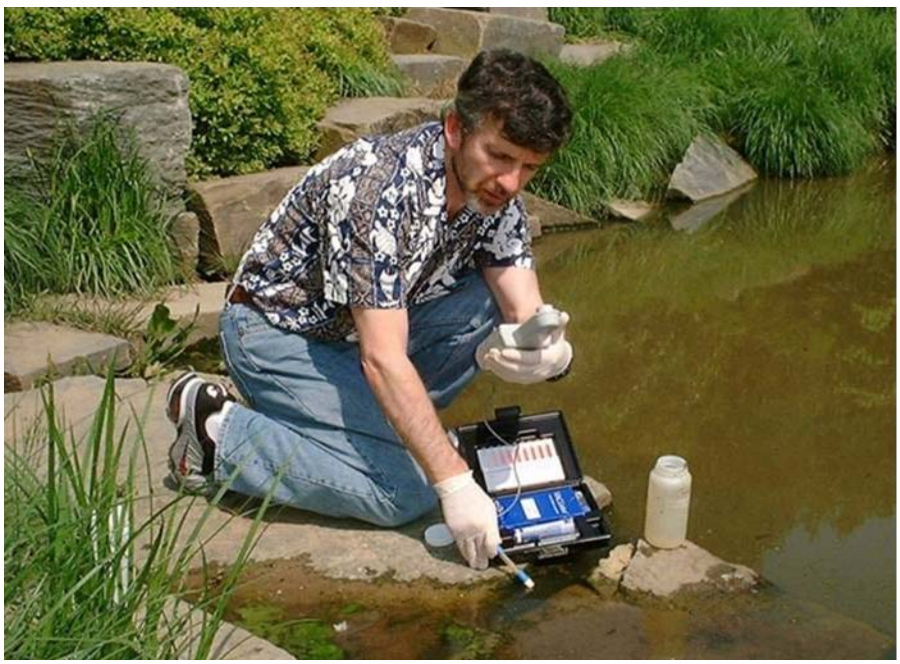
Turfgrass and Environmental Research Online

...Using Science to Benefit Golf



In a study led by Dr. Stuart Cohen (shown above), Environmental & Turf Services, Inc., Wheaton, MD conducted surveys and evaluated water quality data from 44 studies covering a 20-year period involving 80 golf courses to comprehensively assess the impact those golf courses had on surface and ground water quality with respect to pesticides, pesticide metabolites, nitrate-nitrogen, and total phosphorus. Results indicate that phosphorus appears to present the greatest water quality problem in those studies.

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PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 400 projects at a cost of $31 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

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Quantitative Analysis of Over 20 Years of Golf Course Monitoring Studies

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SUMMARY

There has been increased focus on turf pesticides since the early 1990s due to the intense public scrutiny proposed golf courses receive during the local permitting process, as well as pesticide registration evaluations by the U.S. Environmental Protection Agency under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). Results from permit-driven studies are frequently not published and knowledge about them is usually not widespread. The purpose of this study was to comprehensively evaluate available golf course water quality data and assess the extent of impacts as determined by comparisons with toxicological and ecological reference points. Results of this study include:

- Forty-four studies involving 80 courses from a 20-year period passed our quality control and other review criteria. A total of 38,827 data entries (where one analysis for one substance in one sample equals a data entry) from pesticide, pesticide metabolite, total phosphorus, and nitrate analyses of surface water and ground water were evaluated. Analytes included 161 turf-related pesticides and pesticide metabolites.
- Widespread or repeated water quality impacts by golf courses did not occur at the sites studied, although concerns are raised herein about phosphorus. Individual pesticide database entries that exceed toxicity reference points for ground water and surface water are 0.15% and 0.56%, respectively.
- Pesticides detected in wells had longer soil metabolism half-lives (49 days) compared with those not detected (22 days), although the means were not significantly different.
- The maximum contaminant level (MCL; 10 mg/L) for nitrate-nitrogen was exceeded in 16/1,683 (0.95%) of the ground water samples.
- There were 1,236 exceedances out of 1,429 data entries (86.5%) of the total phosphorus ecoregional criteria in five ecoregions, although many of these exceedances arose from storm events. Thus, phosphorus appears to present the greatest water quality problem in these studies.

Editor's Note:

This paper is an adaptation from the original paper published in *Environmental Toxicology and Chemistry* 29(6):1224-1236 published online April 1, 2010.

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The subject of golf course design, construction, and management raises many environmental issues that are frequently discussed among government officials and the general public, particularly in the context of reviews of land-development permit applications. This issue has practically no limitation in scope, geographically or in subject matter. For example, comprehensive environmental impact assessments are required for proposed golf courses in China and Korea (4). Avian impacts had been noted for turf insecticides whose turf use has since been banned in the U.S. (24). Concerns about aquatic macroinvertebrate impacts have been documented in Canada (34), and analogous concerns about amphibians have been studied elsewhere (16, 19, 22).

Pesticide use on golf courses has been examined in comparison with agricultural pesticide use on more than 80 crops (5). Proactive environmental stewardship approaches for golf course development and management have been written and recommended for overall environ-

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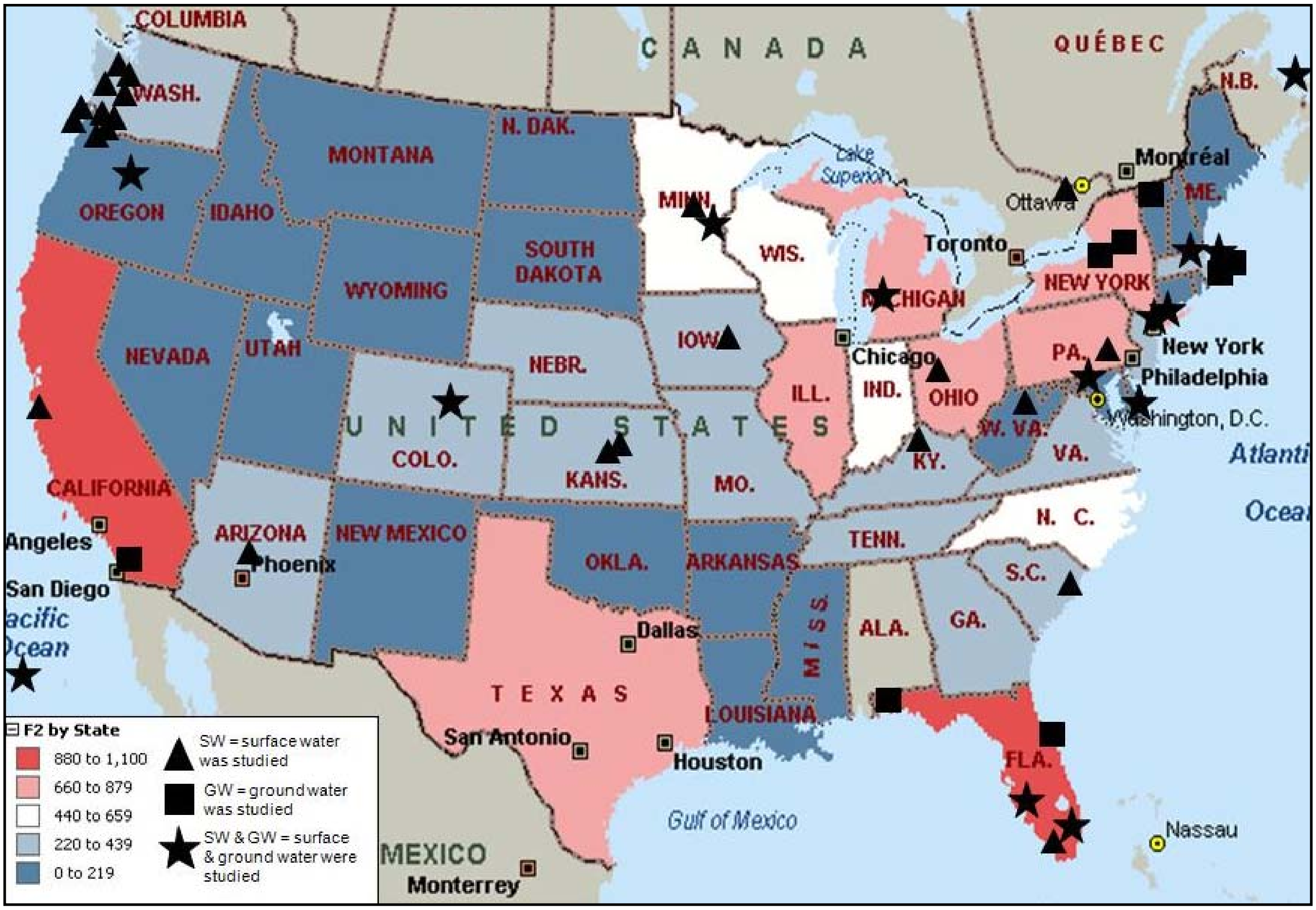

Figure 1. Golf course distribution in the United States and location of study sites (adapted from J. Kass, Director of Research, National Golf Foundation, Jupiter, FL, personal communication, 2007). Figure is reprinted from *Environmental Toxicology and Chemistry* 29(6), page 1,225 with permission from *ET&C* editors.

mental protection (1, 12, 25), as well as for protection of amphibians and their habitats (7). A key focus of many discussions regarding known or potential golf course impacts has been water quality.

Comprehensive data and assessments of golf course water quality impacts in several regulatory and scientific contexts are needed. Regulatory decisions regarding environmental permitting at the local scale, as well as pesticide registration decisions at the state and national levels, could be better advised by such analyses. Researchers could use such information to guide the filling of data gaps and the data could be used as one component of analyses of ecosystem impacts.

In a report published in 1999, we obtained water quality monitoring data from 17 studies of 36 golf courses and conducted a meta-analysis of the data (6). This review did not include phosphorus, and the U.S. Environmental Protection Agency (U.S. EPA) has since published ecoregional criteria for total phosphorus and total nitrogen that are very low (i.e., typically 0.2 ppm or less for total phosphorus in lakes and reservoirs), concentrations that are often below background in our experience. Data from large areas of the North American continent were also lacking. Finally, data were insufficient for evaluating temporal trends of the analytes. Many more monitoring studies were in progress at the time of our 1999 paper. Thus, the purpose of this study was to update the data collection from the previous effort and expand the analyses of the data to include total phosphorus, as well as an evaluation of temporal and spatial trends in the data.

The 1999 dataset had other limitations, such as the inability to conclude that the reported concentrations provided true national estimates for golf course impacts on water quality due to the

Analyte[a]	GW	SW	Analyte[a]	GW	SW	Analyte[a]	GW	SW	Analyte[a]	GW	SW	Analyte[a]	GW	SW
1,2 dichloropropane	Y	N	bromacil	Y	Y	endosulfan II	Y	Y	lindane	Y	Y	propiconazole-a	Y	Y
cis-dichloropropene	Y	N	*butachlor*	N	Y	endosulfan sulfate [b]	Y	Y	linuron	Y	Y	propiconazole -b	Y	Y
trans-1,3 dichloropropene	Y	N	captan	N	Y	endrin	Y	Y	malathion	Y	Y	propoxur	Y	N
3,5,6-trichloro-2-pyridinol [b]	Y	Y	carbaryl	Y	Y	endrin aldehyde [b]	Y	Y	mancozeb	N	Y	*prothiofos/tokuthion*	N	Y
3-hydroxy-carbofuran [b]	Y	N	carbofuran	Y	Y	endrin ketone [b]	Y	Y	MCPA	Y	Y	quinclorac	N	Y
1-naphthol [b]	N	Y	carfentrazone-ethyl	Y	Y	EPN	N	Y	MCPP	Y	Y	ronnel	N	Y
2,4,5-T	Y	Y	chlordane	Y	Y	EPTC/eptam	N	Y	merphos	N	Y	siduron	Y	N
2,4,5-TP	Y	Y	*chlordecone*	N	Y	ethalfluralin	N	Y	metalaxyl	Y	Y	siduron (A)	Y	N
2,4-D	Y	Y	chloroneb	Y	Y	ethion	Y	Y	methamidophos	Y	Y	siduron (B)	Y	N
2,4-DB	Y	Y	chloropicrin	Y	N	ethofumesate	Y	Y	methomyl	Y	N	simazine	Y	Y
DDD	Y	Y	chlorothalonil	Y	Y	ethoprop	Y	Y	methoxychlor	Y	Y	simetryn	N	Y
DDE	Y	Y	chlorpyrifos	Y	Y	ethyl parathion	Y	Y	methyl bromide	Y	N	sulfotep	N	Y
DDT	Y	Y	chlorpyrifos ethyl	Y	Y	ethylene dibromide	Y	N	methyl isothiocyanate	Y	N	sulprofos	N	Y
acephate	Y	Y	cis-permethrin	N	Y	etridiazole	Y	N	methyl parathion	Y	Y	*terbacil*	N	Y
acetochlor	N	Y	clopyralid	Y	Y	fenamiphos sulfone [b]	Y	Y	metolachlor	N	Y	*terbufos*	Y	Y
alachlor	Y	Y	*coumaphos*	N	Y	fenamiphos sulfoxide [b]	Y	Y	metribuzin	Y	Y	terbuthylazine	N	Y
aldicarb	Y	N	*cyanazine*	N	Y	fenamiphos	Y	Y	mevinphos	Y	Y	*terbutryn*	N	Y
aldicarb sulfone [b]	Y	N	cyfluthrin	Y	N	fenarimol	Y	Y	mirex	N	Y	tetrachloroethylene	Y	N
aldicarb sulfoxide [b]	Y	N	dacthal diacid [b]	Y	N	fenoxaprop ethyl	Y	Y	Inorganic arsenic	Y	Y	*tetrachlorvinphos*	N	Y
aldrin	Y	Y	DCPA	N	Y	fensulfothion	N	Y	MTBE	Y	N	thiophanate-methyl	Y	Y
alpha-BHC	Y	Y	dalapon	Y	Y	fenthion	N	Y	myclobutanil	Y	Y	thiram	Y	Y
alpha-chlordane	N	Y	delta-BHC	Y	Y	fludioxonil	N	Y	naled	Y	Y	*toxaphene*	Y	Y
ametryn	Y	Y	deltamethrin	Y	Y	flutolanil	Y	Y	oryzalin	Y	Y	trans-permethrin	N	
AMPA [b]	N	Y	demeton	N	Y	fluvalinate	Y	N	oxadiazon	Y	Y	triadimefon	Y	Y
anilazine	Y	Y	demeton-O	N	Y	fonophos	Y	Y	*oxamyl*	Y	N	triadimenol [b]	Y	Y
Arsenic [b,c]	Y	Y	demeton-S	N	Y	gamma-chlordane	Y	Y	paclobutrazol	Y	N	tribufos	N	Y
atraton	N	Y	diazinon	Y	Y	gamma-BHC	Y	Y	parathion-methyl	N	Y	trichlorfon	Y	N
atrazine	Y	Y	dibromochloropropane	Y	N	glufosinate	N	Y	PCNB	Y	Y	*trichloronate*	N	Y
azinphos-methyl	N	Y	dicamba	Y	Y	glyphosate	Y	Y	pendimethalin	Y	Y	triclopyr	Y	Y
azoxystrobin	Y	Y	dichlobenil	N	Y	halofenozide	Y	N	phorate	Y	Y	trifloxystrobin	N	Y
bendiocarb	Y	Y	dichlorprop	Y	Y	halosulfuron-methyl	Y	N	picloram	Y	Y	trifluralin	Y	Y
benefin	Y	Y	dichlorvos	N	Y	heptachlor	Y	Y	prodiamine	N	Y	trinexapac-ethyl	N	Y
benfluralin	N	Y	*dieldrin*	Y	Y	heptachlor epoxide [b]	Y	Y	prometon	N	Y	vernolate/vernam	N	Y
benomyl	Y	N	*dinoseb*	N	Y	*hexachlorobenzene*	N	Y	prometryn	Y	Y	vinclozolin	Y	Y
bentazon	Y	Y	dimethoate	N	Y	hexazinone	Y	Y	pronamide	Y	Y			
beta-BHC	Y	Y	diquat	N	Y	imidacloprid	Y	Y	propachlor	N	Y			
bifenthrin	Y	Y	disulfoton	Y	Y	iprodione	Y	Y	propamocarb	Y	N			
bispyribac-sodium	Y	N	dithiopyr	N	Y	isofenphos	Y	Y	propanil	N	Y			
boscalid	Y	N	diuron	Y	Y	isoxaben	N	Y	propazine	N	Y			
butylate	N	Y	endosulfan I	Y	Y	lambda-cyhalothrin	Y	Y	propiconazole	Y	Y			

[a] AMPA=aminomethylphosphonic acid; BHC=benzene hexachloride; 2,4-D=dichlorophenoxyacetic acid; 2,4-DB=4-(2,4-dichlorophenoxy) butyrc acid; DBCP=dibromochloropropane; DCPA=dimethyl tetra-chloroterephthalate; DDD=dichlorodiphenyldichlorethane; DDE=dichlorodiphenyldichloroethylene; DDT=dichlorodiphenyltrichloroethane; DSMA=disodium monomethylarsenate; EPN=O-ethyl O-(4-nirophenyl) phenylphosphonothioate; EPTC=S-ethyl dipropylthiocarbamate: GW= ground water: MCPA=methylchlorophenoxypropionic acid; MSMA=monosokium methane arnonate; MTBE=methyl-tert-butyl ether; PCNB=pentachloronitrobenzene; SW=surface water; 2,3,5-T=2,4,5-trichlorophenoxy acetic acid; 2, 4, 5-TP=2, 4, 5-trichlorophenoxy propionic acid. Chemicals in italics were initially included in the data-base after the quality control review, but deleted due to the low probability of use at the subject golf courses.

[b] Pesticide metabolite.

[c] Arsenic is a component of the organoarsenical herbicides MSMA and DSMA. It can also arise from natural sources, as well as from historic use of inorganic arsenicals such as lead arsenate. Researchers usually did not/or were not able to distinguish among the various potential arsenic sources, nor between the different forms of arsenic, when they reported their results.

Table 1. Pesticides and pesticide metabolites analyzed in one or more of the studies in ground water and surface water.

Region	Description
1	Western Mountain Ranges
2	Alluvial Basins
3	Columbia Lava Plateau
4	Colorado Plateau and Wyoming Basin
5	High Plains
6	**Nonglaciated Central Region**
7	**Glaciated Central Region**
8	Piedmont and Blue Ridge
9	**Northeast and Superior Uplands**
10	**Atlantic and Gulf Coastal Plain**
11	**Southeast Coastal Plain**
12	**Alluvial Valleys**
13	**Hawaii**
14	Alaska
15	Puerto Rico and Virgin Islands

Table 2. The studies that were evaluated spanned seven of the 15 ground water regions (10) and are designated in bold typeface.

analytical and spatial limitations of the data, as well as the fact that the results do not arise from a single, comprehensive, statistically based monitoring survey (e.g., stratified random sampling). This current effort still lacks a unified statistical design, but it is more spatially representative. It contains data from more golf courses in the mid-continent, as well as more areas known to have large numbers of golf courses (Figure 1).

This analysis also includes an attempt to capture data from the analyses of pesticides that were actually applied to golf courses based on a questionnaire administered to participating golf course superintendents. Thus, we attempted to include analytical results only for pesticides that were definitely or likely used on a particular golf course. Finally, the publication of rather strict total nitrogen and total phosphorus ecoregional criteria allows for a more meaningful interpretation of the nutrient results.

Materials and Methods

Solicitation and Review of Studies

Results of surface water and ground water studies conducted on golf courses throughout the U.S. and Canada were solicited through a variety of sources. Initially, press releases were issued requesting information, followed by articles in six golf course trade magazines. Letters requesting information were sent to all 104 chapter leaders of the Golf Course Superintendents Association of America, all 50 state environmental water quality regulatory agencies, and 22 contacts in the U.S. EPA's headquarters and 10 regional offices. The response rate was 36% from the state agencies and 100% from the U.S. EPA.

Attempts were made to contact all golf course superintendents and/or lead investigators from the 17 studies used for the original 1999 research effort to obtain monitoring data subsequent to 1996. Finally, the peer network (word of mouth) was used. Thus, it is likely we identified most of the completed golf course water quality monitoring studies as of June 2007 for which individual sample results and adequate documentation were available.

Analytes

The focus was pesticides, pesticide metabolites, nitrate-N, and total phosphorus. Often, analytical results were reported for pesticides that were not known to be used on golf course turf. Those pesticide results were almost always non-detects, and an effort was made to exclude these pesticides. We previously included solvents used as pesticide product carriers (6). We did not include solvents in this analysis because of the lack of detections in the previous study, and the fact that most golf turf pesticide products are applied either in aqueous solutions or as dry granular materials.

Total organic analytes initially consisted of 194 pesticides and pesticide metabolites. Organic chemicals that were almost certainly never applied to golf courses were deleted from this list for a total of 161 turf-related pesticides and metabolites that were analyzed in at least one of the studies included in the present study (Table 1). We estimate that fewer than 120 pesticide active ingredients are currently registered for use on turf, but other turf pesticides have also been registered during the period covered by the studies and have since been withdrawn from the market. Further, some pesticides may be applied to nonturf areas at golf courses — ornamental plants and water features.

Part of the effort to identify whether golf courses actually used or applied the pesticides that were being analyzed included a questionnaire. Pesticide-use information was requested from all golf course superintendents in the studies. The response rate was 50%, and, on average, 71% of pesticides analyzed had actually been applied to the golf courses. The 71% value should be regarded as a lower limit because at many golf courses, records of pesticide applications more than two years prior to the study were not readily accessible or did not exist.

Quality Control

Each study was subject to a two-stage quality control review. First, study directors and/or laboratory staff were contacted to ensure that adequate quality control measures were followed by the participating laboratories, including proper state certification and assurance that blank, matrix spike, and duplicate analyses were run. Second, approximately 10% to 20% of the data entered for each study were checked for completeness and accuracy in an in-house quality control review prior to statistical evaluation. In addition, detailed internal data queries and spot checks for data entry errors were done in the preparation of the manuscript.

Twenty-nine new studies were initially reviewed for potential inclusion in this meta-analysis. The new studies included 46 additional golf courses. Twenty-seven of these 29 new studies passed our quality control review criteria and were included with the original 17 studies, yielding a total of 44 studies that include 80 golf courses in the database. All of these studies were conducted in the U.S. except for two studies that were conducted in Canada (Figure 1).

Data Entry and Statistical Analyses

After the preliminary review for content and data quality, data were entered into Microsoft Access 2003 (Microsoft Corporation©). Data from the 1999 effort had been previously entered into Borland Paradox Version 5.0 (Borland

Ecoregion Number	Name of Ecoregion
I	Willamette and Central Valleys
II	Western Forested Mountains
III	Xeric West
IV	Great Plains Grass and Shrublands
V	South Central Cultivated Great Plains
VI	Corn Belt and Northern Great Plains
VII	Mostly Glaciated Dairy Region
VIII	Nutrient Poor Largely Glaciated Upper Midwest and Northeast
IX	Southeastern Temperate Forested Plains and Hills
X	Texas-Louisana Coastal and Mississippi Alluvial Plains
XI	Central and Eastern Forested Uplands
XII	Southern Coastal Plain
XIII	Southern Florida Coastal Plain
XIV	Eastern Coastal Plain

[a] http://epa.gov/waterscience/criteria/nutrient/ecoregions/index.html

Table 3. Draft Aggregate Level III Ecoregions for the National Nutrient Strategy[a]

	Organics[a]	Nitrate-N	Total Phosphorus	Total
Ground Water	15,774	1,683	970	18,427
Surface Water	15,752	2,493	1,429	19,674
Total	31,526	4,176	2,399	38,101

[a] Organics refers to pesticides and metabolites.

Table 4. Net database entries following removal of pesticides/metabolites that would never be applied to a golf course.

International), and these data were transferred into the new Access database. Statistical analyses were performed using SigmaPlot® v10.0 (Systat Software©).

The data contained a large number of non-detects (NDs). That is, the substance analyzed was not detected above the detection limit or, more appropriately, the method reporting limit, analogous to the practical quantitation limit (PQL). It is not clear how these data should be entered when calculations are done, particularly considering the fact that the detection limits or practical quantitation limits were not consistent. The actual concentration represented by non-detect is some value below the detection limit, however, the analytical method cannot determine whether the non-detect is truly zero or some unquantifiable value between zero and the practical quantitation limit.

We used the U.S. EPA's accepted method of replacing the non-detects with half the detection limit (30, 31) for the two datasets that contain less than 20% non-detects: nitrates in ground water, and total phosphorus in surface water. This method is also known as the substitution method, where a specific number is substituted for each non-detect. Although it is expedient, it can impact the reliability of standard deviation estimates (11), particularly when the detection limit is not extremely low. The substitution method should not be used when uncertainty/error analysis will be important, nor when the non-detects exceed 20% of the data set.

A Winsorized mean was computed (i.e., the data at the tails were censored) for those datasets where the number of non-detects are greater than 20% but less than 40% of the dataset (31). The Winsorized mean method was applied to the nitrate in surface water and total phosphorus in ground water results. Thus, all nitrate or total phosphorus non-detects in surface water or ground water, respectively, were replaced at the low end of the concentration distribution by the next highest value. An analogous replacement was made at the high end. This allows reasonable estimates of the mean and median, but sacrifices the ability to reliably estimate the standard deviation. For datasets with greater than 40% non-detects (all pesticide analyses), neither the substitution method nor the Winsorized mean approach is appropriate, nor is Cohen's method due to varying PQLs. For these data, a range of the mean was computed (i.e., the lower end of the range assumes ND=0 and the upper limit assumes ND=PQL).

The Mann-Kendall (M-K) test is a non-parametric test that tests for trends within a dataset (9) and was used to determine if there were increasing total phosphorus and nitrate-N trends. However, the M-K test does not discriminate very well between weak and strong trends. Therefore, a regression analysis was also used to discern trends in the multi-year data because regression analyses provide a better sense of the relationship between concentration and time.

Toxicity Reference Points

Drinking Water

Ground water and surface water pesticide results were compared with chronic (lifetime) drinking water standards or guidelines. Surface water pesticide results that exceeded lifetime limits were compared with acute reference points. The maximum contaminant levels legally enforceable by U.S. EPA were only available for seven of the pesticides, and nonenforceable lifetime drinking water health advisory levels were available for an additional seven pesticides (29). Chronic reference doses adjusted with the Food Quality Protection Act uncertainty factors (the maximum dose in mg chemical/kg body wt/day calculated that one could consume without suffering any adverse effects) were obtained from the U.S. EPA's Office of Pesticide Programs Registration Eligibility Decision documents or food tolerance notices published in the Federal Register. A secondary source was the U.S. EPA's Integrated Risk Information System, and these served as the basis for health advisory levels caculated by us.

Maximum Allowable Concentrations for Aquatic Organisms

The aquatic toxicity reference points (maximum contaminant levels) have two sources. The U.S. EPA Office of Pesticide Program's Aquatic Life Benchmark Table contains criteria for 21 of the detected pesticides. The remaining pesticide maximum allowable concentrations were calculated using 1/10th the LC_{50} or EC_{50} (concentration of pesticide that would kill or affect 50% of a test population) of the most sensitive freshwater species listed in the U.S. EPA's Ecotoxicity Database or obtained from other available sources.

Golf Course Environment

As of 2008, there were over 18,300 golf courses in the United States (National Golf Foundation, Jupiter, FL) and 2,390 in Canada (Royal Canadian Golf Association, ON, Canada). The area of an average 18-hole U.S. golf course is 61 hectares or 150 acres (15). Golf courses consist of several types of management zones. The four types of playing surfaces are, in descending order of management intensity (average percentages of total area): greens and tees (3.9%), fairways (20%), driving range/practice areas (4.6%), roughs (34%), and out-of-play areas (variable) (15). Thus, the average 18-hole golf course consists of approximately 38 ha (74 acres) of managed turf, but only 28% of the total area typically consists of the more intensively managed playing surfaces: tees, greens, and fairways.

Typically, the most dominant or troublesome pest pressures are weeds in warm climates, diseases in cooler climates, and a combination of weeds, diseases, and insects in the transition zone. Herbicides are used mostly on fairways and roughs, fungicides are applied more intensively to greens and tees, and insecticides are often used throughout the course. Roughs, which constitute the largest area of golf courses, receive the fewest and least intensive pesticide and fertilizer treatments. It should be noted that turfgrass is a living filter that is often used as part of phytoremediation (20, 23) and is used as a best management practice to treat stormwater runoff (21). This filtration efficacy is likely due partly to its extensive shoot and root density (2).

Results

Overview

Figure 1 depicts the distribution of golf facilities in the U.S. and the location of study sites. A golf facility may include more than one golf course, and a single symbol may denote more than one golf facility. Note that multiple study sites may be represented by a single symbol due to the small scale of the figure.

The studies that were evaluated spanned seven groundwater regions (Table 2) and 14 level III aggregate ecoregions (Table 3). Level III ecoregions are defined by the patterns and composition of biotic and abiotic phenomena (e.g., geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology) that reflect or affect differences in ecosystem quality and integrity.

The database included 38,827 entries prior to refinement, where one entry is one analysis for a single analyte in one sample. The numbers in this table were refined by deleting from further analysis pesticides and their metabolites that were almost certainly not used on the subject golf courses. This action resulted in the omission of 726 database entries for a total of 38,101 analytes (Table 4). Approximately 3.7% of all surface water organic database entries were detections (quantifiable concentrations) and approximately 1.2% of the ground water organic entries were quantified detections (Tables 5 and 6).

Surface Water Results

Pesticides and Metabolites

There were 15,752 surface water pesticide/metabolite entries (Table 4), of which 590 (3.7%) were detections. The highest number of pesticides that were detected was from the insecticides (26 detections), followed by herbicides (17 detections) and fungicides (14 detections).

Table 5 provides information on pesticides detected in surface water, including water quality reference point exceedances. Two main categories of drinking water reference points are listed in Table 5, maximum contaminant levels and lifetime health advisory levels developed for chronic exposures and acute health advisory levels for short-term exposures. Concentrations of pesticides in surface water were initially compared with the maximum contaminant levels and lifetime health advisory levels. Any concentration exceedances were then compared with acute health advisory levels. Surface water contamination by golf course pesticides tends to be episodic, therefore acute health advisory levels are more appropriate toxicological reference points for this exposure pattern.

Ten pesticides exceeded their respective enforceable drinking water standard (i.e., maximum contaminant level) or their lifetime drinking water health advisory level at least once (Table 5). Sixty detections exceeded their respective enforceable drinking water standard. The exceedance rate was 0.38% of pesticide entries or 12.5% of the 481 detections. The lifetime health advisory level/maximum contaminant level is an overly conservative but convenient comparison with infrequent episodic concentrations because the health advisory level is usually established from a lifetime exposure of an adult drinking two liters of water per day. Only ethoprop appeared to exceed its acute health advisory level, a more appropriate reference point (Table 5).

We found that 28 of the 481 detections exceeded a maximum allowable concentration (an exceedance rate of 5.8% of the detections, and 0.18% of total surface water pesticide entries). Nine different active ingredients yielded the 42 exceedances. The range of average concentration of pesticides in surface water was 0.16 to 4.14 μg/L. We documented at least 60% of the pesticides analyzed in surface water samples were actually used during the monitoring period, but the true number could be greater.

Nitrate-N

Nitrate-N detections were compared to the ecoregional criteria for total nitrogen. It is important to note that this is not a conservative comparison because the total nitrogen ecoregional criteria are composed of inorganic-N and TKN (organic-N plus ammonia). Nitrate-N detections occurred in 12 of the 14 ecoregions: I–III, V–IX, and XI–XIV. The average number of detections per ecoregion was 151 with detections ranging from 1 (in ecoregion VIII) to 503 (in ecoregion VI). Total nitrogen ecoregional criteria ranged from 0.12 to 2.18 mg/L for rivers and streams and 0.1 to 1.27 mg/L for lakes and reservoirs. The 553 total nitrogen ecoregional criteria exceedances by nitrate-N were 22% of the nitrate-N surface water analyses.

There were, on average, 46 ecocriteria exceedances in the ecoregions with exceedances, ranging from none (ecoregions VIII, XIII) to more than 150 (ecoregion II). An average of two golf courses per ecoregion were responsible for the exceedances, ranging from 1 (ecoregions I, V, VIII, XI, XIII) to 12 (ecoregion II).

Total Phosphorus

The number of surface water total phosphorus entries was 1,429, with 1,379 (96.5%) detections. The average total phosphorus concentration was 0.43 (± 0.66) mg/L. There were 1,227 exceedances of total phosphorus ecoregional criteria in five ecoregions, 1,083 in rivers and streams and 153 in lakes and reservoirs. The 1,227 total phosphorus ecoregional criteria exceedances represented 86% of the total phosphorus surface water analyses.

The U.S. EPA has created two total phosphorus criteria for each ecoregion: one for lakes and reservoirs and one for streams and rivers. Each detection was compared to the appropriate criterion based on the type of the sample (e.g., flowing stream versus pond sample) and location. Detections of total phosphorus occurred in ecoregions II, V, VI, XII, and XIV. There were, on average, 215 detections per ecoregion with detections ranging from 9 (ecoregion XII) to 832 (ecoregion VI).

There were, on average, 185 ecocriteria exceedances in the ecoregions with exceedances ranging from 0 (ecoregion XII) to 693 (ecoregion VI). The majority of these exceedances per ecoregion occurred at one golf course, except for ecoregion II where two golf courses were responsible for the exceedances.

Ground Water Results

Pesticides and Metabolites

There were 15,774 ground water pesticide/metabolite entries (Table 4) of which 191 (1.2%) were detections (Table 6). Detections by categories are herbicides (11 detections), followed by insecticides (8 detections) and fungicides (8 detections). Twenty-four detections (12.6% of detections, 0.15% of the total entries) exceeded a maximum contaminant level standard or lifetime health advisory level, representing eight different pesticides. The range of average concentration of pesticides in ground water was 0.08 to 6.32 µg/L, depending on whether nondetects = 0.0 or the detection limit (Table 6).

There were pesticide detections in four ground water regions (GW regions 7, 9-11). The average number of detections per ground water region was 46 with detections ranging from 2 (GW region 7) to 74 (GW region 9). There were, on average, two golf courses per ground water region responsible for the detections ranging from one (GW region 7) to three (GW region 9). Additionally, an average of nine different pesticides were detected per ground water region ranging from 1 pesticide (GW region 7) to 14 (GW region 9).

Nitrate-N

There were 1,683 ground water nitrate-N entries, of which 1,377 (82%) were detections. The detection limits ranged from 0.005 to 0.5 ppm and were typically 0.1 ppm. There were 16 (1.2%) detections exceeding the 10 mg/L maximum contaminant level in ground water. The average concentration of nitrate-N was 1.08 mg/L.

Nitrate-N was detected in ground water regions 6, 7, 9–13. There were, on average, 155 detections per ground water region, ranging from 6 (GW region 11) to 577 (GW region 9). There were also, on average, two golf courses per ground water region responsible for the detections, ranging from one (GW regions 6, 12, 13) to four (GW region 9).

Total Phosphorus

The number of ground water total phosphorus entries was 970, of which 688 (71%) were detections. The average total phosphorus concentration in ground water was 0.12 mg/L. There were 101 total phosphorus detections in five ground water regions (6, 7, 9–11), ranging from 8 (GW regions 10, 11) to 334 (GW region 7). A majority of these detections were from one golf course in each region, the exception being from ground water region 7, where two golf courses were responsible for the exceedances.

Surface water pesticides[a]	Total entries	Total number of detections	No. of detections exceeding MAC	No. of detections exceeding MCL or chronic HAL	MAC U.S. EPA Aquatic Life Benchmark or calculated by ETS (ppb)[b,c]	Chronic HAL/MCL (ppb)	Acute HAL (ppb)	Max. Conc. (ppb)
2,4-D	761	52	0	0	12,500	70 [d]	---	34.35
acephate	29	2	0	1	130[e]	7.5[e]	35	19
ametryn	66	2	0	0	1,800	60	---	0.06f
AMPA (glyphosate metab.)[f]	23	11	N/A	N/A	N/A	N/A	---	21.6
atrazine	77	22	0	0	360	3[d]	---	2.5
azoxystrobin	113	2	0	0	8.4[e]	1,260[e]	---	5.8
bentazon	48	1	0	0	50,000	20	---	2.4
Beta-BHC	240	2	N/A	0	N/A	0.0091	---	0.085
carbaryl	251	7	1	0	2.55	40[g]	---	227
chlorothalonil	544	14	0	2	11.5	2[g]	200[d]	6.
chlorpyrifos	449	21	17	0	0.05	2[d]	30[d]	0.4
3,5,6-trichloro-2-pyridinol	55	11	0	0	1,000[h]	7[e]	---	0.9
clopyralid	32	2	0	0	1,722 (MAC VT)	3,500[e]	---	0.42
DDD	223	4	N/A	4	N/A	0.00031[i]	---	0.051
DDE	223	2	N/A	2	N/A	0.00022[i]	---	0.0093
DDT	223	4	4	4	0.001	0.00022[i]	---	0.059
Delta-BHC	240	2	N/A	N/A	N/A	N/A	---	0.16
diazinon	248	19	15	1	0.05[e]	1.0[d]	20	1.4
dicamba	561	12	0	1	14,000	4,000/200[ej]	2,000	200
dieldrin	220	2	0	0	0.2[i]	1.75	---	0.007
disulfoton	184	1	0	0	1.95	0.3	---	0.21
dithiopyr	89	1	0	0	46[e]	122	---	0.1
diuron	30	7	0	0	80	2[e]	---	1.4
endosulfan I	238	1	1	0	0.22[i]	3[e]	---	0.055
endosulfan II	232	1	0	0	0.22[i]	3[e]	---	0.0065
ethofumesate	45	1	0	0	50	8,750[e]	---	0.65
ethoprop	114	2	0	2	22	0.2	0.5	7.7
fenamiphos sulfone[f]	22	2	1	0	0.2[e]	2[e]	20 (est.)	0.36
fenamiphos sulfoxide[f]	22	7	2	0	0.9[e]	2[e]	20 (est.)	3.2
fenamifos	77	7	1	0	0.13[e]	0.7[d]	---	0.13
fenarimol	100	5	0	0	90[e]	4,200[e]	---	0.24
fonophos	2	2	N/A	0	N/A	10	---	0.32
glyphosate	253	13	0	0	27,500	700	---	170
heptachlor	270	1	0	0	0.37[e]	0.4	---	0.07
imidacloprid	48	6	0	0	8,300[e]	399[e]	---	8.95
iprodione	298	27	4	0	2.4[e]	280[e]	---	4
isofenphos	30	1	0	0	0.43[e]	35[e]	---	0.046
lindane	271	8	2	0	0.17[e]	0.2	1,000[d]	0.25
malathion	405	3	0	0	0.25	100	---	0.21
MCPP	417	1	N/A	0	N/A	1,400[e]	---	0.3
metalaxyl	106	5	0	0	910[e]	400[e]	---	0.84
methamidophos	29	1	0	0	2.6[e]	46	---	1.1
MSMA (as arsenic)[k]	3	3	0	3	1,200[e]	0.02	---	7
myclobutanil	45	17	0	0	240[e]	175[e]	---	1.6
oryzalin	65	1	0	0	700	46	---	2.2
oxadiazon	57	3	0	0	53[e]	40	---	0.13
PCNB	464	25	0	0	24[e]	21	---	13
pronamide	30	2	0	0	2,800	50	---	1
propiconazole	169	16	0	0	425	9.2[e]	---	1.1
propiconazole-a	56	19	N/A	0	---	9.2[e]	---	2.7
propiconazole-b	55	20	N/A	0	---	9.2[e]	---	3.8
simazine	252	67	0	39	500	4	1,000	152
triadimefon	198	2	0	0	100[e]	210[e]	---	4.7
triadimenol[f]	42	15	0	0	250[e]	27[e]	---	3
triclopyr	139	18	0	0	180	140	---	1.1
vinclozolin	73	2	0	0	284[e]	2[e]	---	0.5

[a]AMPA=aminomethylphosphonic acid; BH =benzene hexachloride; 2,4-D=dichlorophenoxyacetic acid; DDD=dichlorodiphenyldichlorethane; DDE=dichlorodiphenyldichloroethylene; DDT=dichlorodiphenyl trichloroethane; DSMA=disodium monomethylarsenate; ETS=Environmental & Turf Services, Inc.; HAL=health advisory level; MAC=maximum allowable concentration; BT=VT; MCL = maximum contaminant level; HAL = health advisory level; MAC = maximum allowable concentration; MCPP=methylchlorophenoxypropionic acid; MSMA=monosokium methane arnonate; N/A=not available; PCNB=pentachloronitrobenzene; U.S. EPA=US Environmental Protection Agency; -- = calculation not necessary; ETS=Environmental & Turf Services, Inc.

[b]U.S. EPA Aquatic Life Benchmarks from www.epa.gov/oppefed1/ecorisk_ders/aquatic_life_benchmark.htm.

[c]The lower of the acute fish or invertebrate benchmarks was used.

[d]U.S. EPA (17)

[e]Values calculated by the authors.

[f]Pesticide metabolite.

[g]Based on 1 X 10^{-6} chronic drinking water cancer risk derivred from the U.S. EPA (29).

[h]Screening level MAC estimated by dividing the lowest end of the toxicity range for the chemical by 10; i.e., the classification MT (moderately toxic) would indicate a screening level of 1 mg/L/10 mL = 100 µg/L.

[i]U.S. EPA Water Quality Criteria (www.epa.gov/waterscience/criteria/wqcriteria.html)

[j]The 1988 U.S. EPA Hal is 4,000 ppb. We calculated 200 ppb using more recent data.

[k] Arsenic is a component of the organoarsenical herbicides MSMA and DSMA. It can also arise from natural sources, as well as from historic use of inorganic arsenicals such as lead arsenate. Researchers usually did not/were not able to distinguish among the various potential arsenic sources when they reported their results.

Table 5. Pesticides detected in surface water with maximum contaminant level/health advisory level and maximum allowable concentration exceedances.

Discussion

Pesticides: Mobility and Persistence

The previous meta-analysis of turf pesticide impacts compared pesticide degradation rates and soil binding trends with an earlier U.S. EPA analysis of data from a national ground water study (32). The hypothesis was that pesticides detected in surface water and ground water are more mobile and persistent than pesticides not detected. Cohen et al. (6) used soil aerobic metabolism half-life ($t_{1/2}$) as the persistence parameter, and the mobility parameter was K_{OC} (the potential for neutral organics to bind to soil organic carbon). The trends supported the hypothesis, but differences were not statistically significant (6).

In the present study, we attempted to refine this comparison by limiting the analysis to those pesticides known to be used on the golf courses. Thus, we calculated the means of the natural logarithms (ln) for half-lives and K_{OC} for 11 pesticides applied and detected in ground water, 19 pesticides that were analyzed and applied but not detected in ground water, 13 pesticides applied and detected in surface water, and 19 pesticides that were applied and analyzed but not detected in surface water samples. The average ln K_{OC} values for nondetected pesticides were nearly identical for surface water (6.20) and ground water (6.22), and higher than the ln K_{OC} values for detected pesticides in surface water (6.08) and ground water (5.95) — although the differences are not significant — which did not support the hypothesis.

The half-lives for detected pesticides versus nondetects supported the hypothesis in ground water (i.e., longer half-lives for detected pesticides). However, the difference in means was only weakly significant. For ground water, ln half-lives (days) is 3.90 for detected pesticides compared with 3.08 for nondetected pesticides. The difference for surface water detections was also not significant: ln half-lives (days) were 3.27 for detects and 4.09 for nondetects.

In summary, the K_{OC} was not a key independent variable for predicting ground and surface water detections in our database in this analysis. The most intriguing result is the ground water/pesticide aerobic soil metabolism half-life analysis. Although the means were not statistically significantly different, the mean half-life for detected pesticides (49 days) is larger than the mean half-life for pesticides reported as used at the site but not detected in wells (22 days).

Many factors are related to pesticide characteristics: hydrology, land cover, application method, slope length, climate, and erosive tendencies that determine detection likelihood in ground water and surface water (8, 14, 26, 33). Not all of these factors need to be considered in a simple assessment of the relative importance of soil metabolism and soil organics partitioning, but some of this knowledge could be integrated. For example, perhaps a simple analytic solution that integrates some of these factors, such as the "attenuation factor" described by Rao et al. (17), could be used.

Pesticides: Reference Point Exceedances

Fourteen of the 24 ground water exceedances were due to arsenic. The specific form of arsenic (As) detected (i.e., inorganic, organic, As^{+3}, or As^{+5}) was not determined in these studies. Most environmental analyses convert the molecule into inorganic arsenic prior to detection and quantitation. The arsenic-containing herbicide that is currently heavily used on turf, monosodium methane arsonate (MSMA), is an organoarsenical. The organoarsenicals have lower toxicity than inorganic arsenic, and they are not considered carcinogenic to humans (28). The extent to which the 14 arsenic exceedances represent use of organoarsenical turf herbicides, old inorganic pesticides, or natural sources, is unknown. Only 0.15% of the ground water data entries for pesticides exceeded a health advisory level or maximum contaminant level, slightly higher than we found previously (0.07%) with 25% fewer data points (6).

It is generally not appropriate to compare pesticide concentrations in surface water with lifetime drinking water health advisory levels due to their episodic nature. Therefore, we calculated acute health advisory levels to compare with surface water detections. We also compared the results with lifetime health advisory levels because we had done that in 1999 (6), and because it is still standard practice.

The data showed that 0.40% of the surface water pesticide entries exceeded a chronic health advisory level, only one detection exceeded an acute health advisory level, and 0.20% of the data entries exceeded a maximum allowable concentration. The maximum allowable concentration exceedance frequency was significantly lower (0.2% vs 0.6–0.9%), but the exceedance frequency for lifetime health advisory levels in surface water was slightly higher than what was found previously (0.4% vs 0.29%) (6).

The relatively low rates of pesticide detections and exceedances in surface water are likely due to a combination of two factors: the turf system (verdure, thatch, dense roots) acts as a living filter (3), and roughs, which typically surround the more intensively managed tees, greens, and fair-

Pesticides[a]	Total Entries	Number of Detections	Number of Detections that exceed MCL or HAL	HAL/MCL	Max. Concentration Detected (ppb)
2,4-D	1024	18	0	70	50
3,5,6-trichloro-2-pyridino[b]	76	2	2	7.5[c]	8.8
arsenic [b,d]	150	14	14	10	126
atrazine	163	2	1	3	7.9
azoxystrobin	47	3	0	1,260[e]	5
bentazon	146	8	1	200	120
bromacil	158	1	0	70	0.85
chlordane	247	19	2	2	7.2
chlorothalonil	532	6	2	2[b]	3.1
chlorpyrifos	750	3	0	2	0.1
dacthal diacid[b]	75	4	0	4,000[c]	1.07
diazinon	163	1	0	1	0.05
dicamba	605	2	0	4000 [c,e] /200 [c,e]	1.9
diuron	166	9	1	2	5.8
fenamiphos sulfoxide[b]	142	6	0	2	0.79
fenamiphos	160	19	1	0.7	0.71
heptachlor epoxide[b]	245	11	0	2	0.16
imidacloprid	106	2	0	399[c]	1.7
iprodione	839	14	0	280[c]	55
isofenphos	701	1	0	35[c]	1.17
myclobutanil	168	12	0	175[c]	0.9
oxadiazon	1	1	0	40[c]	0.05
paclobutrazol	140	3	0	460[c]	4.2
propiconazole	386	3	0	9.2[c]	0.72
simazine	162	6	0	4	3.3
triadimefon	1,030	13	0	210[c]	90.2
triadimenol[b]	272	6	0	27[c]	8.4

[a] 2,4-D, dichlorophenoxyacetic acid; HAL, health advisory levels; MCL, maximum contaminant level.

[b] Pesticide metabolite.

[c] Values calculated by authors.

[d] The element arsenic is a component of the organoarsenical herbicides MSMA and DSMA. Inorganic arsenic can also arise from natural sources, as well as from historic use of inorganic arsenicals such as lead arsenate. Researchers often did not/were not able to distinguish among the various potential arsenic sources when they reported their results.

[e] The 1988 U.S. Environmental Protection Agency HAL for dicamba is 4,000 ppb. We calculated 200 ppb using more recent data.

Table 6. Pesticide detections in ground water and maximum contaminant level (MCL)/health advisory levels (HAL) exceedances.

ways, have minimal pesticides applied to them. Thus, it could be said that golf courses are inherently designed with built-in best management practices, in addition to the best management practices typically required during the permitting process for stormwater management.

Nutrients: Temporal Trends

The annual average concentrations of nitrate-N in groundwater show a slight increasing trend. There was no significant annual trend for concentrations of nitrate-N in surface water. There were no statistically significant annual trends for total phosphorus in groundwater or surface water. Below are two examples of these specific trends analyses.

Basic Time-Series Comparisons (surface water)

Basic time-series comparisons of the entire database were done for pesticides, nitrate-N, and total phosphorus (pre- and post-1997). There were a greater number of pesticide detections, more golf courses with pesticide detections, and more pesticides detected in the pre-1998 data compared with the post-1997 time period. There were a greater number of detections and more golf courses with nitrate-N detections in the pre-1998 time period compared to the post-1997 time period.

The time-series analyses for total phosphorus showed there were more detections and a greater number of golf courses with total phosphorus detections in the pre-1998 time period (including 1997) compared to the post-1997 time period. It is important to note that these comparisons are skewed because many of the golf courses that participated in the initial meta-analysis did not submit additional data for this new effort, and many of the new golf courses were added after 1997 to the overall study.

Basic Time-Series Comparisons (ground water)

A time-series comparison for analytes in ground water was done that is similar to the basic time-series comparison for surface water. There were fewer pesticide detections, fewer golf courses with pesticide detections, and fewer pesticides detected in the pre-1998 data compared with the post-1997 time period.

The time-series analyses for nitrate-N (pre- and post-1997) showed there were fewer nitrate-N detections and fewer golf courses with nitrate-N detections pre-1998 (including 1997) compared with the post-1997 time period. There was a slight increasing trend of nitate-N concentrations in ground water (r^2=0.29, p=0.021).

The time-series analysis for total phosphorus (pre- and post-1997) showed there were more total phosphorus detections and a greater number of golf courses with total phosphorus detections in the pre-1998 (including 1997) compared to the post-1997 time period. Again, it is important to note that these comparisons are skewed because many of the golf courses that participated in the initial meta-analysis did not submit additional data for this new effort, as well as many of the new golf courses were new to the overall study.

In our experience, a small increase in nitrate-N can be expected, typically 1 ppm above baseline in the shallow part of the aquifer, at sites where a golf course is built and the previous land use is unmanaged vegetation. Part of this increase can manifest as an initial spike that results from land clearing and/or pre-emergent fertilization. Increases in total phosphorus concentrations in ground water may or may not occur.

Nutrients: Exceedances

An overwhelming majority of the total phosphorus surface water results exceeded their respective ecoregional criteria. This could be a function of overfertilization and/or very strict criteria (i.e., ecoregional criteria are often less than 0.04 ppm). Additionally, the U.S. EPA ecoregional criteria are based on baseflow data. Results in this database were derived from storm flow and baseflow. As a result, many of the background samples exceed these ecoregional criteria. In our experience, the irreducible concentrations from vegetated areas, including unfertilized areas, can often yield total phosphorus concentrations greater than the ecoregional criteria. We recommend that golf course superintendents base their phosphorus applications on soil tests conducted at least annually.

Nitrate-N maximum concentration level exceedances in ground water were low (1.4%), and the average concentration (1.08 ppm) was in the typical background range for most regions of the country. Surface water nitrate-N concentrations were often elevated relative to ecoregional criteria for total nitrogen. The Winsorized mean was 0.23 mg/L, and total nitrogen ecoregional criteria vary from 0.10 to 2.18 mg/L.

Summary

The present study addresses the large data gap in the availability of reliable water quality data for golf course environments, which has been a key focus of many discussions regarding known or potential golf course impacts. There is a continued need for additional high quality, reliable data on the water quality impacts by golf courses. More data are needed from states with large numbers of golf courses including Texas, Illinois, Michigan, Ohio, and Pennsylvania, as well as the mid-continent region, in general. The present study expands the existing database of 36 golf courses from 17 studies (6) with the addition of 44 golf courses from 29 studies encompassing over 20 years of data collection and adds the critical parameter, total phosphorus, to the analysis.

The present effort has greatly increased the spatial and temporal coverage of the dataset. Exceedances of pesticide water quality criteria in surface and ground water were infrequently observed. Total phosphorus concentrations in surface water appear to be the analyte of greatest concern, based on this database. It is appropriate for golf course superintendents to implement best management practices to reduce total phosphorus loading to the surrounding environment (13, 18).

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