's through the mid-1980's. However, their reliability and specificity were debated when studies of fluorescent, dissolved organic carbon compounds (FDOC), including natural humic and fulvic acids, suggested significant interferences (Carlson and Shapiro, 1981).

Alhajjar, et al (1990) reported in a study of seventeen residential septic systems in central Wisconsin that optical brighteners were unsatisfactory as indicators of shallow aquifer sewage contamination. Utilizing upgradient and downgradient drivepoints for sampling and filter fluorometry for FWA analysis of aqueous samples, they reasoned that the undetectable optical brighteners were decomposing or sorbing to soil. They found that dissolved solids (detected as specific conductance) moved through the soil, and chloride was cited as the most reliable sewage indicator. However, use of non-chlorine bleach-stable DASC optical brighteners, well placement and sampling, aqueous sample filter fluorometry and FDOC interference may account for the lack of FWA detections.

Optical brighteners are reliable tracers in karst hydrogeologic investigations despite FDOC interefences and dye costs (Smart and Laidlaw, 1977; Aley, 1985; Alexander and Quinlan, 1992). Fay, et al, (this publication) describe the use of scanning spectrofluorophotometry for solid phase detection of optical brighteners and other fluorescent dyes. Such advances in selective filter media adsorption, fluorometric technology and procedures and the computer processing of resulting spectral data address concerns of low and variable optical brightener concentrations, interfering background fluoresence and subjective data evaluation appearing in the literature.

Figure 1. Study Area Location Map



METHODS AND MATERIALS

Site Selection, Evaluation and Sampling

This Minnesota Legislature-approved research project (Spong, 1993) encompasses a nine-county area of southeastern Minnesota (Figure 1.), and the four communities selected represent a variety of cultural, topographic and hydrogeologic settings (Table 1.) with which to test the hypothesis that optical brighteners selectively sorbed to cotton, other cellulosic fibers and selective filter media can be reliable qualitative and, perhaps, semi-quantitative indicators of septic system contamination of groundwaters. The villages of Castle Rock, Coates, Empire City and Vasa are rural residential communities comprised of urban laborers and local agribusiness, service industry and retired persons. All are characterized by early 1900's structures, limited road and drainage improvements and pre-Code wells and septic systems. New buildings, wells, septic systems and other enhancements occur infrequently.

Older residences were chosen for the project primarily because they were served by wells completed in surficial, unconfined aquifers above regional aquitards. Participation in the project was voluntary and required access for sampling and a brief survey. An average of 75 percent of those solicited declined to participate which limited site selection in most communities. Once selected, participants were interviewed about a number of residential living habits, knowledge of their wells, septic systems and other practices, general health and concerns. Sanitary surveys were conducted of the wells and water supplies, septic systems and other waste and wastewater disposal devices with particular attention to potential cross-contamination.

Filter holders were secured in the reservoirs of the most used toilet in buildings, and water supplies were sampled and analyzed in the field and laboratory. Owners were apprised of test results and any recommendations if problems were observed. Filter holders were retrieved and replaced periodically, and water supplies were resampled to help resolve certain problems (e.g., coliform bacteria present).

Table 1. Cultural, Topographic, Geomorphic and Hydrogeologic Features of Four Communities

Feature	Castle Rock	Coates	Empire City	Vasa
County (area)	Dakota (southwest)	Dakota (north)	Dakota (central)	Goodhue (north)
Occupied Buildings	67(7 nonresidential)	62(5 nonresidential)	57(2 nonresidential)	43(7 nonresidential)
Polygonal Area	121 ha (299 acres)	65 ha (160 acres)	19 ha (47 acres)	53 ha (130 acres)
Vertical Relief	9 m (29.5 ft)	7 m (23 ft)	4 m (13 ft)	21 m (69 ft)
Slope (% gradient) **Soils**	0% ~ 6% loam, silty loam (cl)	1% ~ 6% silty to sandy loam	0% ~ 2% loam to loamy sand	2% ~ 12% silty loam to loam
Geomorphology	pre-Qw morraine - outwash plain	loess-mantled Qw outwash plain	buried bdrk valley alluvial/Qw outwash	loess-mantled pre-Qw till
Surficial Bedrock	rsdl ss, dolostone	rsdl ss, dolostone	dolostone	rsdl ss, dolostone
Bedrock Depth	3-14 m (9-46 ft)	15-27 m (50-90 ft)	3-91m (10-300 ft)	1-15 m (3-50 ft)
Water Table Depth	3-12 m (10-40 ft)	21-27 m (70-90 ft)	3-12 m (10-40 ft)	12-18 m (40-60 ft)
Shallow Well Depth	Drivepoints 6-9 m Drilled wells 12-55m	Drilled wells 21-61m	Drivepoints 6-9 m Drilled wells 12-46m	Drilled wells 18-76m
Shallow Aquifer Flow	East-southeast	Northeast	Northeast	North-northeast

NB: ha = hectares; m = meters; ft = feet; cl = clay loam; Qw = Wisconsinan; rsdl ss = residual sandstone

Optical Brightener Filter Media, Sampling and Analysis

Immersion filter holders were constructed of fine-mesh, black fiberglas window screening which was distilled water-rinsed, folded and stapled to form separate compartments for the filter media and channels for plastic tywraps that were used to secure filter holders to the toilets' standpipes. Filter media included untreated cotton facial pads (Target and Johnson & Johnson brands), activated carbon (Fisher Scientific: 6-14 mesh) and polysulfone/polyethersulfone 0.45 um-pore membrane filters (Gelman Science: trademarks "Tuffryn", "Supor", "Biotrace" and "UltraBind"). Precautions were taken to isolate the filter media and holder materials from possible optical brightener contamination. Completed holders and filter media were tracked as lots, randomly sampled and analyzed as "blanks" to control for false positives. If a blank tested positive, the entire lot was discarded.

In place of direct aqueous samples where FDOC interference significantly limits detection of very low optical brightener concentrations in groundwaters, cotton was selected due to its success in karst water tracing studies (Aley, 1985; Alexander and Quinlan, 1992). Side-by-side comparisons were run with cotton and activated carbon, the latter being a non-selective FDOC adsorption medium. Cotton was found to be largely uneffected by FDOC adsorption. However, solid phase fluorometric analysis of cotton blanks consistently found a characteristic peak (emission wavelength of 414 nm) which could interfere with sample analysis. Cotton blank reference spectra were then used for background comparisons. Also, some cotton products were excluded from use as they were found to contain traces of optical brighteners likely from the inclusion of recycled, formerly brightened cotton.

Laboratory trials with syringe filter capsules (Gelman Science: trademark "Acrodisc" and "Acrodisc PF"), in which 0.2 um-pore polyethersulfone membrane filters preferentially sorbed optical brighteners (Fay, et al, this publication) during column experiments, was followed by field sampling utilizing disposable syringe and peristaltic and manual vacuum pump collection methods. Insufficient data precludes reporting at this time.

Solid phase fluorometry was performed at the University of Minnesota Hydrogeochemistry Laboratory utilizing a Shimadzu RF5000U scanning spectrofluorophotometer, lab-developed methodologies and electronic data storage and processing (Fay, et al, this publication). Pure optical brighteners were obtained from Ciba-Geigy (1989) [Trademark: Tinopal CBS-X (ASTM DSBP-1) and Tinopal 5BM-GX (ASTM DASC-4)] to provide reference spectra for the two most common optical brightener derivative groups. Because of the proprietary nature of laundry product formulations, popular liquid and solid detergents were purchased, fluorometrically analyzed and compared with the pure optical brightener reference spectra. Excitation, emission and synchronous scans of calibrants, blanks and samples were conducted, and 60 nm synchronous scans were utilized to match 440 nm reference and sample peaks yielding positive FWA detections above the background cotton blank spectra. Several to many scans were run of each sample to ensure surface area coverage, and indeterminate results were treated as negatives.

Water Supply Sampling and Analysis

Sites were sampled periodically from taps supplying cold, untreated water close to the well. Water was allowed to run for 45 or more minutes until stabilized, i.e., 1 percent or less variation of temperature, pH, oxidation-reduction potential, specific conductance and dissolved oxygen. Stabilization instruments (YSI, Inc.: Model 3560 Water Quality Monitoring System and Model 50B Dissolved Oxygen Meter) were calibrated before each sampling event and then cleaned and rinsed with distilled water thereafter. Sample taps were flamed with a propane torch, and then water was allowed to run an additional 5 minutes before sampling. Appropriate sample containers, preservatives and coolers were utilized in accordance with Standard Methods (APHA, AWWA, WEF, 1992), as were the analytical protocols for the examination of the water samples whether in the field [e.g., total and bicarbonate alkalinity (titration) and ammonia/ammonium-nitrogen (Orion Model 290A ion selective electrode meter)], at contracted Minnesota Department of Health-certified environmental laboratories or the University of Minnesota Hydrogeochemistry Laboratory. A field and laboratory quality assurance plan was followed to ensure the representivity, precision and accuracy of the test results.

RESULTS AND DISCUSSION

Thirty-five sites were selected among the four communities with the majority sampled periodically over the 1993-1995 project period. Table 2 summarizes fluorometric, physicochemical and bacteriological data collected with mean, range or percent positive reported for selected analytes.

Table 2. Water Supply Test Data and Optical Brightener Detections from Four Communities

Parameter	Castle Rock	Coates	Empire City	Vasa
Sample Sites	7	9	4	4
Positive FWA's	29%	89%	50%	75%
pH (units)	7.06 [6.75 ~ 7.33]	7.13 [6.48 ~ 7.65]	7.15 [6.66 ~ 7.42]	7.05 [6.33 ~ 7.32]
Redox Potential (mV)	+146 [-56 ~ +212]	+146 [+123 ~ +166]	+140 [+111 ~ +173]	+132 [+117 ~ +149]
Conductivity (mS/m)	82.8 [71.3 ~ 108.3]	83.3 [59.8 ~ 120.1]	60.9 [41.1 ~ 69.7]	84.3 [69.0 ~ 119.8]
Tot Dis Solids (mg/L)	509 [446 ~ 650]	513 [383 ~ 715]	389 [280 ~ 437]	518 [433 ~ 713]
T Hard (mg CaCO3/L)	386 [346 ~ 475]	388 [305 ~ 516]	309 [240 ~ 340]	391 [338 ~ 515]
Tot Coli Bacteria-pos	22%	18%	14%	25%
Nitrate-N (mg N/L)	7.9 [<0.2 ~ 15.5]	11.8 [6.8 ~ 20.4]	8.5 [0.2 ~ 12.2]	8.2 [0.6 ~ 13.0]
Chloride (mg/L)	64 [26.7 ~ 131]	67 [14.2 ~ 110]	18.6 [15.8 ~ 26.6]	65 [36 ~ 111]
Sulfate (mg/L)	45 [24.7 ~ 62]	30.5 [28.0 ~ 33.1]	24.2 [22.7 ~ 25.6]	37 [24.0 ~ 55]
Tot Alk(mg CaCO3/L)	259 [221 ~ 340]	262 [205 ~ 355]	220 [195 ~ 255]	260 [225 ~ 375]

NB: One or more samples/site; mean [minimum~maximum]; percent positive; T / Tot = total; mV = millivolts; mS/m = millisiemens/meter = 10 umhos/cm; mV = millivolts; mg/L = milligrams/liter; N = nitrogen; CaCO3 = calcium carbonate

Immersion filter holder media, depending upon length of exposure, water quality and other factors, were prone to physical erosion (surficial cotton fibers), masking by precipitates (e.g., carbonate scaling, iron hydroxides and staple corrosion), bacterial colonization (e.g., iron bacteria) and adsorption site competition. At spring sites, the physical removal of cotton fibers was aided and abetted by colonized bacteria and their consumption by grazing aquatic invertebrates. Despite cotton's sorptive affinity for optical brighteners, negative or indeterminate fluorometric results were sometimes reported when one or more of the above conditions occurred.

Castle Rock

Castle Rock was selected because of available water quality data and continuing investigations of significant groundwater impacts from former herbicide spill and rinsate disposals (Minnesota Superfund Site), residential and commercial waste dumping and road salt stockpiling, as well as the presence of nonconforming and failed septic systems (cesspools, seepage pits and nonconforming drainfields). Originally, 18 sites were chosen, but a County-sponsored well replacement project during 1993-94 removed 11 sites from this study. Before 10 of the 11 existing wells were disconnected and sealed, abbreviated screening tests were conducted with negative results for optical brighteners.

However, one well (site 1009) disconnection was delayed several months allowing additional exposure time and strong positive optical brightener results (Figure 2). These results are compared with site 1033 which has been consistently negative. Because the owner of site 1009 had plumbed the toilet with hot water to prevent condensation during the summer months, we surmise that cotton sorption of optical brighteners was enhanced by increased water temperatures. Optimum FWA adsorption varies with its solubility in water, temperatures between 15 and 50 degrees Celsius and other factors (Ciba-Geigy, 1989). Since ambient groundwater temperatures are colder (7 to 12 degrees Celsius), the obvious answer was to prolong the filter holder exposure time. Unfortunately, increasing the period of immersion to facilitate slower FWA adsorption likewise increases the masking of the cotton by precipitates and bacterial colonization which reduces the available surface area for FWA adsorption.

Completing the sampling and analysis of the remaining sites may provide additional clues to FWA detection problems in moderate ionic strength groundwater environments with mixed-source contaminants.

Coates

The City of Coates was chosen for its thick unsaturated zone of outwash sand and gravel overlying weathered dolostone, its proximity to large agricultural tracts and the Rosemount Research Center (National and Minnesota Superfund Site), and the prevalence of nonconforming septic systems (cesspools, seepage pits and deep, undersized drainfields). Rapid recharge and oxidation accounts for the consistently elevated nitrate, total dissolved solids, chloride and some fecal bacteria breakthrough (Table 2.). These correlated well with the 89% positive optical brightener detection rate although earlier samples at the same sites were less likely to be positive. As with Castle Rock, the early Coates negative results probably represent the early stage of the study when methods and materials were being refined, as well as possible dilution of optical brighteners during heavier precipitation periods.

Figure 3 compares an early low positive optical brightener detection from site 1034 [positive coliform bacteria and elevated nitrate (7.6 mg N/L)] with indeterminate results from site 1031 [negative coliform but very high nitrate (20.0 mg N/L)]. Subsequent sampling has given consistent positive results for site 1034 along with repeated positive coliform bacteria. There has been a single positive FWA result for site 1031 but continuing negative results for site 1030 which is adjacent and cross-gradient to site 1031, has a shallower well but similar nitrate, TDS, chloride and other water test results.

Figure 2. Fluorometric Scans - Castle Rock

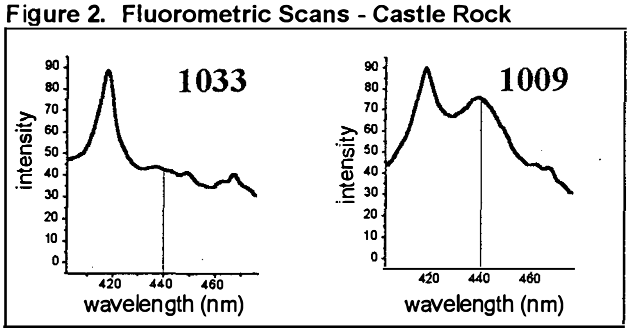
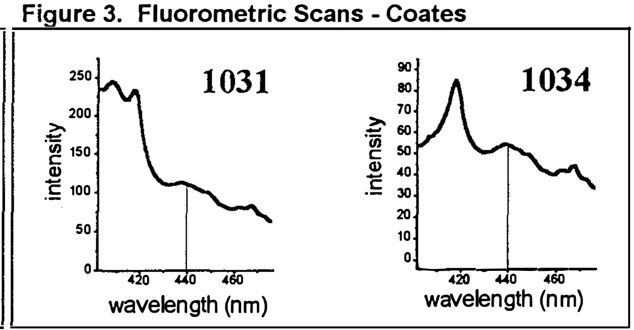


Figure 3. Fluorometric Scans - Coates



Empire City

Situated in an alluviated and outwash-filled buried bedrock valley and on and adjacent to the floodplain of the Vermillion River, the village of Empire City is characterized by a very shallow water table in highly permeable sand which has invited drivepoint well installations in basements in close proximity to septic systems (older, nonconforming drainfields and seepage pits are common) and other waste disposal.

Figure 4 contrasts a downgradient well location (site 1035) having a positive detection for optical brighteners on cotton at 440 nm with an upgradient well (site 1028) which yielded indeterminate results. The downgradient well water persists with positive FWA detects but slightly lower nitrate values (9.6-11.0 mg N/L) while the upgradient well is now positive for optical brighteners with nitrate at 11.8 to 12.2 mg N/L. All coliform bacteria tests have been negative.

However, in contrast, a reportedly shallower drivepoint at site 1038 located even farther downgradient than site 1035 has been consistently negative for optical brighteners and coliform bacteria. Nitrate has been 0.2 mg N/L, but most of the other parameters are similar to the water quality of the more upgradient wellpoints. The site is within the floodplain and that may hold the answer to the differences cited.

Vasa

An unincorporated village in Goodhue County, Vasa occupies a loess and till-capped upland ridge underlain by weathered sandstone and dolostone, both of which crop out in the vicinity. It appears that locally the fractured and karsted dolostone provides sufficient groundwater for the shallow wells completed in it but is also prone to pollution from waste and wastewater disposal practices. Several residents still utilize both rainwater and groundwater cisterns, but their proximity to deep, nonconforming septic systems and possible interconnection with well-supplied household water are problematic. It appears that all of the older, functioning wells are completed in bedrock with some of the shallower dug wells, now dry, having been converted to sewage pits.

As with the above examples, Figure 5 compares site 4040, formerly with indeterminate optical brightener results, to site 1041 located to its east and slightly downgradient which has had consistently positive detections. Both sites are routinely positive for FWA's now. Another positive FWA site (1045) is northwest and situated slightly downgradient from site 1040. Originally a shallower well, it was "deepened" a number of years ago to a reported 250 feet. However, its water quality is similar to that of the shallower bedrock wells.

Figure 4. Fluorometric Scans - Empire City

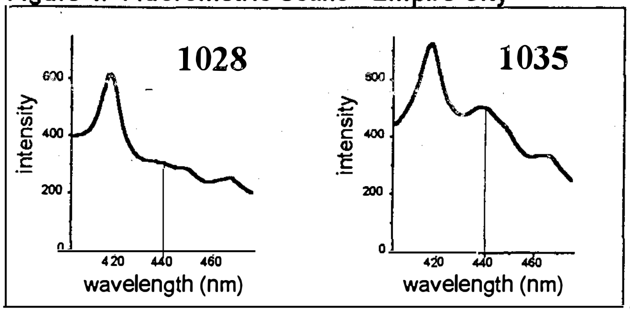
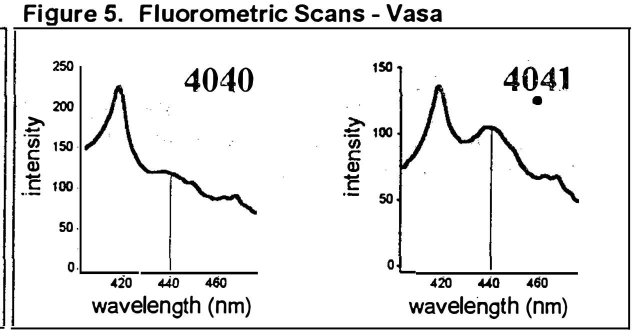


Figure 5. Fluorometric Scans - Vasa



CONCLUSIONS

Employing novel methods for immersion and in-line sampling of cotton and other selective filter media and solid-phase, scanning spectrofluorophotometric techniques and computer-processed spectral analysis, the development of cost-effective qualitative screening and possible semi-quantitaive testing of optical brighteners (fluorescent whitening agents or FWA's) in groundwaters has been demonstrated in the field and laboratory. The methods obviate the concerns of fluorescent dissolved organic carbon compound interference that hampers low fluorometric detection limits for aqueous samples. Instead, they rely on solid media which preferentially sorbs and accumulates FWA's. By electronically storing excitation, emission and synchronous scans of sample spectra, comparing the results to optical brightener reference spectra at 440 nm, and resolving cotton or other filter media blank interference, relatively low detection limits are feasible. Preliminary correlations with sample site groundwater test data and sanitary survey information on water supply and waste/wastewater practices suggest moderately good agreement in utilizing positive optical brightener detections as indicators of septic system contamination of shallow, unconfined aquifers. The study will be completed with additional sampling and analysis to verify the optical brightener detection system and statistically correlate the data and information. The methods and materials are readily transferrable to surface water and wastewater optical brightener screening and testing.

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BIOGRAPHICAL SKETCHES

Ronald C. Spong

Ronald C. Spong is the project manager for the two-year, state-funded study entitled "Optical Brighteners: Indicators of Sewage Contamination of Groundwaters". He is Environmental Supervisor of the Water and Land Management Section, Dakota County (Minnesota) Environmental Management Department. He has 21 years full-time regulatory experience in public and environmental health and 7 years part-time consulting experience, including well and water supply sanitation, waste water treatment, solid and hazardous waste management, groundwater contamination and remediation, and karst hydrogeology. He holds a Baccalaureate degree in biology and chemistry, 1972, and is a MPH candidate in environmental health, both from the University of Minnesota.

Steffan R. Fay

Steffan Fay received his Bachelor of Science degree in Geology from Imperial College of Science, Technology and Medicine, University of London, UK. in 1990. Between 1990 and 1993 Mr. Fay was employed as a hydrogeologist with Barton & Loguidice, P.C. Consulting Engineers in Syracuse, New York, USA. Mr. Fay is currently enrolled in a Masters degree program at the Department of Geology and Geophysics, University of Minnesota, USA, where his interests focus on ground water contaminant fate and transport, laboratory analytical techniques and field hydrogeology teaching. Mr. Fay was awarded a fellowship by the National Ground Water Association in 1994 to study the transport behavior of selected fluorescent organic chemicals in natural porous media.

E. Calvin Alexander, Jr.

Calvin Alexander received a BS in Chemistry from Oklahoma State University in 1966 and a PhD in Chemistry from the University of Missouri at Rolla in 1970. After 3 and 1/2 years post-Doctoral research in Physics at the University of California, he joined the Geology and Geophysics Department at the University of Minnesota in 1973. He is currently a sabbatical visiting Professor at the University of Auckland in New Zealand.

The central theme of Dr. Alexander's research interests is the rate of movement of fluids in hydrogeology. This research includes the use of isotopic techniques (tritium, carbon-13, and stable oxygen and hydrogen isotopes) and inadvertent tracers (pollutants, pesticides, and nutrients) to measure fluid flow or residence times on time scales ranging from months to tens of thousands of years. Much of his current work involves the use of artificial tracers such as fluorescent dyes and anions to measure fluid flows on time scales of minutes to years. His initial interests in karst hydrology have expanded into a range of non-Darcian phenomena such as preferential flow in soils, and flow in fractured and granular media. He is also interested in how the results of recent hydrogeologic research can be incorporated quickly and effectively into public policy questions of non-point source pollution, Best Management Practices, and Well Head Protection Regulations.