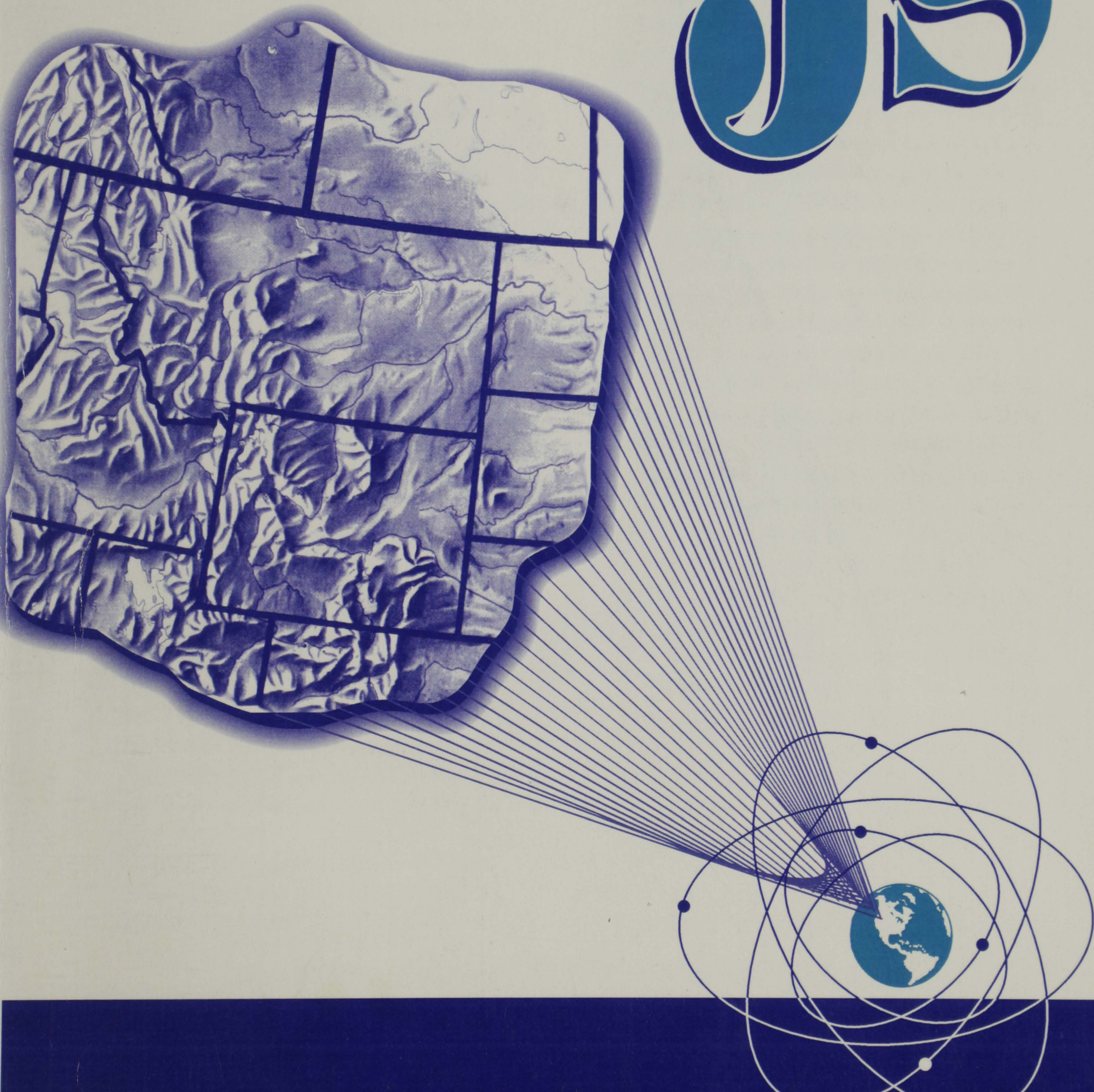
Intermountain Journal of Sciences

(ISSN 1081-3519)

Vol. 9, No. 2/3 - 2003



INTERMOUNTAIN JOURNAL OF SCIENCES

The Intermountain Journal of Sciences is a regional peer-reviewed journal that encourages scientists, educators and students to submit their research, management applications or view-points concerning the sciences applicable to the intermountain region. Original manuscripts dealing with biological, environmental engineering, mathematical, molecular-cellular, pharmaceutical, physical and social sciences are welcome.

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ISSN #1081-3519

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Manuscripts are submitted to the Editor-in-Chief (EIC) for initial consideration for publication in the IJS. This review shall include, but not be limited to, appropriateness for publication in this journal, correct formatting, and inclusion of a letter of submittal by the author with information about the manuscript as stated in the "Guidelines for manuscripts submitted to the *Intermountain Journal of Sciences*" (Dusek 1995). This cover letter must also include a statement by the author that this paper has not been submitted for publication or published elsewhere. The EIC notes the date of receipt of the manuscript and assigns it a reference number, IJS-xxxx. The EIC forwards a letter of manuscript receipt and the reference number to the corresponding author. The corresponding author is the author who signed the submittal letter.

Three hard copies of the submitted manuscript, with copies of the "Guidelines and checklist for IJS referees" attached are forwarded to the appropriate Associate Editor. The Associate Editor retains one coy of the manuscript and guidelines for his/her review, and submits a similar package to each of two other reviewers. A minimum of two reviewers, including the Associate Editor, is required for each manuscript. The two other reviewers are instructed to return the manuscript and their comments to the Associate Editor, who completes and returns to the EIC a blue "Cover Form" and all manuscripts and reviewer comments plus a recommendation for publication, with or without revisions, or rejection of the manuscript. This initial review process is limited to 30 days.

The EIC reviews the recommendation and all comments. The EIC then notifies the corresponding author of the results of the review and the publication decision.

ACCEPTANCE

For accepted manuscripts, each copy of the manuscript containing comments thereon and other comments are returned to the corresponding author. Revised manuscripts are to be returned to the EIC in hard copy, four copies if further review is required, or one hard copy plus the computer disk if only minor revision or formatting is necessary. The revised manuscript shall be returned to the EIC within 14 days of the notification. Review of the revised manuscript by the Associate Editor and reviewers shall be completed and returned to the EIC within 14 days. An accepted manuscript will then be forwarded to the Managing Editor (ME) for final processing.

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Each manuscript that is rejected for publication is returned by the EIC to the corresponding author along with the reasons for rejection. The author is also advised that the manuscript may be resubmitted, provided all major criticisms and comments have been addressed in the new manuscript. The new manuscript may be returned to the initial review process if deemed appropriate by the EIC. If the manuscript is rejected a second time by either the EIC or the Associate Editor and reviewers, no further consideration will be given for publication of the manuscript in IJS. The corresponding author will be notified of this decision.

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The identity of all reviewers shall remain anonymous to the authors, called a blind review process. All criticisms or comments by authors shall be directed to the EIC; they may be referred to the ME or the Editorial Board by the EIC for resolution.

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Each manuscript submitted by an Associate Editor shall be reviewed by the EIC and a minimum of two other reviewers with expertise in the subject being addressed. Each manuscript submitted by the EIC shall be forwarded with the necessary review materials to the Chairman of the Editorial Board of IJS, who will serve as the EIC for that manuscript.

ABSTRACTS

Only abstracts from the annual meetings of the sponsoring organizations will be published in IJS. Other submissions of abstracts shall be considered on a case-by-case basis by the Editorial Board. Sponsoring organizations shall collect abstracts, review them for subject accuracy, key or scan them onto a 3.5" diskette, and submit the diskette and hard copy of each abstract to the EIC on or before November 1. Each abstract shall be reviewed by the EIC to assure proper grammar, compliance with IJS "Guidelines for Abstracts Only" and for assignment to the appropriate discipline section. All abstracts will be published in the December issue only.

COMMENTARY

Submissions concerning management applications or viewpoints concerning current scientific or social issues of interest to the Intermountain region will be considered for publication in the "Commentary" Section. This section will feature concise, well-written manuscripts limited to 1,500 words. Commentaries will be limited to one per issue.

Submissions will be peer reviewed and page charges will be calculated at the same rate as for regular articles.

LITERATURE CITED

Dusek, Gary L. 1995. Guidelines for manuscripts submitted to the *Intermountain Journal of Sciences*. Int. J. Sci. 1(1):61-70.

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EFFECT OF ACUTE EXPOSURE TO CHLORINE, COPPER SULFATE, AND HEAT ON SURVIVAL OF NEW ZEALAND MUD SNAILS

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ABSTRACT

The New Zealand mud snail (*Potamopyrgus antipodarum*) is a recent invader to aquatic systems in North America. The biology, ecology, and contemporary distribution of New Zealand mud snails in Europe and Australia suggest that the snail will spread rapidly in North America. Because the species can seal the opening of the shell with its operculum and survive out of water in a moist environment for long periods, improperly cleaned fishing and other gear may facilitate their dispersal. A proposed solution is to provide cleaning stations for sterilization of equipment at public access sites along snail-infested waters. We assessed the acute effectiveness of several commonly used biocides on New Zealand mud snails. Lethal exposure tests were conducted over short durations using chlorine (Cl) and copper sulfate ($CuSO_4$) solutions, as well as heated water. Mortality of snails exposed to Cl at levels ranging from 500 to 3000 mg/L at all exposure durations rarely exceeded 30 percent. We observed similar results for dilute $CuSO_4$. Effectiveness increased with concentrations of $CuSO_4$ with mortality generally exceeding 60 percent for 100 and 1000 mg/L at all durations. Exposure to hot water at temperatures of 45 °C for 60 sec or 50 °C for 15 sec killed most of the snails, which suggested this treatment offered the best option for sterilizing field equipment of those tested.

Key words: acute toxicity, chlorine, copper sulfate, heat, New Zealand mud snail, *Potamopyrgus antipodarum*

INTRODUCTION

The New Zealand mud snail (*Potamopyrgus antipodarum*) (Gray 1843) is an exotic species recently introduced to North America (Zaranko et al. 1997). The history of its spread in Europe and Australia, where it was introduced in the 19th century and is now found across these continents (Bondesen and Kaiser 1949, Ponder 1988), suggests that the mud snail potentially could spread widely in North America. The mud snail was first found in North America in 1987 in the Snake River of eastern Idaho where it now occupies at least 640 km of river (Bowler 1991, Zaranko et al. 1997). Since then it has been found in streams of the Greater Yellowstone Ecosystem, the Great Lakes, the mouth of the Columbia River, the Owens River in California, the Colorado River in the Grand Canyon, and several other streams in western North America (Zaranko et al. 1997, Gangloff 1998, D. L. Gustafson, Montana State University, personal communication).

Curtailing the spread of mud snails is important because invasive populations without natural predators or control mechanisms are often very successful and may ultimately negatively affect native invertebrate fauna and their food resources. Invasive populations of mud snails often increase rapidly because they are ovoviviparous (Winterbourn 1970), parthenogenetic (Wallace 1992), and can tolerate a broad range of environmental

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conditions (Jacobsen and Forbes 1997). In the United States and Europe, mud snail densities have been reported to exceed 100,000 individuals/m^2 (Dorgelo 1987, Gangloff et al. 1999). Mud snails now are the numerically dominant invertebrates in the Middle Snake River, Idaho, and in several streams in the Upper Madison River in Yellowstone National Park (Bowler 1991, Gangloff et al. 1999, Richards et al. 2001, Vanderloop and Hall 2001). However, direct evidence of the effect of mud snails on native macroinvertebrate assemblages is rare. In a spring creek of the Madison River drainage in fall, periphyton (the algal food resource of mud snails and many macroinvertebrates) biomass and density, and biomass of macroinvertebrate functional groups, e.g., grazers and gatherers, were lower where mud snail abundance was moderate (~30,000/m^2) than where mud snail abundance was low (~0-100/m^2) (Cada and Kerans 2002). On the other hand, Schreiber et al. (2002) showed that the mud snail facilitated colonization of native fauna in an Australian stream. Clearly, the effects of invasive mud snails on native macroinvertebrates are complex.

The mud snail is an excellent colonist. Fish and floating aquatic vegetation have been implicated as possible within-system dispersal vectors (Haynes et al. 1985, Ribi 1986). Long-range and between-system dispersal of mud snails are facilitated by their ability to use an operculum to seal the shell opening (Burch 1989), and tolerate significant periods out of water (25 days) in moist and shaded environments (Winterbourn 1970). Moreover, the mud snail's small size, i.e., typically <10 mm, makes it difficult to detect in vegetation, gravel, or other debris thought to be likely mediums of transport. Thus, fishing and outdoor equipment, e.g., neoprene waders and wetsuits, wading boots, aquatic sandals, canoes, kayaks, bait buckets, and tackle boxes, if improperly cleaned and dried, can possibly facilitate dispersal of this exotic snail.

Providing stations for anglers and boaters to sterilize potentially contaminated equipment has been proposed as a possible way to minimiz human-caused risk of mud snail dispersal beyond its present range. Sterilization methods such as chlorine solution (Cl), copper sulfate solution (CuSO4), and hot water have been proposed. To be useful a molluscicide needs to be 1) effective with short duration application, 2) cost-effective, and 3) environmentally benign. Chlorine solutions are inexpensive, become inert quickly in the environment, and are widely used to minimize transmission of water-born fish pathogens (Warren 1991). Copper sulfate is a widely used algacide but is also toxic to fish and invertebrates (Watson and Yanong 1989). Dr. Robert McMahon (Department of Biology, Texas A&M University) suggested that hot water (~ 50 °C) would effectively kill snails and is the least environmentally harmful option.

Our objective was to evaluate how well three recommended treatments—chlorine (Cl) and copper sulfate ($CuSO_4$) solutions and high water temperature—killed mud snails. We designed trials to simulate concentrations and durations that might be realistically used at equipment sterilization sites, e.g., short duration and rapid application, in the field.

MATERIALS AND METHODS

We collected mud snails used in these experiments from the Madison River near West Yellowstone and held them in aquaria at room temperature (~17 °C) at the Wild Trout Laboratory, Montana State University, Bozeman. These snails in the Greater Yellowstone Ecosystem are genetically identical to the Snake River population.

We exposed mud snails to multiple concentrations of chlorine and copper sulfate solutions and temperatures of water over a series of time intervals to determine the most effective treatment as measured by mortality. Clorox® (5.25% active ingredient) and de-chlorinated tap water were used to make a stock Cl solution that we diluted to five exposure concentrations of 250, 500, 1000, 2000, and 3000 mg/L (verified using a Hach® Chlorine Test Kit).

Snails were initially exposed to the three lower chlorine concentrations for 15, 30, and 60 sec. However, mortality was extremely low so we conducted a second series of tests using concentrations of 2000 and 3000 mg/L for 30, 60, and 90 sec. We made copper sulfate stock solution by dissolving 10 g of hydrated copper sulfate ($CuSO_4$ x $5H_2O$) in 1 L of de-chlorinated tap water. The stock solution was then diluted to three concentrations (10, 100, or 1000 mg/L) and mud snails were exposed for three time intervals (30, 60, and 90 sec) at each concentration. Snails were also exposed to heated dechlorinated water at 40, 45 and 50 °C for 15, 30, or 60 sec. For each series of tests we included an appropriate control of either clean water or water at room temperature (~17 °C) (see Tables 1, 2, 3).

For each concentration and exposure interval, we conducted three replicates. A replicate consisted of five snails (in a few cases <5 snails were tested) that were placed in a strainer and then dipped into a beaker containing 1 L of the treatment solution. After exposure, snails were rinsed in plain de-chlorinated tap water and placed in a Petri dish with aquarium water. Because the treated mud snails held their opercula tightly closed for some time after exposure, survival was assessed 24 hrs after treatment. However, in some cases in which snails were exposed to copper sulfate, it was difficult to tell if the snails were dead at 24 hrs. A final determination of mortality was made at 72 hrs post exposure. We examined the snails in the Petri dish for movement by prodding with a probe or forceps. Dead snails exhibited no visible movement of the foot, head, tentacle, or operculum (in closed snails) after contact. We calculated mortality by combining all replicates for each treatment level (*n* = 15 typically) and dividing the total deaths by the total number of mud snails in each treatment level.

RESULTS

Chlorine treatments were moderately effective in killing mud snails (Table 1), and increasing the concentration and duration of chlorine exposures had little effect. All mud snails survived when exposed to 250-500 mg/L Cl for 15, 30, and 60 sec. Further, the mortality rates for the 1000 mg/L exposure were 0, 6.6, and 26.6 percent at 15, 30, and 60 sec, respectively. At 2000 mg/L, we observed a mortality rate of 13.3 percent for all exposures (30, 60, and 90 sec) and at 3000 mg/L we obtained mortality rates of 13.3, 33.3 and 20 percent, respectively (Table 1).

Copper sulfate was more effective than chlorine and snail mortality rates increased with $CuSO_4$ concentration (Table 2). Mortality increased from 0 percent in the control to 15, 73, and 93.4 percent after 90-sec exposures to 10, 100, and, 1000 mg/L respectively (Table 2).

Snails exposed to 40 °C water showed an increase in mortality rate with exposure time with a maximum of 28-percent mortality at 60 sec of exposure (Table 3). At water temperatures of 45 °C we attained 100-percent mortality after 60 sec of exposure. Water at 50 °C was lethal to snails at all exposure intervals (Table 3).

DISCUSSION

New Zealand mud snails proved remarkably resistant to chlorine treatments. Based on the results of these trials we suspect that most equipment contaminated with snails and field treated with chlorine at the levels and time intervals tested could still transport viable individuals to other locations. Increasing chlorine concentrations could improve effectiveness but might become irritating to mucus membranes of humans using the treatment and harmful to sensitive materials in recreational or research equipment, i.e., membranes, scales, fabrics.

Copper sulfate was more effective than chlorine but did not achieve 100-percent mortality at the levels and time intervals tested. An additional risk is its toxicity to a wide variety of non-target organisms at or below the levels tested, making it an undesirable solution in environmentally sensitive areas (Pimentel 1971). Even at

Table 1. Acute chlorine toxicity data for New Zealand mud snails showing treatment concentration, exposure time, total number living and dead snails in three replicates (24-hr post exposure), range (lowest and highest number of dead snails in a replicate), and percent mortality.

Concentration mg/L	Exposure (sec)	Number of snails Total/Dead	Range of dead snails per treatment	Mean % Mortality
0 (control)	15	15/0	0	0
0 (control)	30	15/0	0	0
0 (control)	60	15/0	0	0
250	15	15/0	0	0
250	30	15/0	0	0
250	60	14/1	0-1	7.1
500	15	15/0	0	0
500	30	15/0	0	0
500	60	13/0	0	0
1000	15	15/0	0	0
1000	30	15/1	0-1	6.7
1000	60	15/4	1-2	26.7
2000	30	15/2	0-2	13.3
2000	60	15/2	0-2	13.3
2000	90	15/2	0-2	13.3
3000	30	15/1	0-1	6.7
3000	60	15/5	1-2	33.3
3000	90	16/3	0-2	18.8

[1] Occasionally the number of snails in a replicated differed slightly from five.

Table 2. Acute copper sulfate solution ($CuSO_4 \cdot 5H_2O$) toxicity data for New Zealand mud snails showing treatment concentration, exposure time, total number living and dead snails in three replicates (72-hr post exposure), range (lowest and highest number of dead snails in a replicate), and percent mortality.

Concentration mg/L	Exposure (sec)	Number of snails Total/Dead	Range of dead snails per treatment	Mean % Mortality
0 (control)	30	15/0	0	0
0 (control)	60	15/0	0	0
0 (control)	90	15/0	0	0
10	30	15/3	0-2	20.0
10	60	15/1	0-1	6.7
10	90	15/2	0-2	13.3
100	30	15/9	2-4	60.0
100	60	15/7	1-3	46.7
100	90	15/11	2-5	73.3
1000	30	15/12	2-5	80
1000	60	10/8	4	80
1000	90	15/14	4-5	93.3

[1] Occasionally the number of snails in a replicated differed slightly from five.

Table 3. Acute temperature exposure data for New Zealand mud snails showing treatment temperature, exposure time, total number living and dead snails in three replicates (24-hr post exposure), range (lowest and highest number of dead snails in a replicate), and percent mortality.

Temperature °C	Exposure (sec)	Number of snails Total/Dead	Range of dead snails per treatment	Mean % Mortality
17 (control)	15	15/0	0	0
17 (control)	30	15/0	0	0
17 (control)	60	15/0	0	0
40	15	14/0	0	0
40	30	14/2	0-2	14.3
40	60	14/5	0-3	35.7
45	15	15/3	0-3	20.0
45	30	15/7	0-4	46.7
45	60	15/15	5	100
50	15	15/15	5	100
50	30	15/15	5	100
50	60	15/15	5	100

[1] Occasionally the number of snails in a replicated differed slightly from five.

recommended rates of application for algae control (1-2 mg/L), it may be toxic to trout, especially in low alkalinity waters. However, its toxicity to fish generally decreases as water hardness increases (Gangstad 1986). In addition, copper sulfate is toxic to aquatic invertebrates; the 96-hr LC50 for pond snails is 0.39 mg/L at 20 °C (U.S. National Library of Medicine, Hazardous Substances Databank 1995). Whereas the toxicity information is interesting, we note that a 96-hr LC 50 is not directly comparable to mortality in acute toxicity tests with exposures of 90 sec.

Heated water appears to be the most simple and effective way of killing mud snails. Hot tap water, which is usually about 49 °C (120 °F), may be the least likely of the tested sterilizing agents to cause environmental harm and would be relatively harmless to most types of equipment. Results of this experiment suggest that simply washing gear in hot water can effectively kill snails. Cleaning stations similar to those used to control the spread of the zebra mussel could be established at fishing access areas and would undoubtedly help contain New Zealand mud snails and other nuisance aquatic species. But ultimately, educating fishery workers, anglers, and boaters will be critical to stopping the spread of this and other exotic species. Anyone using or working in infested waters can and should take steps to disinfect their equipment.

ACKNOWLEDGEMENTS

We thank the anonymous reviewers for their thoughtful comments and suggestions and the Fish and Wildlife Service for providing funding that made this project possible.

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Received 29 March 2002
Accepted 30 May 2003

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SUCCESSFUL OUT-OF-SEASON SPAWNING OF WESTSLOPE CUTTHROAT TROUT MALES

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Key words: captive broodstock, *Onchorhynchus clarki lewisi*, spawning, westslope cutthroat trout

The present range of westslope cutthroat trout (*Onchorhynchus clarki lewisi*) is greatly reduced compared to the historic distribution of the subspecies. Degradation of the environment and competition with introduced species are considered major causes of the reduction (Liknes and Graham 1988). In response to declining populations of westslope cutthroat trout across Montana, the Montana Department of Fish, Wildlife and Parks developed a captive broodstock in the early 1980s to assist in conservation and restoration efforts. The broodstock is held at the Washoe Park trout hatchery in Anaconda, Montana.

In October 2002, we initiated a project to spawn wild males with captive broodstock females the following spring to relieve the broodstock of any genetic effects of prolonged hatchery rearing. However, synchronized availability of wild males and captive broodstock females was a concern.

Protocols for the project required collection of genetic and health samples from wild fish in possible donor streams. During health examinations, we found some males to have secondary sexual characteristics, i.e., kype/compressed body, and enlarged gonads. Additionally, we expressed milt from males not sacrificed for sampling. Because these collections took place in early October, months after the normal spring spawn timing of the species, the viability of the milt was unknown, but of interest.

Our objective was to determine if we could use sperm collected from out-of-season males to successfully fertilize eggs. If westslope cutthroat males successfully fertilize eggs several months away from the typical spawn time, wild westslope cutthroat males might be usable during captive broodstock spawning, just weeks before the normal spawn time. This information may also be valuable to biologists attempting to spawn wild fish in the field where asynchronous maturation or low numbers of spawners may be hindering efforts.

Eggs were collected from a fall spawning rainbow trout (*Oncorhynchus mykiss*) at the Jocko River trout hatchery in Arlee, Montana, on 19 November 2002. A random sample of eggs (~ 1500) from a pooled group of four females was transferred in a hard plastic container on ice to the Washoe Park hatchery (2 hr) and stored unfertilized in a refrigerator at 4 °C overnight. The following day, fish from 3-year-old westslope cutthroat broodstock were anaesthetized with tricaine methanesulfonate (MS-222). We found two males exhibiting secondary sexual characteristics from which milt could be freely expressed by gently squeezing the abdominal area. We used milt from these males to fertilize approximately one-half the eggs. Approximately 2 min post-fertilization, eggs were rinsed in fresh water, water-hardened in an iodine solution at 100 ppm for 20 min and placed into a partitioned heath tray for incubation at 13 °C.

Next, we found two males that exhibited secondary sexual characteristics but from which we could express little or no milt. The two males were lethally anaesthetized with MS-222 and transferred into the hatchery laboratory. One teste was surgically removed from each fish. The teste was placed on a sterile cutting board, cut into small pieces with a scalpel and the liquid/gel material poured onto the remaining eggs. After 2 min, eggs were rinsed in fresh water and handled in an identical manner as the previous group. We did not attempt to replicate groups and no control was utilized. Results represent a documented event rather than a controlled experiment. Therefore, we performed no statistical analyses.

Eye-up occurred at 14 days post-fertilization. Average eye-up for both groups of eggs was 69 percent. No difference in eye-up occurred between the group of eggs fertilized with sperm from live fish (68.7%) and eggs fertilized with sperm collected post mortem (69.2%). While the resulting fry would have been of interest to observe, we disposed of all eggs after evaluating eye-up due to the background of the contributing parents (rainbow x cutthroat).

Out-of-season spawning of other fish species is quite common when the rearing environment is manipulated. Kelly and Kohler (1996) induced channel catfish (*Ictalurus punctatus*) to spawn out-of-season using photothermal and hormonal manipulation. Mischke and Morris (1997) were able to induce sunfish (*Lepomis* spp.) to spawn over a 6-month period by manipulating temperature and photoperiod in a laboratory setting. It is noteworthy, however, that we made no attempt to manipulate any part of the environment of the westslope cutthroat males used in this experiment.

An additional incident of out-of-season spawning was observed at the Washoe Park hatchery. The hatchery has a visitor center with a living trout stream display that contains westslope cutthroat trout, arctic grayling (*Thymallus arcticus*), and a single rainbow trout. In November 2002, the rainbow trout female was observed building a redd in a riffle portion of the stream. During this time, we observed a westslope cutthroat male from the captive broodstock in typical courtship displays with female rainbow. Approximately one month later, we observed and photographed numerous sac fry in the gravel underneath the redd. Because no other fall spawning species were present in the display stream, we assumed that any offspring produced would be from that male or another westslope cutthroat male—grayling males were never observed in the area.

Our results and observations document two successful out-of-season spawning events of westslope cutthroat trout males. We are not aware of any other literature documenting successful out-of-season spawning of any strain of cutthroat trout. Because westslope cutthroat males successfully produced progeny so far from the typical spawning time, we believe that we can successfully collect viable milt from wild males during spring for spawning with captive broodstock.

In addition to benefiting captive broodstock, the fact that these males were fertile over an extended period may benefit biologists attempting to collect eggs from wild trout where asynchronous maturation is occurring, or where there is an attempt to fertilize eggs from neighboring populations. Using the techniques described here, a biologist should be able to use sperm from any known male to fertilize eggs. Additionally, sperm from one teste could be used immediately while the other teste could be transported to a neighboring population to fertilize other females, potentially doubling its use.

ACKNOWLEDGEMENTS

We wish to thank the Jocko River hatchery crew for providing the eggs used in this experiment. We also thank Michael E. Barnes and the anonymous peer reviewers for their critical review of this manuscript.

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Received 19 February 2003
Accepted 23 September 2003

EXOTIC PISCIVOROUS FISHES AND REDUCED INTERMITTENCE AFFECT SUCKERMOUTH MINNOWS IN A SOUTHEASTERN WYOMING STREAM

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Key words: conservation, irrigation diversion, *Phenacobius mirabilis*, suckermouth minnow

INTRODUCTION

Suckermouth minnows (*Phenacobius mirabilis*) are widespread throughout the central United States and are most abundant in streams and rivers of the upper Mississippi and lower Ohio river basins (Lee et al. 1980, Pflieger 1997). Stream systems in southeastern Wyoming and eastern Colorado represent the western boundary for suckermouth minnows (Lee et al. 1980). Recent sampling in Wyoming, i.e., since 1990, has identified only two suckermouth minnow populations: one in the lower Laramie River and one in Horse Creek. In the Laramie River, suckermouth minnows are rare, but a relatively abundant population occurs in a segment of Horse Creek. We describe the current distribution of suckermouth minnows in the Horse Creek watershed and identify factors that could affect their status and conservation.

Horse Creek originates in the Laramie Mountains and meets the North Platte River near Lyman, Nebraska (Rahel and Hubert 1991). Like most streams and rivers in southeastern Wyoming, Horse Creek has experienced extensive water development. Over 30 small impoundments and 40 diversion structures have been constructed in the watershed to store and divert water from the creek (Jeffrey Geyer, Wyoming State Engineer's Office, personal communication). Water is also diverted from the North Platte River to Horse Creek via the Fort Laramie Canal (Fig. 1). Approximately 5 km upstream from the point where the Fort Laramie Canal supplements flows in Horse Creek, the Springer Diversion Dam (~1 m high) spans Horse Creek and diverts water to storage reservoirs in the watershed. Fish assemblage structure and habitat characteristics of Horse Creek prior to settlement by Europeans are unknown. However, Horse Creek was probably similar to other streams in the western Great Plains having dynamic channels with fine substrate, variable flow, i.e., flood, intermittence, and thermal regimes, and fish assemblages dominated by cyprinids and catostomids (Baxter and Stone 1995). Large-bodied piscivores, e.g., centrarchids, were absent from streams in eastern Wyoming due to unstable flows and substrates.

Personnel from the University of Wyoming and Wyoming Game and Fish Department collected fish from 100- to 300-m reaches during 1960-2001 using electrofishing or seining techniques (see Baxter and Stone 1995, Rahel and Hubert 1991, Patton 1997). Surveys indicated that suckermouth minnows are restricted to a 25-km-long segment of Horse Creek between the mouths of Bear and Dry creeks (Fig. 1, Table 1). Exotic salmonids and several common native cyprinids dominated upstream of reaches containing suckermouth minnows, fish assemblages in

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[1] The Unit is jointly sponsored by the University of Wyoming, Wyoming Game and Fish Department, U.S. Geological Survey–Biological Resources Division, and Wildlife Management Institute.

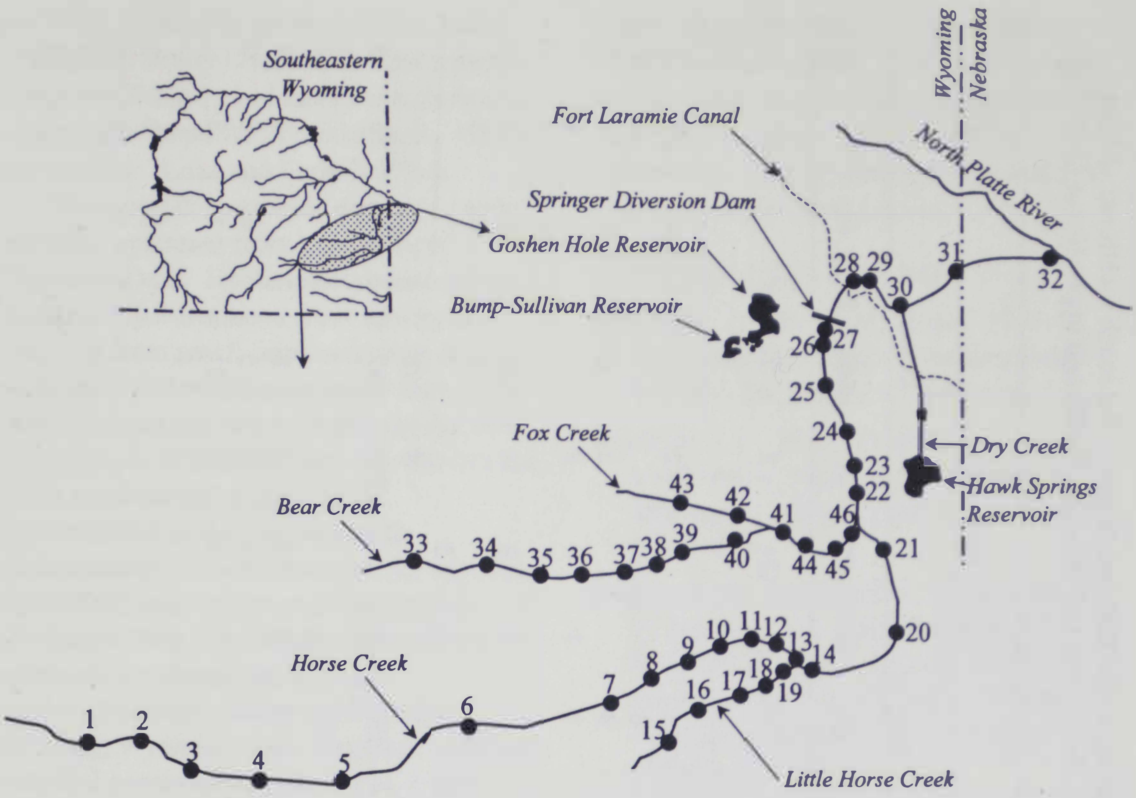

Figure 1. Location of stream reaches sampled in the Horse Creek drainage of Wyoming during 1960-2001.

Bear Creek and upper Horse Creek, i.e., reaches 1-21 (Table 1). In the stream segment where suckermouth minnows occurred, native cyprinids, stonecats, and plains killifish dominated fish assemblages. Conversely, reaches downstream of the suckermouth minnow segment of Horse Creek contained a variety of exotic piscivores including green sunfish, yellow perch, and largemouth bass.

Although these results do not identify specific mechanisms influencing suckermouth minnows, they suggest that water development and interactions with exotic piscivores have isolated the suckermouth minnow population in Horse Creek. We attributed absence of suckermouth minnows in upstream reaches, i.e., upstream of reach 22, to several factors. Water diversion structures are prevalent in lower Bear Creek and in the segment of Horse Creek between the mouths of Bear and Little Horse creeks (Fig. 1). Consequently, lower reaches of Bear Creek and most of Horse Creek between Bear and Little Horse creeks are frequently dewatered for most of the year. Exotic salmonids, e.g., brown trout, were common and often dominated fish assemblages in upstream reaches. Therefore, stream dessication, water diversion structures, and exotic piscivores likely limit upstream movement and persistence of suckermouth minnows in upstream reaches. Alternatively, the upstream distribution of suckermouth minnows may be limited by water temperature, as it is for other warm water species in Wyoming (Baxter and Stone 1995).

In downstream reaches, these data suggest that the distribution of suckermouth minnows was restricted by interactions with exotic piscivores. Suckermouth minnows were generally absent from reaches with introduced piscivores. Presence of a few suckermouth minnows in the two reaches immediately downstream of the Springer Diversion Dam likely resulted from downstream displacement from the abundant suckermouth minnow population

Table 1. Number of individuals sampled from specific reaches of lower Horse Creek during 1960-2001 (see Figure 1 for reach locations). Mean numbers of individual species sampled per reach and standard errors (in parentheses) for Bear Creek (i.e., reaches 35-46) and upper Horse Creek (i.e., reaches 1-19) are also provided.

		Bear Creek	Horse Creek													
			Upper								Lower					
Common name	Scientific name	35-46	1-19	20	21	22	23	24	25	26	27	28	29	30	31	32
Suckermouth minnow	*Phenacobius mirabilis*					10	2	2	10	124	3	1	5			
Brook trout	*Salvelinus fontinalis*	24 (9.9)	3 (2.0)													
Brown trout	*Salmo trutta*	5 (4.5)	7 (2.5)													
Creek chub	*Semotilus atromaculatus*	6 (2.4)	23 (11)	2	2		1	5			2	19	2	191	29	3
Longnose dace	*Rhinichthys cataractae*	6 (2.7)	15 (5.6)		27		2	6				1			3	1
White sucker	*Catostomus commersoni*	5 (1.8)	6 (2.1)				1	4			2	5		124	2	3
Johnny darter	*Etheostoma nigrum*	2 (0.7)	1 (0.6)		3	23	1	1	1	2	2				1	
Longnose sucker	*Catostomus catostomus*	1 (1.2)	20 (19.1)				3							11	3	
Bigmouth shiner	*Notropis dorsalis*	1 (0.3)	<0.5	3	3	2	1		2	2	15	15		10	3	
Fathead minnow	*Pimephales promelas*	<0.5	<0.5	1		3	3	10			1	1		6	3	
Central stoneroller	*Campostoma anomalum*	<0.5	<0.5	3		1		1	3	3						
Stonecat	*Noturus flavus*		1 (0.3)				32	1			2	26	3			
Sand shiner	*Notropis stramineus*	<0.5	<0.5	2	2	1	2	103	1		105	245	2		29	3
Common shiner	*Luxilus cornutus*	<0.5	<0.5				3									1
Brassy minnow	*Hybognathus hankinsoni*	<0.5		2	2				3				1			1
Plains killifish	*Fundulus zebrinus*					2	1	2	2	2	3	5	2		1	1
Common carp	*Cyprinus carpio*						3	1		3	5	5		5	3	3
Red shiner	*Cyprinella lutrensis*									3	10	11		1	3	
Black bullhead	*Ameiurus melas*										2	1				
Green sunfish	*Lepomis cyanellus*												1	3	3	2
Yellow perch	*Perca flavescens*												1	5	3	2
Largemouth bass	*Micropterus salmoides*															1
Quillback	*Carpiodes cyprinus*															3
Shorthead redhorse	*Moxostoma microlepidotum*															1

upstream. Similarly, plains killifish had a distribution nearly identical to suckermouth minnows (Table 1) and have been shown to be highly susceptible to predation by exotic centrarchids (Lohr and Fausch 1996).

No exotic centrarchids or percids were collected upstream from the Springer Diversion Dam. Exotic piscivores may be occasionally introduced from upstream resulting from small impoundments in the watershed, but exotic piscivores were only sampled from reaches with permanent flow. Therefore, it is unlikely they can survive the harsh environmental conditions characteristic of the segment with suckermouth minnows because the segment of Horse Creek upstream of the Springer Diversion Dam, i.e., where suckermouth minnows are abundant, becomes intermittent nearly every year (Gary Mehling, Wyoming State Engineer's Office, personal communication). Thus, water managers must allow enough water to enter the suckermouth minnow segment so that the stream does not become completely dewatered, while preventing permanent flow that allows exotic species to persist.

Although the ecological significance of suckermouth minnows in the western Great Plains is unknown, loss of any native species is considered detrimental to overall ecosystem function (Frissell 1993). The ecology and evolutionary history of suckermouth minnows in Horse Creek may be similar to many western Great Plains species. Exotic piscivores and reduced frequency of intermittence may be contributing to the decline of other native cyprinids throughout much of the western Great Plains and future research should focus on similar mechanisms causing declines of native fishes.

ACKNOWLEDGEMENTS

We thank Dirk Miller for assistance in obtaining fish assemblage information and Jeffrey Geyer and Gary Mehling for providing information on the irrigation system in Horse Creek. Carter Kruse and two anonymous reviewers provided helpful comments on an earlier draft of the manuscript. The Wyoming Game and Fish Department provided funding.

Received 30 April 2003
Accepted 21 July 2003

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RADAR MONITORING OF VERNAL BIRD MIGRATION IN CENTRAL MONTANA

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ABSTRACT

Marine surveillance radar was configured to determine distance from radar and height of birds within a 5600-m long east-west transect near the town of Judith Gap in spring 2002. Located in a physiographic gap between two mountain ranges, data were intended as control for impact studies related to proposed wind power development in the vicinity. A single echo or target displayed on the radar screen was considered an event and consisted of a single bird or many birds of one or several species. Highest event rate recorded was 716/hour on the night of 18 May and was the larger and second of two prominent peaks evident during the season. Detectability of events was a function of proximity to radar. Event rate was adjusted for radar detectability and defined as activity rate. Mean activity rate at night was over 2.5 times that of daylight. Daylight activity rates/100-m segment of transect were inversely correlated with topographical relief. Median height of night events (278 m) was 1.5 times higher than daylight events ($P < 0.001$). Median heights of daylight events/100-m segment of transect were inversely correlated with topographical relief ($P < 0.001$). A larger ($P < 0.001$) proportion (29.3%) of events in daylight were at or below maximum height of rotor swept area (105 m) of wind turbines proposed in the vicinity than night events (18.5%). Although an estimated 2 million birds may have passed over the radar transect in spring 2002, as many as 6.7 million may have passed through the Gap. Event rate may be an appropriate metric for impact analysis of future wind resource development.

Key Words: activity rate, birds, central Montana, height, radar, vernal migration

INTRODUCTION

Development of wind power resources in the western United States is increasing and additional sites are proposed or under consideration (National Renewable Energy Laboratory 2001). Considerable avian mortality induced by older wind energy developments, e.g., early stages of Altamont, California (Orloff and Flannery 1992), has increased scrutiny and review of proposed projects with respect to impacts on wildlife. Recent studies have recorded additional mortality of birds and bats associated with wind turbines in the United States (Erickson et al. 2002) and the contribution to cumulative impacts to bird populations may be cause for concern (Johnson et al. 2002). The USDI Fish and Wildlife Service and the wind power industry now recommend pre- and post-development monitoring of proposed wind resource areas to identify and manage impacts to natural resources, especially birds and bats (Anderson et al. 1999, USDI Fish and Wildlife Service 2002). Further, they recommend monitoring regimes be consistent with a Before–After, Control–Impact (BACI) study design (Green 1979).

Proposed wind power development in central Montana stimulated evaluation of avian activity in the vicinity of Judith Gap. Because many birds migrate at night (Evans and Mellinger 1999), radar (**RA**dio **D**etection **A**nd **R**anging) monitoring is a useful technique to study bird movements and assess impacts of resource development (Harmata et al. 1999). Therefore, a marine surveillance radar (MSR) monitoring system was employed to obtain a more complete picture of avian activity near Judith Gap in spring 2002. Study objectives were to (1) determine profiles of avian activity during spring migration, and (2) develop metrics of avian activity useful in impact assessment of any future wind power development in the Judith Gap area.

STUDY AREA

A site 6.4 km east and 0.4 km north of the town of Judith Gap, Wheatland County, in northcentral Montana (UTM = 602427E - 5170648N) was chosen for monitoring. Dominant wind directions are 196° (SSW) and between 350° and 15° (NNW to NNE). Sustained wind velocities ≥96 kph (60 mph) are common. Mean elevation of the area is 1490 m (4900 ft). Monitoring site was located between two east-west running mountain ranges, an assumed "migration focal point" (Kerlinger 1989). The monitoring site was on a small hill on a bluff in the approximate geographic center of the physiographic gap between the Snowy Mountains to the east and the Little Belt Mountains to the west. Land use within the gap was livestock grazing of native Northern shortgrass prairie and dryland crop production and was devoid of forest cover. The site permitted unimpeded radar scanning for at least 3 km due east and west of the site.

METHODS

Equipment

An X-band, 10-kilowatt Raytheon™ 1210XX MSR described by Harmata et al. (1999) was used for monitoring bird activity. The radar system was mounted on a vehicle and configured to determine height of birds above and respective horizontal distance from the radar (Harmata et al. 2003). This configuration created a vertical "curtain" of radar waves that radiated the length of the area scanned and expanded in width as it traveled at an angle of 25°. Objects penetrating the radar beam created a signature on the screen (Fig. 1) that permitted measurement of distance up to 133 km left, right, and above the radar antenna.

Harmata et al. (1998) found that data obtained at range setting 1.5 nm (2.8 km) best represented avian activity. This setting permitted monitoring of a 5.6-km east-west transect and height of 5.5 km above the radar. Range discrimination of the Raytheon 1210 XX MSR is < 20 m with a bearing accuracy of ± 1° at maximum surveillance range (Raytheon Marine Company 1995). Maximum error of height above radar calculation would be ± 40 m, but error probably was much less at a surveillance range of 2.8 km.

Data Recording and Management

Monitoring periods usually occurred between 2300 and 0300 hr nightly and 1100 and 1500 hr daily because avian activity rates at Norris Hill Wind Resource Area (NHWRA) in southwestern Montana were highest during these hours (Harmata et al. 1999). Attempts were made to make each monitoring period 90 min to minimize observer fatigue.

Number of monitoring periods/week varied between 0 and 3 to accommodate logistics, accidents, and weather while attempting to provide as close to an even distribution of effort over the season as possible. At the beginning of a monitoring period, observers oriented the vehicle so area scanned was perpendicular to the suspected direction of migrant bird flight, i.e., north. Heading data were obtained from an Electronic Heading Sensor, an accessory of the radar system, and assured the vehicle was positioned to obtain consistent coverage. The radar vehicle left the site after each monitoring period.

An individual target (echo, signature) displayed on the radar screen was considered an *event* (Fig. 1). As events appeared on the radar screen, observers positioned the cursor (a cross that appears on screen in "CURSOR" mode) on the event and recorded time, distance, and bearing from the radar displayed for the cursor position. Bearings usually fell between 0-90° and 270-359°. Events below the radar often were detected because

Figure 1. Screen of radar (center of concentric rings) in vertical mode displaying an event signature, probably a flock of Canada geese, moving from right (east) to left (west). Height of flock is approximately 470 m above radar. Horizontal irregular blob is ground level.

scanning arc extended to areas of elevation lower than the radar site. Each event and associated data were afforded a record line on the data sheet. If the event progressed across the screen (e.g., Fig. 1), position data at the lowest point were recorded.

Distance and bearing data in Microsoft® Excel 2000 files were imported to and analyzed in various modules of STATISTICA '99™ (StatSoft 1999). Distance and bearing were converted to horizontal distance from radar and height (above radar) by solution of right triangles. Formula for horizontal distance (left or right) from radar was (cosine (bearing-270))*d, where d = distance from radar to events. Height above radar level was calculated by (sine(bearing-270))*d.

Number of events detected overall, i.e., in daylight, at night, or by 100-m segment, were divided by respective hours of monitoring time expended and expressed as *event rate.*

Estimating Spatio-temporal Bird Numbers

Adjusting Event Numbers.—The probability of an observer detecting a target on screen was not evaluated but most likely was unaffected by position or rate of events. However, previous radar study (Harmata et al. 1998) indicated raw number of events displayed by radar did not reflect actual number or spatial distribution of events. The likelihood of events being detected by the radar decreased with increasing horizontal distance from the radar. Capacity of birds to reflect radar waves probably was more a function of configuration rather than mass, e.g., a B-117 stealth bomber probably has less reflective capacity than a White Pelican (*Pelecanus erythrorhynchos*) and a Prairie Falcon (*Falco mexicanus*) less than an American Crow (*Corvus brachyrhyncos*).

Event numbers adjusted for a decline in detection capability of the radar more accurately depicted numbers and spatial relationships. The radar was treated as an observer moving south along a transect parallel to assumed south-to-north travel direction of vernal migrant birds. Distances to events detected to the left or right (and above) were assigned to 1 of 50 horizontal 100-m segments emanating to the west (0 to -2500) and east (0 to +2500) of the radar site. Line transect analysis (Burnham et al. 1980) and program DISTANCE (Laake et al. 1993) were used to generate detection probabilities (Harmata et al. 1999). Observed frequencies of events for each category (daylight, night, or combined) on either side and above the radar were corrected for detectability by dividing the observed number in each segment by the respective detectability of that segment. Frequency of events/100-m segment/unit time was adjusted for detectability and defined as *activity rate*.

Profile of Vernal Migration.— In an effort to detect associations of activity rates with topography, the highest point of elevation in each 100-m distance interval of the scanning transect was determined from contour lines on 7.5-in topographical maps of the study area. This elevation was considered ground level in each 100-m distance interval because migrating birds would likely fly over local topography rather than around.

Magnitude of avian migration within radar range between 11 April and 2 June 2002 was crudely calculated by two estimation techniques. One estimator (N_e) was designed for comparison with other impact assessment categories (i.e., Before-Impact, etc.) and included only mean event rate/100-m segment/hour of monitoring. Resultant expression was $N_e = r_e * 56 * h$, where r_e = mean event rate, 56 = number of segments in scanned transect, and h = number of hours in the estimate period (703 for night; 994 for daylight; 1704 for the season). The other estimator (N_p) was an attempt to estimate avian vernal migrant populations passing through the gap. It included multipliers for detectability, i.e., activity rate) and mean/event flock size (3.5) determined at NHWRA in southwestern Montana (Harmata et al. 1998), but transect length was reduced to 50 segments. Resultant expression was $N_p = r_a * 50 * h * f$, where r_a = activity rate, 50 = number of segments in scanned transect and f = average number of birds/event (3.5).

Height of Bird Flights

Detectability adjustments were not incorporated in any analysis involving event height. Height of an event was categorized into 3 levels relative to configuration of wind turbines proposed for siting within Wheatland County (Leib, L., AMERESCO Energy Services, pers. comm.). Rotor swept area of these machines extends between 25 and 105 m above ground level and a collision "risk" may be presented to birds flying between these heights (Anderson et al. 1999). Height of events also was displayed relative to ground level in each 100-m distance interval of the scanning transect.

If any analysis indicated data were not normally distributed, nonparametric tests were employed. Tests used for specific data sets are indicated in Results. A difference was considered statistically significant if $P \leq 0.05$.

RESULTS

Radar Detections

Radar monitoring consumed a total of 31.7 hours between 11 April and 2 June 2002. Radar detected 3537 events during 23.2 hrs of 19 night monitoring sessions and 478 events during 8.6 hrs of 10 daylight monitoring sessions (Fig. 2).

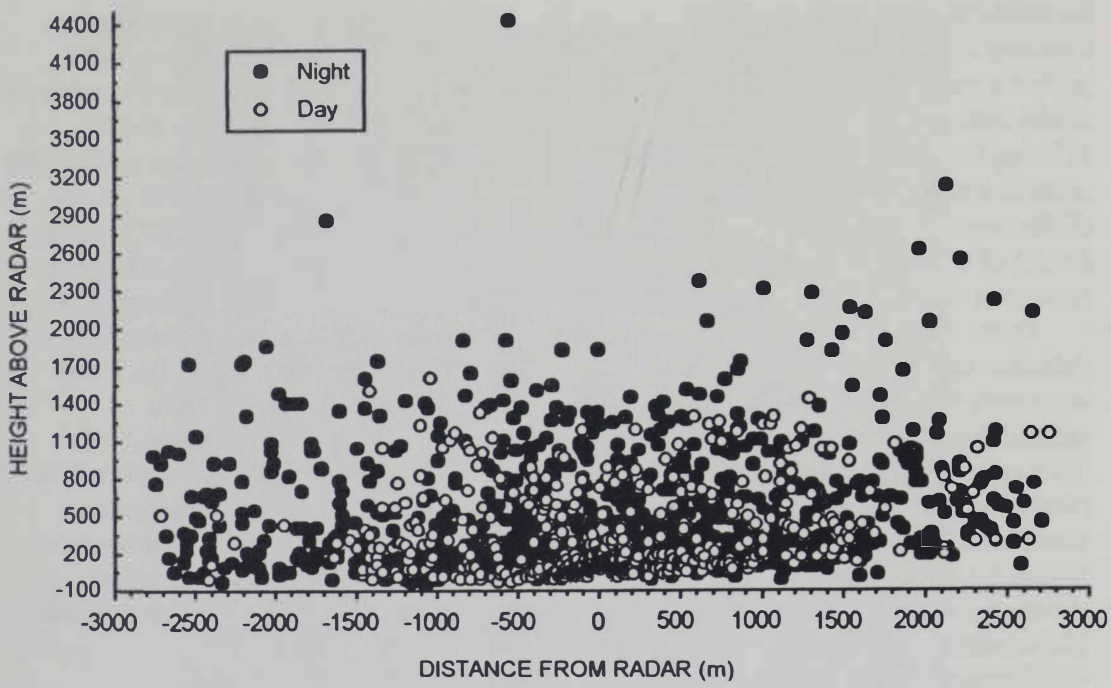

Figure 2. Events detected during radar monitoring of a 5600 m transect, 6.4 km east of Judith Gap, Wheatland Co., Montana, spring 2002. Open circles are daylight events, closed dots are night events. Radar site was located at distance 0. Right (+) is east, left (-) is west.

All events detected were assumed to be birds. No signatures displayed could be attributed to insects (Larkin 1991) and monitoring ceased before many bats returned to Montana or emerged from hibernacula (Flath, D. pers. comm.).

An event may have consisted of a single bird or many birds of one or several species, grouped tightly enough to present one signature on the display screen per antenna rotation (Harmata et al. 1999). Aircraft were easily distinguishable. Composition of night events, i.e., biological Class, Order, Family, species, could not be determined visually for obvious reasons and was beyond the scope of this study. However, characteristics of events confirmed visually in daylight suggested at least biological Class or group (waterfowl, passerine) of some events detected at night.

Rates of Vernal Migration

Event rates were higher at night (median = 121.8/hr, quartile range = 94.13) than in daylight (median = 50.8/hr, quartile range = 14.09) (Mann-Whitney $U = 17.00$, $P < 0.001$). Highest event rate for the season was 716 events/hr on the night of 18 May, the larger of two dramatic peaks evident during the season (Fig. 3). Respective night and daylight event rates by date were not correlated (Spearman's $Rho = 0.10$, $P = 0.873$). However, lack of daylight sampling (due to weather and logistics) in late April and mid May could have missed temporally correlative high event rates evident at night (Fig. 3).

Probability of event detection decreased as ground level distance from radar increased (Fig. 4). Mean night activity rate/100-m distance segment was > 2.5 times that of daylight (Mann-Whitney $U = 80.00$, $P < 0.001$) (Table 1). No correlation between night and daylight activity rates/100-m segment of the 5-km transect was found (Spearman's $Rho = 0.7$, $P < 0.62$). Daylight activity rates/100-m segment were inversely correlated with topographical relief (Spearman's $Rho = -0.32$, $P < 0.03$) but night rates were not (Fig. 5).

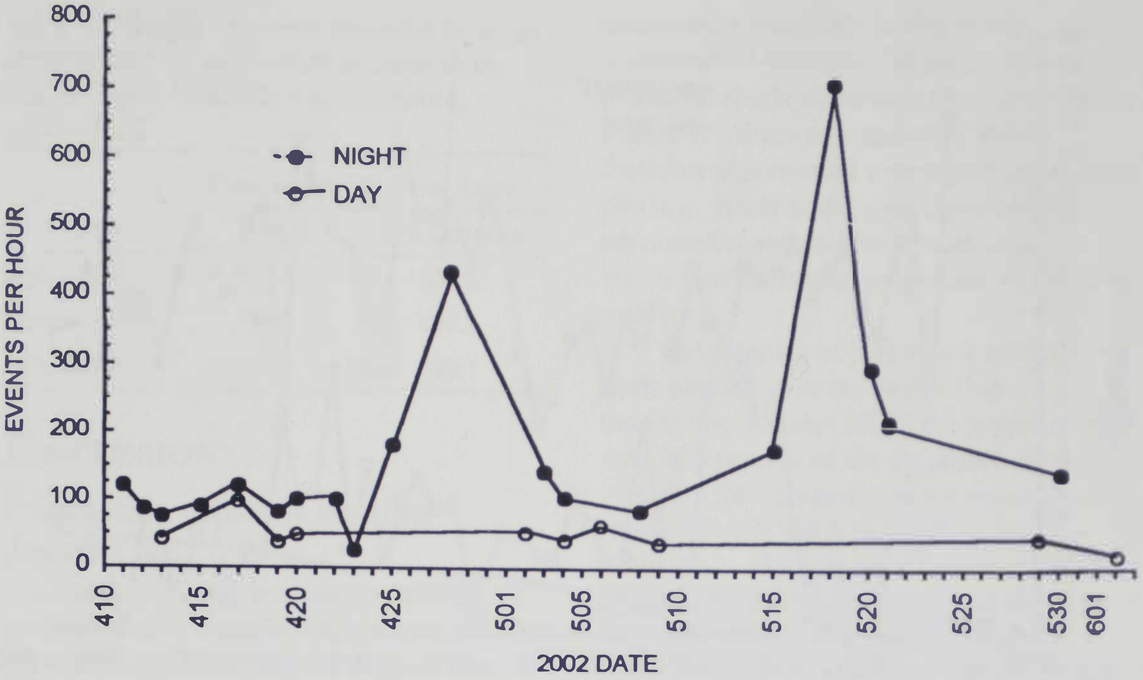

Figure 3. Seasonal night and daylight event rates recorded during radar monitoring near Judith Gap, Wheatland County, Montana, spring 2002

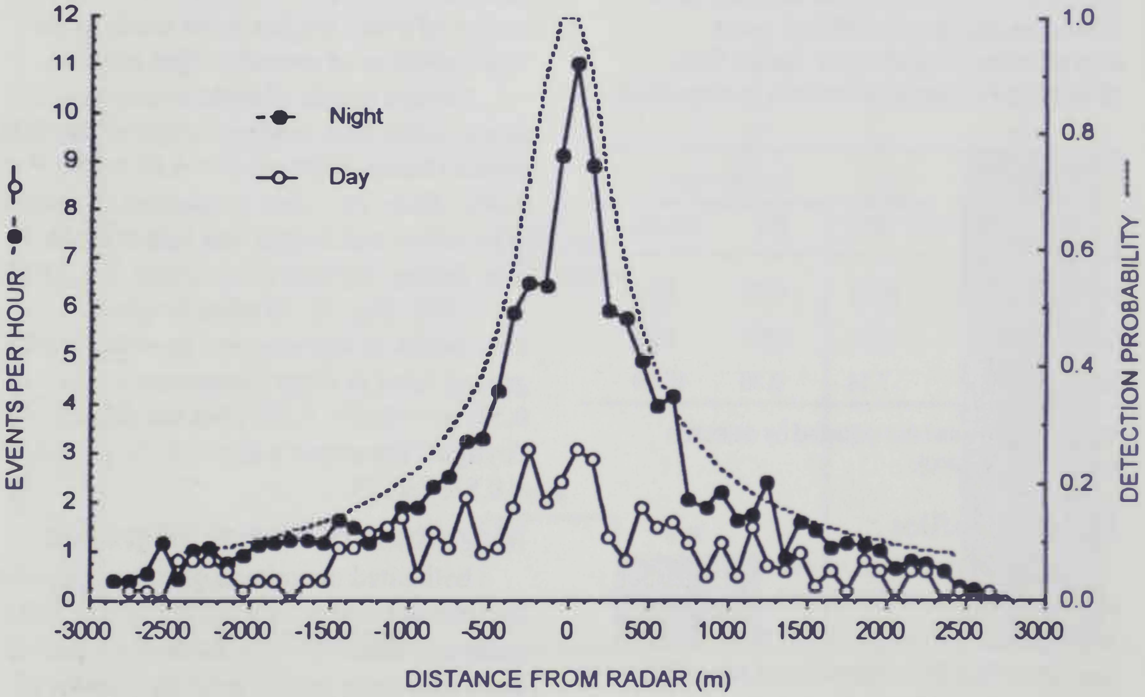

Figure 4. Event rates and detection probability (dotted line) at increasing distance from marine surveillance radar in vertical monitoring mode during night (closed circle) and daylight (open circle) monitoring near Judith Gap, Wheatland County, Montana, spring 2002. Right (+) is east, left (-) is west.

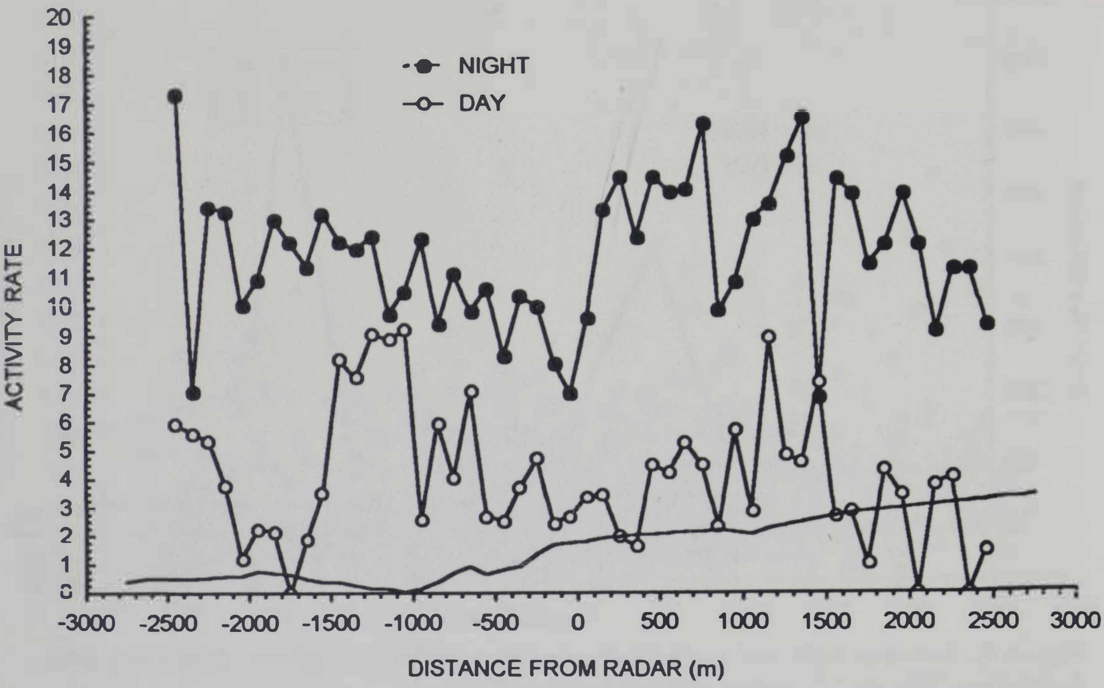

Figure 5. Night and daylight activity rates/100-m segment of a radar transect relative to ground level (irregular horizontal line) near Judith Gap, Wheatland County, Montana, spring 2002. Radar site was located at distance 0. Right (+) is east, left (-) is west.

Table 1. Avian migration activity rates/100-m segment of a 5000-m radar surveillance transect near Judith Gap, Wheatland County, Montana, spring 2002.

	Activity Rate[1]		
Diel (n)	$\bar{x}$	SE	Range
Night (50)	10.25	0.33	9.14
Daylight (50)	4.04	0.34	9.20
Total (110)	7.14	0.38	15.09

[1] Number of events/hour adjusted by detection probability (see text).

Height Profiles

Maximum height of events recorded above radar was 4420 m (19,400 ft msl) at night and 1604 m (10,100 ft msl) during daylight (Fig. 2); neither were aircraft. Heights of night and daylight events were not normally distributed (Shapiro-Wilk's $W > 0.79$, $P < 0.001$). Mean heights in some 100-m segments were skewed by a few very high events (e.g., Fig. 2). Therefore, analysis and display of medians and quartile ranges of event heights were much more representative of overall height profiles.

Median height of night events was 1.5 times higher than median height of daylight events (Mann-Whitney $U = 5.81 \times 10^5$, $P < 0.001$; Table 2). Also, proportion of events at or below risk height was less at night than during daylight (Bonferroni $Z = 2.933$, $P = 0.001$; Fig. 6). Median height of events/100-m segment was correlated with ground level at night (Spearman's $Rho = 0.52$, $n = 55$, $P < 0.001$) but not during daylight (Spearman's $Rho = 0.11$, $n = 37$, $P = 0.51$; Fig. 7).

Magnitude of Vernal Migration

Estimated magnitude of migration over the monitoring transect during spring 2002 exceeded 2 million (N_p, Table 3). Up to 423 birds may have passed over each meter of transect during the season and the majority (> 60%) at night. Number of birds estimated by event rate (N_e) averaged only 12.5 percent ($n = 3$, SD = 4.5) N_p (Table 3).

Table 2. Height of events detected by radar along a 5600-m east - west transect near Judith Gap, Wheatland Co., Montana, spring 2002.

	Event Height (m) Above Radar	
Diel (*n*)	Median	75% Quartiles
Night (3537)	278.8	135.2 - 534.8
Daylight (478)	186.0	90.2 - 480.2
Both (4015)	270.7	125.6 - 529.1

DISCUSSION

Population of Birds Passing Judith Gap

Calculating the migrant population passing over the monitoring transect (5600 m) with event rates (N_e, Table 3) resulted in an estimate of just over 200,000 events occurring between 11 April and 2 June. Clearly, single events often were composed of large numbers birds. One flock of Snow Geese (*Chen caerulescens*) observed over Judith Gap was composed of ≥ 300 birds and flocks of Canada Geese (*Branta canadensis*) observed farther south contained 20-60 birds. These events produced single signatures similar to that in Figure 1. Absolute number of events therefore represented only a portion of birds passing. Rates employing detectability adjustments are probably much more representative of true magnitude of avian activity.

The estimate of just over 2 million birds passing over the Judith Gap monitoring transect (5000 m) in spring 2002 was 58.8 percent of the estimated vernal migrants that passed over a comparable transect in NHWRA in southwestern Montana in 1995-96 (Harmata et al. 1998). Magnitude difference between study sites may be a result of the proximity of the NHWRA radar site to Ennis Lake, a strong ecological magnet and a historical migration stopover site for many species of birds. NHWRA was less than 4 km due north of Ennis Lake and many birds leaving the lake to continue northward flew directly over the radar site. Judith Gap is in a physiographic gap, but the actual portal is a

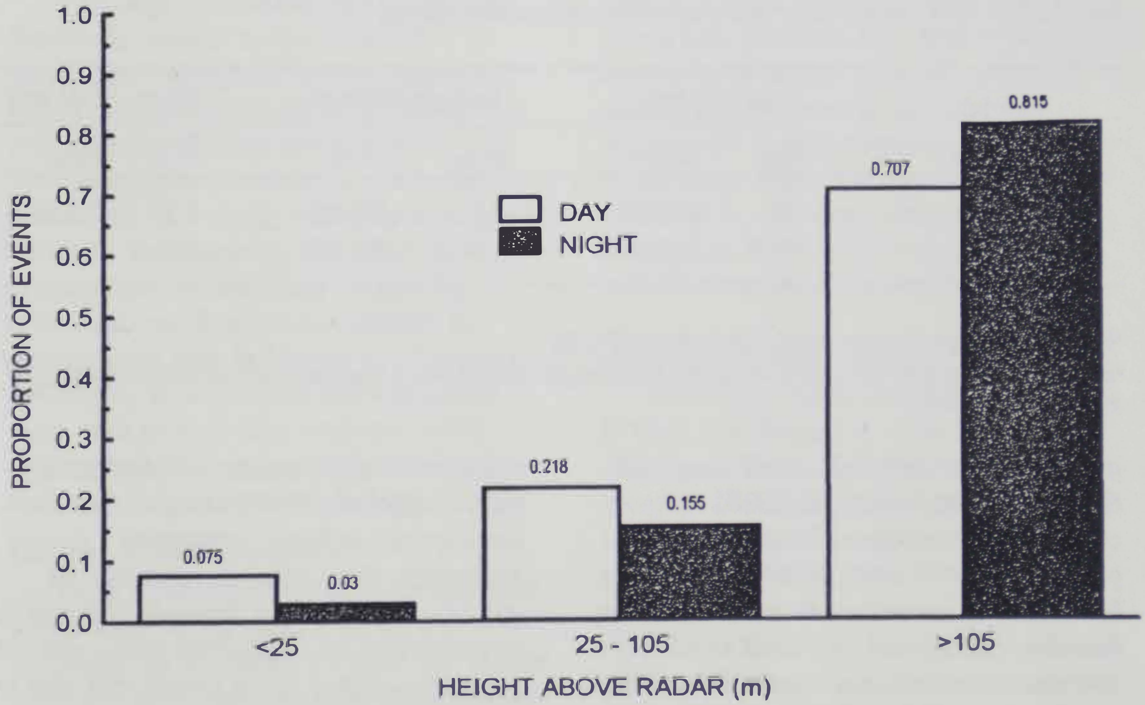

Figure 6. Height of events above radar during monitoring near Judith Gap, Wheatland County, Montana, spring 2002. Categories are relative to rotor swept area (25 – 105 m) of wind turbines proposed in the vicinity.

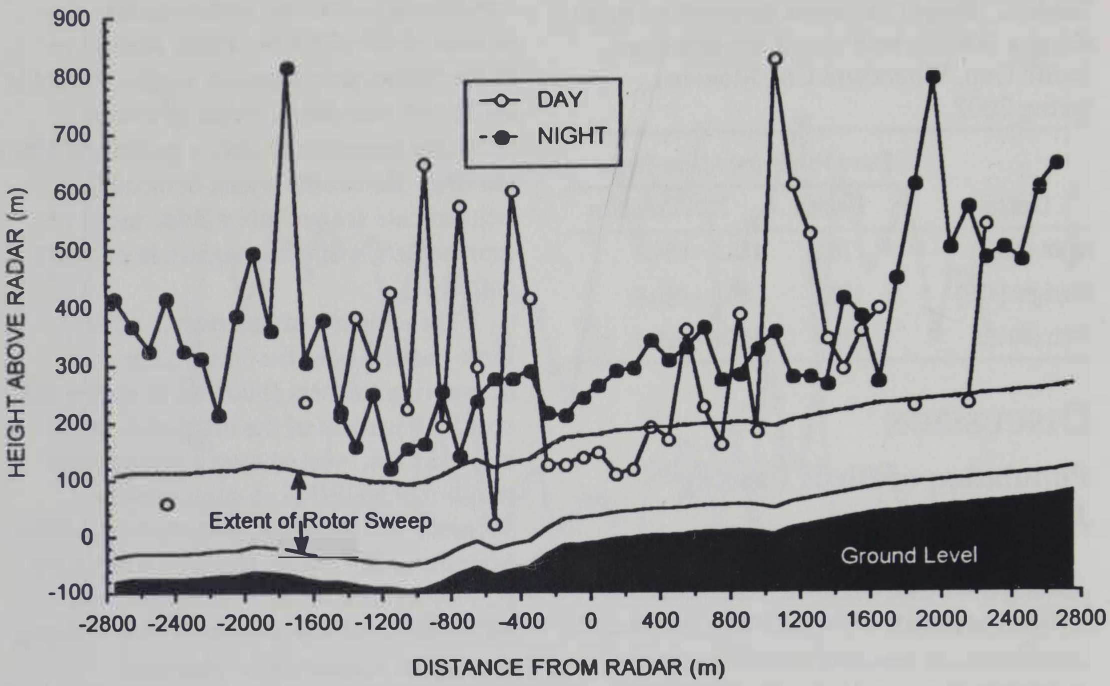

Figure 7. Median height of night and daylight events above radar and relative to ground level and rotor swept area of proposed wind turbines along a 5.6-km transect, near Judith Gap, Wheatland County, Montana, spring 2002 during. Perspective is from an observer south of the site, facing due north. Radar site is at distance and height 0. Turbines are not proposed for the site but for other sites in Wheatland County.

Table 3. Two estimators of numbers of birds flying over an east - west transect during radar monitoring near Judith Gap, Wheatland Co., Montana, spring 2002.

	Night (703 hrs)		Daylight (994 hrs)		Season (1704 hrs)	
Estimator	Rate	Birds	Rate	Birds	Rate	Birds
N_e[1]	2.8	110,230	2.2	122,460	2.5	238,560
N_p[2]	10.25	1,261,006	4.04	702,758	7.1	2,117,220

[1] Estimator uses event rate over a 5.6 km transect (Fig. 3).

[2] Estimator uses activity rate (event rate/radar detection probability) over a 5 km transect and a mean flock size multiplier (3.5/event).

minimum of 16 km wide. Birds may pass through the Gap widely dispersed or concentrated over the radar site or other portions, e.g., the foothills of the Snowy Mountains to the east, to disperse again on the other (north) side. If vernal avian movement were dispersed over the width of the Gap, as many as 6.7 million birds may pass through.

Although waterfowl were observed migrating over Judith Gap, behavior and signature of night events indicated many were composed of either single birds or small groups of birds, suggesting passerines, shorebirds, or other smaller species. Magnitude differences between the two sites may be a reflection of the relative population size of avian groups that tend to pass over them (i.e., waterfowl vs. passerines).

Interpretation of event composition may confound population estimates. It is unlikely multiple night events at high altitude in spring were composed of individual birds or flocks reversing direction or circling, passing through the radar beam several times. Such phenomena would over-estimate actual numbers. Many daylight events, however, were probably composed of multiple detections of a single bird and may have resulted in an over-estimate of daylight populations. Flock size multipliers used here also may be unrepresentative. Passerine flocks may consist of many more individuals than waterfowl flocks. Conversely, more events detected at Judith Gap may have consisted of single birds than those detected at NHWRA.

Timing of Migration

Peaks in night activity rates were evident in late April and mid May (Fig. 3). Radar monitoring 6 km farther south in Wheatland County in 2003 also showed temporally identical peaks in late April and mid May (Harmata 2003). Remarkably, timing and number of peaks in Wheatland County were nearly identical for vernal migrant birds at NHWRA.

Although movement may be episodic from influences of meteorological phenomena throughout spring, pulses in vernal migration of birds were clearly evident at Judith Gap and NHWRA. Movement may therefore be relatively predictable (± 1 week) each year throughout the state. Predictability has important implications for designing monitoring regimes to verify migration activity at development sites in Montana. Minimizing monitoring time to a few dates spanning these peak periods may produce results representative of seasonal migration and eliminate the need for season long effort.

Height Considerations

Only 3 percent of events were detected within 25 m above radar level during total darkness (Fig. 6). Many of these low events may have been Lark Buntings (*Calamospiza melanocorys*) because of similarity of signature behavior to their courtship flights. Most diurnal birds are not known to forage at night. Aside from courting, there seems to be little reason to be aerial at night other than to migrate. Additional height would facilitate avoidance of structures (trees, towers, topography) and migrating in darkness would facilitate avoidance of diurnally active predators. This and the dramatic difference in median height and activity rates between night and daylight events (Table 3) suggest most night events were indeed composed of migrant birds. Also, correlation of night heights with topographical relief suggests nocturnal migrant birds may fly at minimum height above ground level.

Impact Analysis Potential

Impact of resource development should be evaluated with adequate data on all aspects of a BACI study. Data generated for Judith Gap can well serve as "Before-Control" avian-activity data for proposed wind-power development. Determining values comparable to those presented here for proposed wind resource areas pre-construction (Before-Impact) may assist in evaluating impacts of development post-construction, if proposed sites are not too distant in space (> 50 km) or time (> 5 yrs). Event rates (Table 3, Fig. 4) may be used in comparisons instead of activity rates, eliminating the need for detectability adjustments in post-construction monitoring. Effect or impact may be indicated by statistical changes in these values (i.e., $P \leq 0.05$) or other biological criteria when considered with controls.

ACKNOWLEDGEMENTS

Rosemary Jaffe, Greg Leighty, Eric O'Neil, and Helga Pac served as radar observers. Kevin Podruzny applied program DISTANCE for detectability analyses. Sam Milodragovich assisted in preliminary site surveys. Funding was provided by Montana State University and AMERESCO Energy Services. H. Brooks graciously allowed us to monitor birds from his ranch property. Judith Gap Mercantile and Miller's Trucking, Judith Gap, Montana provided repair and logistical support. Jay

Rotella provided helpful comments on earlier drafts.

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Received 27 May 2003
Accepted 1 September 2003

INVERTABRATE ABUNDANCE AND BIOMASS DISTRIBUTION PATTERNS IN WESTERN AND CENTRAL MONTANA

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ABSTRACT

We measured terrestrial invertebrate abundance and biomass at six different locations in western and central Montana from 2000 to 2002. Habitats at these sites included grass, shrub, or forest. Each of the three habitats occurred at two separate locations. At each site, 10 pitfall traps were constructed and sampled on a monthly basis from June through October. We searched for 15 taxonomic orders or classes and found all but two. Grass habitats had the highest invertebrate abundance and biomass followed by shrub and forest habitats respectively. Terrestrial invertebrate abundance and biomass were highest in mid-to-late summer (July and August) in western and central Montana. Average peak invertebrate abundance occurred in August and average peak invertebrate biomass occurred in July.

Key words: abundance, biomass, class, forest, grass, habitat, invertebrates, order, shrub

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INTRODUCTION

We studied invertebrates as possible food sources for small mammals that carry Sin Nombre virus (SNV), a hantavirus that has been contracted in Montana. The invertebrate study was part of an ongoing longitudinal hantavirus study (Douglass et al 1996). Invertebrates are known to be food sources for small mammals such as shrews, voles, and mice (Burt and Grossenheider 1980). White-footed mice (*Peromyscus leucopus*) have been found to be the major predator of gypsy moth pupae (Hastings et al 2002). In western Montana, 84-86 percent of deer mouse (*P. maniculatus*), the major SNV vector, winter diets can consist of gall fly larvae (Pearson 1999).

During the longitudinal SNV rodent study, we had the opportunity to incorporate a survey of invertebrates at several locations in western and central Montana. The objective of our invertebrate study was to describe invertebrate animal communities by order or class in three general habitat types. To the best of our knowledge, terrestrial invertebrate communities have not been studied in Montana on a broad geographic scale. Because of the lack of published material relating to our objectives, and the fact that *Peromyscus* species demonstrate opportunistic food habits, we initiated our investigations with an initial broad scale inventory of invertebrates. Terrestrial invertebrates are active in Montana seasonally and are limited by temperature. Winter typically lasts from October until April, which gives terrestrial invertebrates up to six months of activity in a wide variety of habitats. We sampled invertebrate communities from May through October 2000-2002. Our data will be useful in understanding deer mouse population ecology and the SNV cycle and provides new information concerning invertebrate communities in Montana.

METHODS AND MATERIALS

We studied invertebrates at six different locations in western and central Montana (Fig. 1). The sites were near Wisdom, Polson, Gold Creek, Cut Bank, Cascade, and on the C. M. Russell National Wildlife Refuge. Because the study was conducted concurrently with the long-term

Figure 1. Locations and habitat types of invertebrate collection sites in Montana. Locations are associated with longitudinal small mammal – hantavirus studies.

longitudinal hantavirus research, all study sites were on the same study grids (100 X 100 m) as the hantavirus project (Douglass 1996). We classified each site as forest, shrub, or grass habitat. Topography was variable among sites and elevations ranged from 738 to 1957 m.

We did not intend this study to be a comprehensive analysis of invertebrate communities. We used pitfall traps in order to capture invertebrates that best represented what deer mice could use as a food. At each site, 10 pitfall traps were constructed at 15.7-m intervals. Two 355-ml (12-oz) plastic cups were placed one inside the other in the ground so the tops of the cups were level with the ground. The bottom cup provided a foundation and easy removal of the top cup. A 15-cm mesh, metal ladder was placed in the top cup to allow small mammals to escape. The top cup was filled one third full of "low-tox" antifreeze to kill invertebrates and to keep the cups' contents from freezing. A 30 X 30 cm board, weighted with rocks or sticks, was placed over the trap about 3 cm off the ground to allow invertebrates access, as well as keeping other animals and precipitation from disturbing the trap.

From 2000 to 2002, invertebrate collections were completed at one-month intervals from June through October with the exception of the Wisdom site, which was sampled July through October due to inaccessibility in June because of snow. On the day of collection, the cups' contents were poured through a strainer and invertebrates were removed and placed in individually marked plastic vials filled with isopropyl alcohol. Each pitfall trap was reset before moving on to the next trap.

Later, we extracted all non-invertebrate debris from each vial. Invertebrates were identified to their taxonomic order or class with the aid of a dissecting microscope. We measured wet biomass to 0.01 gm using a digital balance, recorded total numbers and biomass of each order or class from each individual pitfall trap site, and entered the data into a computer data base for analysis.

RESULTS

We searched for 15 taxonomic orders within three taxonomic classes during the project (class Crustacea; order Isopoda, class Arachnida; order Araneida, class

Insecta; orders Coleoptera, Collembola, Dermatera, Diplura, Hemiptera, Hymenoptera, Isoptera, Lepidoptera, Neuroptera, Orthoptera, Thysanura, Diptura, and Homoptera). In addition, two classes, Chilopoda and Diplopoda, were found but not identified to order. Only two orders, Diplura and Neuroptera, of the 15 initially chosen were not identified during the project.

Several orders and one class were abundant. We calculated the average number and biomass of invertebrates/month (sampling period) by class or order over the course of the three-year study (Table 1). We found that in terms of abundance over three summers, Hymenoptera, which consisted mainly of ants, was most abundant ($\bar{x}$ = 100.2 individuals/month) for all six study sites. The following included average number of individuals for other groups: Orthoptera ($\bar{x}$= 61.0/month), Araneida ($\bar{x}$ = 59.4/month), Diptera ($\bar{x}$ = 55.1/month), Coleoptera ($\bar{x}$ = 53.8/month), and Diplopoda ($\bar{x}$ = 40.4/month). Orthoptera (mainly grasshoppers and crickets), Araneida (spiders), Diptera (flies), and Coleoptera (beetles) were common orders found among all six study sites. However, Diplopoda (millipedes) was mainly collected (89% of all collected Diplopodans) at the Gold Creek site. The ranking from highest three-year average invertebrate abundance to lowest by site (Table 2) was Cascade (542.4), Gold Creek (511.6), Cut Bank (407.7), Polson (396.9), CMR (395.6), and Wisdom (312.7).

The most productive, i.e., highest average biomass/month, taxonomic group over 3 years for the combined study sites was Orthoptera ($\bar{x}$ = 18.2 g; Table 1). While Orthopterans were most abundant and individual body size was larger than other orders/classes, which in turn produced an average biomass more than twice that of other orders/classes except Coleoptera ($\bar{x}$ = 11.6 g). Diplopoda ($\bar{x}$ 6.1 g), Hymenoptera ($\bar{x}$ = 2.9 g), Araneida ($\bar{x}$ = 2.9 g), and Diptura ($\bar{x}$ = 1.8 g) were also among the highest in average biomass. The most productive sites from most to least by 3-yr average biomass/sampling period (Table 2) were Cascade (64.8 g), Gold Creek (53.1 g), CMR (52.6 g), Cut Bank (50.7 g), Polson (24.5 g), and Wisdom (14.5).

As noted above for Diplopoda, certain orders or classes were strongly associated with certain habitats/sites. We found Phalangida (daddy-long legs) to be very abundant in a grassland at the Cascade study site but not at other study sites. Eighty-eight percent of all Phalangidans were collected at Cascade. Thysanura was strongly associated with sagebrush at the Polson study site and consisted of nearly 98 percent of all Thysanurans collected from all sites. Homoptera was very common in the grassland at Cascade (but absent from grassland at Cutbank) and consisted of 93 percent of all Homopteran specimens collected from all sites. Table 2 shows the most productive sites in relation to each taxonomic order or class.

Abundance of orders/classes was also analyzed by sampling period (Table 1). Over three years, the highest average abundance peaked during the August sampling period at 569.3 invertebrates. Abundance gradually increased until August and gradually declined after the August sampling period. Biomass, however, was variable among the 6-month sampling period. Average biomass started at 43.2 g on average in June, peaked in July with 59.0 g, fell to 53.8 g in August, increased to 55.8 g in September and then dropped to 17.6 g in October. Some of the low biomass in June resulted from not including the Wisdom site, which was not sampled due to accumulations of snow. Additionally during June 2001, collections were completed at all sites but misplaced, and thus, limiting our samples to only four periods for 2001 (Jul-Oct).

Of the six most abundant orders/class, average numbers of three (Araneida, Diplopoda and Diptura) peaked during August. Average numbers of Coleoptera and Hymenoptera were highest in June; and average numbers of Orthoptera peaked in September. The respective highest to lowest average invertebrate biomass/year

Table 1. Invertebrate abundance and biomass averaged for six locations in central and western Montana for five sampling periods from 2000 through 2002.

		ABUNDANCE							BIOMASS (grams)					
Order	Common Name	June	July	August	Sept	Oct	3 yr. Avg.		June	July	August	Sept	Oct	3 yr. Avg.
Isopoda	Sowbugs (pillbugs)	2.0	0.7	2.2	0.7	0.3	1.1		0.1	0.0	0.1	0.0	0.0	0.03
Araneida	Spiders	61.0	72.6	83.2	50.3	30.6	59.4		3.1	4.3	3.3	2.2	1.7	2.9
Phalangida	Harvestmen & daddy-l.l.	28.9	23.3	14.6	18.3	12.1	18.5		1.2	1.2	0.7	1.1	0.7	1.0
Chilopoda (class)	Centipedes	1.2	1.9	1.4	1.9	1.9	1.7		0.0	0.2	0.1	0.1	0.1	0.1
Diplopoda (class)	Millipedes	14.9	42.3	72.6	39.4	21.4	40.4		1.5	6.3	10.2	7.9	2.6	6.1
Coleoptera	Beetles	91.3	86.1	52.2	40.4	15.5	53.8		18.7	19.2	10.6	10.4	2.3	11.6
Collembola	Springtails	0.7	0.0	0.0	0.7	0.0	0.2		0.0	0.0	0.0	0.1	0.0	0.02
Dermaptera	Earwigs	0.0	0.0	0.0	0.0	0.1	0.01		0.0	0.0	0.0	0.0	0.0	0.04
Diplura	Diplurans	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0
Hemiptera	True bugs	0.0	1.0	0.2	0.8	0.0	0.4		0.0	0.0	0.0	0.0	0.0	0.0
Hymenoptera	Ants, terrestrial wasps	184.4	152.8	118.5	67.5	19.9	100.2		4.5	5.6	2.6	1.9	0.6	2.9
Isoptera	Terrestrial termites	0.1	0.2	0.1	0.0	0.0	0.1		0.0	0.0	0.0	0.0	0.0	0.0
Lepidoptera	Larvae only (caterpillars)	3.1	2.8	1.7	7.3	0.9	3.2		0.6	0.6	0.2	0.2	0.1	0.3
Neuroptera	Antlions	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0
Orthoptera	Grasshoppers, crickets,	29.8	63.7	72.7	91.4	31.7	61.0		12.1	20.1	21.0	26.8	8.2	18.2
Thysanura	Silverfish, Bristletails	0.8	6.3	19.6	9.7	2.4	8.5		0.0	0.1	0.3	0.2	0.1	0.1
Diptura	Flies	16.7	26.8	106.2	67.7	38.7	55.1		0.7	0.7	3.4	2.7	1.0	1.8
Homoptera	Cicads, Aphids	0.2	5.8	4.2	31.6	0.0	9.3		0.0	0.2	0.0	0.8	0.0	0.2
Lepidoptera	Butterflies, Moths	9.3	2.8	6.7	5.3	0.9	4.5		0.7	0.3	1.2	1.1	0.1	0.7
Other:		1.6	6.0	13.3	13.4	4.5	8.5		0.0	0.3	0.2	0.2	0.1	0.2
	Total	446.0	495.0	569.3	446.2	180.8		**Total**	43.3	59.0	53.8	55.8	17.6	

Table 2. Three year average invertebrate abundance and biomass for each of six locations in western and central Montana from 2000 through 2002.

				ABUNDANCE			
Order	**Common Name**	**Cascade**	**CMR**	**Cutbank**	**Gold Cr.**	**Polson**	**Wisdom**
Isopoda	Sowbugs (pillbugs)	1.8	0.0	0.0	0.0	4.6	0.0
Araneida	Spiders	39.9	76.9	44.5	60.0	63.6	73.4
Phalangida	Harvestmen & daddy-l.l.	95.6	2.5	0.3	9.3	0.4	0.6
Chilopoda (class)	Centipedes	1.4	1.1	3.2	0.8	0.3	3.8
Diplopoda (class)	Millipedes	0.2	25.4	0.0	210.8	0.1	0.0
Coleoptera	Beetles	47.7	20.8	92.6	74.9	33.2	53.2
Collembola	Springtails	0.0	0.0	0.5	0.9	0.0	0.0
Dermaptera	Earwigs	0.1	0.0	0.0	0.0	0.0	0.0
Diplura	Diplurans	0.0	0.0	0.0	0.0	0.0	0.0
Hemiptera	True bugs	0.0	0.3	1.3	0.0	0.7	0.3
Hymenoptera	Ants, terrestrial wasps	108.0	36.9	47.9	117.2	184.1	119.3
Isoptera	Terrestrial termites	0.0	0.0	0.0	0.1	0.1	0.3
Lepidoptera	Larvae only (caterpillars)	11.1	0.6	1.1	2.4	2.8	0.3
Neuroptera	Antlions	0.0	0.0	0.0	0.0	0.0	0.0
Orthoptera	Grasshoppers, crickets,	98.8	115.2	116.7	4.9	29.1	8.8
Thysanura	Silverfish, Bristletails	0.1	0.2	0.2	0.4	48.3	0.0
Diptura	Flies	74.6	101.9	80.9	21.6	19.1	34.5
Homoptera	Cicads, Aphids	50.1	1.1	0.0	0.6	0.2	1.9
Lepidoptera	Butterflies, Moths	4.9	3.4	11.4	0.1	7.6	0.1
Other:		8.1	9.5	7.1	7.5	2.7	16.3
	Total	**542.4**	**395.6**	**407.7**	**511.6**	**396.9**	**312.7**

				BIOMASS (grams)			
Order	**Common Name**	**Cascade**	**CMR**	**Cutbank**	**Gold Cr.**	**Polson**	**Wisdom**
Isopoda	Sowbugs (pillbugs)	0.0	0.0	0.0	0.0	0.1	0.0
Araneida	Spiders	1.9	0.4	2.2	3.5	3.1	3.7
Phalangida	Harvestmen & daddy-l.l.	5.0	0.2	0.0	0.4	0.0	0.0
Chilopoda (class)	Centipedes	0.3	0.1	0.2	0.0	0.0	0.1
Diplopoda (class)	Millipedes	0.0	2.4	0.0	33.4	0.0	0.0
Coleoptera	Beetles	13.5	9.3	6.7	9.1	5.2	4.8
Collembola	Springtails	0.0	0.0	0.0	0.1	0.0	0.0
Dermaptera	Earwigs	0.0	0.0	0.0	0.0	0.0	0.0
Diplura	Diplurans	0.0	0.0	0.0	0.0	0.0	0.0
Hemiptera	True bugs	0.0	0.0	0.0	0.0	0.0	0.0
Hymenoptera	Ants, terrestrial wasps	5.2	3.0	0.8	4.2	3.4	3.1
Isoptera	Terrestrial termites	0.0	0.0	0.0	0.0	0.0	0.0
Lepidoptera	Larvae only (caterpillars)	0.6	0.1	0.1	0.4	0.5	0.0
Neuroptera	Antlions	0.0	0.0	0.0	0.0	0.0	0.0
Orthoptera	Grasshoppers, crickets,	33.2	34.1	35.3	1.1	9.3	1.9
Thysanura	Silverfish, Bristletails	0.0	0.0	0.0	0.0	0.7	0.0
Diptura	Flies	2.5	2.3	4.1	0.5	1.0	0.5
Homoptera	Cicads, Aphids	1.1	0.0	0.0	0.0	0.0	0.2
Lepidoptera	Butterflies, Moths	1.2	0.7	1.2	0.0	1.1	0.0
Other:		0.3	0.1	0.2	0.2	0.1	0.2
	Total	**64.8**	**52.6**	**50.7**	**53.1**	**24.5**	**14.5**

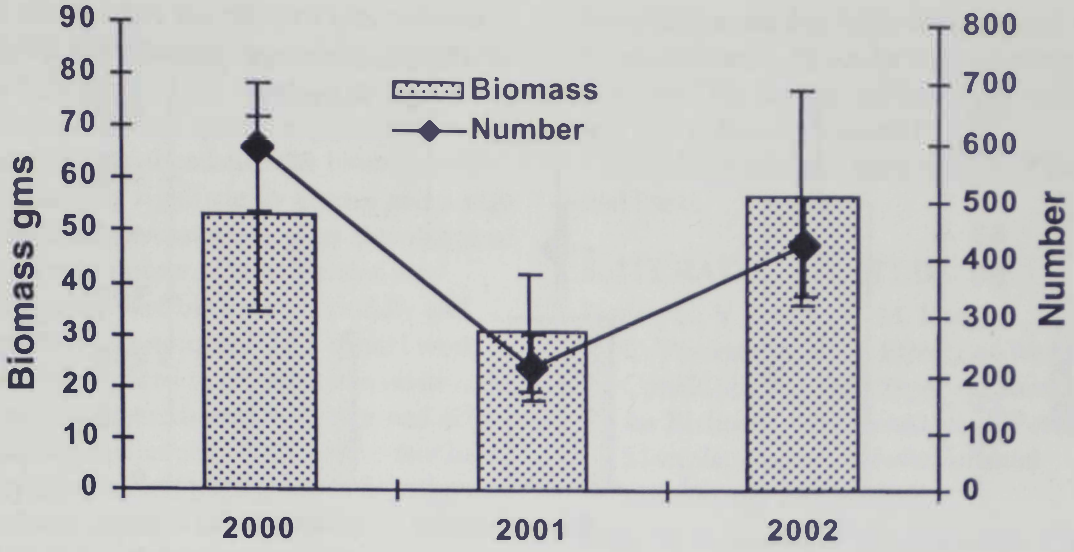

Figure 2. Average abundance and biomass of invertebrates captured in 10 pitfall traps at each of six locations in central and western Montana from 2000 through 2002. Error bars represent 95-percent CI for 30 sampling periods for 2000 and 2002 and 24 sampling periods for 2001.

was 2000, 2002, and 2001 (Fig. 2). Because averages included all habitats, the variance within years for both biomass and abundance was very high as indicated by the large 95-percent confidence intervals. Average invertebrate biomass by year from highest to lowest was the same as abundance—2000, 2002, and 2001 (Fig. 2). In 2001 average invertebrate biomass and abundance declined considerably (Fig. 2). The 2001 decline was consistent for all study sites except Cascade. Part of the 2001 decline could have been due to the loss of data from the 2001 June sampling period.

Grass habitats at Cascade and Cut Bank had the highest invertebrate biomass and abundance (Fig. 3). Shrub habitats at Polson and CMR had the next highest biomass, but the lowest abundance (Fig. 3). Forest habitats at Gold Creek and Wisdom had the lowest average invertebrate biomass (Fig. 3). Forested habitats had intermediate (between grass and shrub habitats) invertebrate abundance. Because the averages represent all sampling periods for each habitat, the intra-habitat variance is large. We found that eight orders/classes were most abundant in grassy habitats. Six orders of invertebrates were most abundant in shrub and forest habitats. Highest average biomass was similar to that of abundance when compared among habitat type. Eleven orders/classes had their highest average biomass in grass habitats, five orders highest in shrub habitat, and four order/classes had their highest biomass in forest habitats.

DISCUSSION

We found all but two (Diplura and Nueroptera) of the 15 targeted taxonomic groups during the study. If pit fall traps effectively capture Diplura and Neuroptera, then the six sites studied were not suitable for sustaining communities of Diplura and Neuroptera. However, several orders were common in all three habitats. For example, orders Araneida, Orthoptera, Coleoptera, Hymenoptera, and Diptura occurred at all six study sites. Other orders or classes were collected at all six study sites but not necessarily in significant numbers at all times. According to McNett and Rypstra (2000), structural complexity of the environment is clearly related to both the abundance and diversity of species in an area as well as behavior of the organisms inhabiting it. Certain habitats might be beneficial to some invertebrates and detrimental to others. Stinson and Brown (1980) found that species richness and

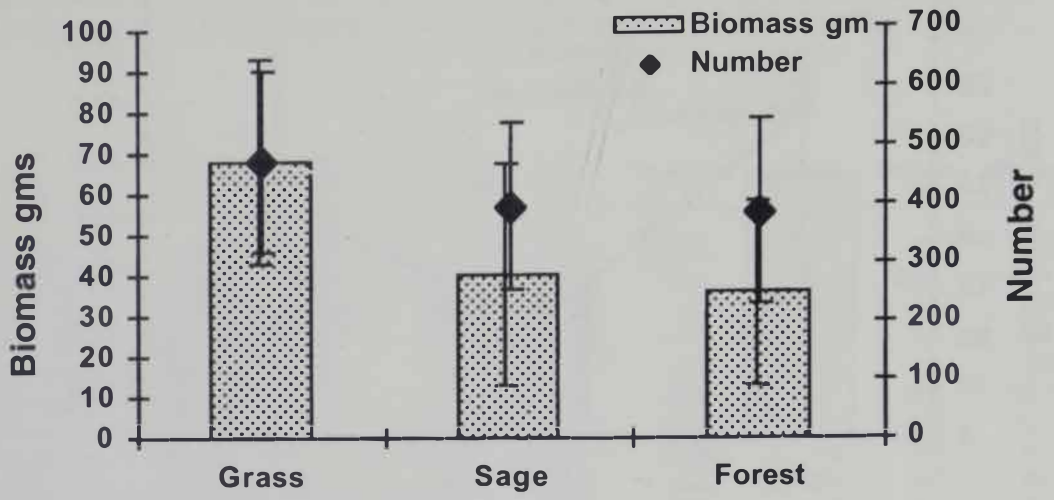

Figure 3. Average abundance and biomass of invertebrates captured in pitfall traps set in three habitats in central and western Montana from 2000 through 2002. Error bars represent 95-percent CI for 29 sampling periods for grass and sage habitats and 26 periods for forest habitats.

abundance of certain leafhoppers was strongly correlated with the architecture of their host plants. Therefore, forested habitats may be beneficial to diplopodans, as long as the architecture of that forest adheres to needs of that particular order or, more specifically, that species. In addition to habitat complexity, food or prey abundance may also contribute to invertebrate distribution (Mcnett and Ryptsra 2000).

Craig et al. (1999) reported that warm and sunny open ground was critical to survival and reproduction of several grasshopper species. At Cut Bank and Cascade, both open grass habitats, Orthoptera was the most common order found. The average biomass of Orthopterans at Cut Bank over the three years during each sampling period was 35.3 g, more than five times the next closest average biomass, Coleoptera, in the same traps.

Many factors may contribute to abundance and distribution of invertebrates across a landscape, including land use activities such as agriculture and silviculture, ambient temperature, moon-phase, air movements, amount of precipitation, amount and time of direct sunlight during a trapping period, local vegetation, natural population fluctuations, time of year, and trap design, kind, and positioning (Butler et al. 1999). In a study conducted by Rogers and Woodley (1978) in South-central Washington, invertebrate density and biomass was highest during April and May and steadily declined through summer and fall. The invertebrate density and biomass patterns paralleled the live plant biomass trend. Peak biomass values for green vegetation occurred during April or May and then declined with the onset of summer drought conditions. The parallel time of vegetation productivity and insect biomass and population density suggests that biomass and density of dominant invertebrate groups are correlated with the green growth period of early spring (Rogers and Woodley 1978). Similar trends occurred throughout our six study sites, except peak values occurred in July and August. Later timing was likely due to longer, colder winter seasons in Montana. By October, invertebrate abundance significantly declined probably reflecting frosts that begin in mid-September.

We intend to incorporate invertebrate data as we try to explain deer mouse population dynamics. However, at this point deer mouse abundance has been highest in sage communities (Douglass et al. 2001) while invertebrate (trappable in pitfall traps) abundance and biomass tended to be highest in grasslands. Data summarized in Figure 2 suggest that neither invertebrate abundance nor biomass differ statistically significantly among grass, sage and forest communities. The abundance of both deer mice and invertebrates are extremely variable both temporally and spatially. Consequently additional work will be required to elucidate the relationship between invertebrate abundance and deer mouse populations. Deer mouse numbers usually increase during fall as freezing reduces captures of invertebrates. Although freezing probably severely limits invertebrate movement in the fall, it may not limit their availability to rodents. Answering our questions about the importance of invertebrates to rodent ecology requires further investigation into the spatial relationship between individual invertebrate taxa and rodent communities and food habits.

Insects dwell within complex ecosystems and interact with other taxonomic groups and the abiotic environment (Hunter 2002). While our study covered a broad scale, we believe our findings can be used as a basis for appropriate future research in geographic areas that we studied. Future analysis will include taxa-by-taxa comparisons among years and habitats conducted simultaneously with rodent stomach content analysis. The results of this project add to our knowledge of invertebrate distribution and abundance in western and central Montana and provide relative abundance and biomass of potential food for vertebrates such as rodents and insectivores.

ACKNOWLEDGEMENTS

We greatly appreciate the permission to work on two private ranches, the Salish Kootnai Reservation, the Blackfoot reservation, C. M. Russell National Wildlife Refuge and Deer Lodge National Forest. Bill Semmens and Erick Hartwig initiated the invertebrate survey and Amy Kuenzi taught us to identify the invertebrates. We especially thank Jim Mills for ideas and encouragement. Financial support came from the U.S, Centers for Disease Control and Prevention Agreement USC3/ CCU813599-03 and Montana Fish, Wildlife and Parks.

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Received 19 June 2003
Accepted 10 October 2003

PEAK CONCENTRATIONS AND PLUME DIFFUSION IN THE ATMOSPHERIC SURFACE LAYER

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ABSTRACT

To improve our understanding of pollutant behavior in the atmosphere, tracer experiments were conducted in 1997 at a field site near Galen, Montana. We developed an empirical method to estimate instantaneous plume spread as a function of standard wind statistics and travel time. Predicted diffusion coefficients are within a factor of 2, or better, of observed values for the 1997 data, and the average predicted-to-observed ratio was 1.03 for an expanded dataset of 97 samples representing a range of terrain types, meteorological conditions, and travel times. The 1997 field data are also used to test a meandering plume model, and modeled time series are similar to observed data including fluctuation statistics such as concentration mean, intensity, intermittency, and peak-to-mean ratio. Finally, we propose a simple approach to predict normalized peak concentrations for ground-level sources. The technique is shown to be realistic, yet conservative, with an average predicted-to-observed ratio of 1.90 for a variety of field studies.

Key words: concentration fluctuations, diffusion modeling, peak concentrations, plume spread, tracer experiments

INTRODUCTION

Peak concentrations are important when addressing short-term exposures to toxic air pollutants and to chemical agents such as nerve gases. Air diffusion programs such as the Industrial Source Complex (ISC) or SCREEN models predict 1-hr average concentrations downwind of contaminant sources. Field studies, however, using gaseous tracers have shown that concentration fluctuates dramatically at fixed receptors during 1-hr periods under all stability conditions, and peak concentrations may be many times higher than average concentrations. Because acute exposures may pose health risks for exposure to toxic or hazardous gases above threshold values, dispersion models should be capable of addressing variability or peak concentrations on time scales similar to human breathing rates.

In this paper we address recent efforts to investigate and model concentration fluctuations and peak concentrations from surface-level, pollutant plumes. The goals of the research are to 1) improve our understanding of plume behavior in the atmosphere, and 2) develop a simple approach of incorporating instantaneous exposure statistics into the regulatory modeling arena. Here, we provide background information and describe recent experiments using tracer technologies to obtain concentration fluctuation data. We analyzed the tracer data in terms of instantaneous plume spread and concentration fluctuation statistics, and examined performance and uncertainties of a meandering plume model. Finally, we used our field data to test a simple method of predicting normalized peak concentrations.

BACKGROUND

Average plume dispersion is a function of two components: diffusion relative to the instantaneous plume centerline, and meander relative to the average plume centerline (Gifford 1959). In general, small-scale eddies are responsible for diffusion whereas large-scale atmospheric motions cause the plume to meander. The separation between large and small wind features changes with plume travel time. For example, at distances close to the source, where the plume is narrow, meandering motions dominate plume behavior. At distances farther from the source, motions that previously contributed to meander, promote internal mixing.

Both diffusion and meander affect the nature of instantaneous pollutant exposure at a fixed receptor located downwind of a source. Specifically, diffusion determines the magnitude of concentrations at a specific downwind distance while meander is responsible for intermittent exposure as the plume wavers back-and-forth in the wind.

Peak concentrations in a pollutant plume are a function of instantaneous plume spread whereas mean concentrations are due to both plume meander and spread. As early as 1959, Gifford derived peak-to-mean ratio (P/M) at the centerline of a time-averaged plume (Gifford 1959) as $P/M = (Y^2 + D^2)(Y^2)^{-1}$. In this equation, Y^2 represents the mean square diffusion of a plume element relative to the centroid; D^2 represents the mean square meander of the plume centroid about the mean plume axis; and $Y^2 + D^2$ corresponds to the average spread of the plume. Gifford's peak-to-mean approach was never formulated into a regulatory tool, and until recently, few data were available regarding concentration peaks and relative diffusion because of a lack of fast-response instrumentation.

During the past two decades, however, a variety of methods have been utilized to study concentration fluctuations with fast-response equipment. For example, Hanna (1984) and Dinar et al. (1988) conducted oil fog experiments and monitored smoke concentrations at fixed receptors located downwind of the source. Sawford (1985) analyzed plumes of smoke and sulfur hexafluoride (SF_6) while Jones (1983) measured ionized air concentrations. Lewellen and Sykes (1986) and Jørgensen and Mikkelsen (1993) used lidar to remotely resolve fluctuations of particle plumes, whereas Mylne (1992), Mylne and Mason (1991), and Yee et al. (1993, 1994) released propylene gas in conjunction with high-resolution photoionization detectors.

In addition, fast-response SF_6 analyzers developed by Benner and Lamb (1985) were used during a series of novel field studies to study concentration fluctuations and plume spread. Specific campaigns included the Washington Wheatfield Study (WWS) and the Washington Desert Study (WDS) of Peterson et al. (1990) and Peterson and Lamb (1992), the Energy Resources Conservation Board (ERCB) experiments described in Peterson and Lamb (1995) and Joshi (1998), and the Galen and Boardman tests by Peterson et al. (1999). In all cases, we released SF_6 at a constant rate near the surface and measured plume concentrations at fixed points and along crosswind traverses with sampling rates between 1 and 20 Hz. Local winds were monitored with fast-response anemometers. These studies represented a wide range of conditions in the intermountain and northwest regions. Surface terrain included flat fields, forest canopies, and rolling hills; average wind speeds varied between 0.8 and 11.6 ms^{-1}; standard deviation of horizontal and vertical wind angles ranged 3-79° and 1-25°, respectively; stability categories A-G were observed; and source-to-receptor distances were between 100 and 1000 m. The remainder of this paper addresses an additional set of experiments performed near Galen, Montana, during August of 1997 in terms of plume diffusion, concentration fluctuations, and peak concentrations.

FIELD EXPERIMENTS

To investigate instantaneous behavior of surface-level plumes, Donovan (1998) conducted a tracer campaign in August of 1997 amid a flat, rural valley located east of Interstate-90, just beyond the Galen exit, in southwest Montana. An abandoned railroad bed running approximately north-south and a rural road running east-west divided the field site. Grasses and weeds, about 0.1-0.3 m in height, were the dominant vegetation. Figure 1 depicts the general layout of the experiments, including the SF_6 release system, the analyzer, and a wind sensor.

The tracer release system consisted of a pressurized tank of sulfur hexafluoride gas. The SF_6 from the tank was released at a constant rate through a calibrated rotameter and through 0.95 cm O.D. tubing with an exit height of approximately 1.5 m.

We measured SF_6 plume concentrations with a Rydock Scientific Microanalyzer at fixed locations with source-to-receptor distances ranging from 324-748 m. The analyzer was based on the electron capture detection (ECD) design of Benner and Lamb (1985) with a response time of 0.6 s, and a detection limit near 30 part-per-trillion (ppt) by volume. We performed calibrations at the beginning and end of each test using zero air and Scott-Marin certified gas standards, and we collected concentration data at a rate of 1 Hz.

The wind sensor for the Galen study was an R.M. Young uvw anemometer positioned at a height of 3.1 m. In this campaign, the uvw anemometer was oriented with the u-propeller facing east, the v-propeller facing north, and the w-propeller directed upward. Wind vector data were collected at a rate of 1 Hz, and ambient temperatures and pressures were recorded at the onset of each test using a digital temperature probe and barometer.

Table 1 summarizes conditions for eight tracer experiments performed at Galen during late afternoon/evening hours. Each test was approximately one hour in duration. Average wind speeds ranged 1.1 to 4.4 m s^{-1}; standard deviation of horizontal and vertical wind fluctuations varied 11-56° and 4-7°, respectively; and stability categories were extremely unstable through neutral (A-D) based on the Sigma-A method (USEPA 1987).

Figure 2 shows wind speed and wind direction time series for one representative experiment, Test S808d. The statistics for this case included an average wind speed of 4 ms^{-1}, an average wind direction of 303°, and a standard deviation for horizontal wind angle of 19°.

RESULTS

Instantaneous Plume Coefficients

Plume spread, on either an average or instantaneous time frame, is assumed to be a function of travel time and atmospheric turbulence. As presented by Draxler (1976) and others, "average" dispersion coefficients should be equal to

$$\sigma_y \cong \sigma_\theta X f_1 \qquad (1)$$

and

$$\sigma_z \cong \sigma_\phi X f_2 \qquad (2)$$

where σ_y and σ_z are standard deviations of the average horizontal and vertical concentration distributions (with units of m), respectively; σ_θ and σ_ϕ are standard deviations of the azimuth and elevation wind angles (in units of radians); X is downwind distance; and f_1 and f_2 are unitless decay functions. For the decay functions, Draxler (1976) incorporated travel time (t) into the following simple equation for ground sources:

$$f_1 \text{ or } f_2 = [1+0.9(t/T_o)^{0.5}]^{-1} \qquad (3)$$

with T_o equal to 300 s for f_1, and T_o equal to 100 s or 50 s for f_2 under non-stable or stable conditions, respectively.

While instantaneous plumes are known to be narrower than time-averaged counterparts, a similar approach can be developed to predict the "relative" diffusion, or spread relative to the plume axis. In particular, the standard deviations of the horizontal and vertical instantaneous

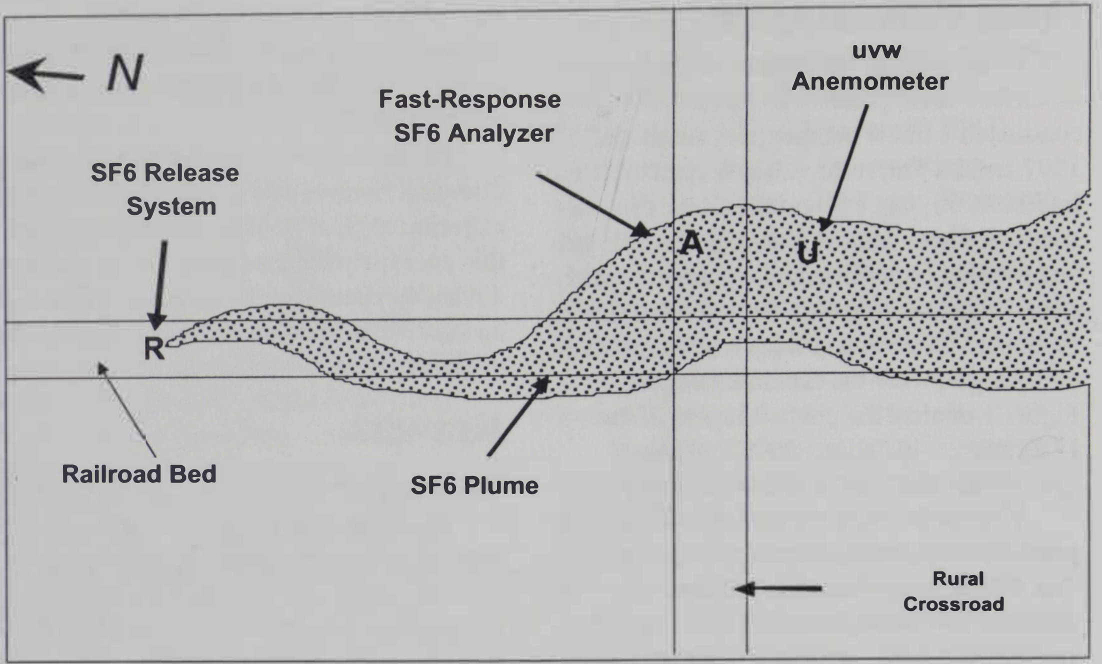

Figure 1. Example experimental setup during Galen tracer experiments.

concentration distributions, σ_{yi} and σ_{zi}, may be written as

$$\sigma_{yi} \cong \sigma_\theta \, X \, f_{1i} \qquad (4)$$

and

$$\sigma_{zi} \cong \sigma_\phi \, X \, f_{2i} \qquad (5)$$

where f_{1i} and f_{2i} are again decay coefficients. Equations (4) and (5) are subsequently combined to estimate to the relative diffusion coefficient, σ_i, as

$$\sigma_i = (\sigma_{yi}\,\sigma_{zi})^{0.5} \cong (\sigma_\theta\sigma_\phi)^{0.5} \, X \, (f_{1i}\, f_{2i})^{0.5} \quad (6)$$

with $f_{1i}\, f_{2i}$ likely to be some function of travel time.

As shown in Table 2, diffusion coefficients for the Galen campaign range from 15.7 to 31.5 m, and travel time (t), as inferred from $t = X\,U^{-1}$, varies between 94 and 453 s. Values of $(f_{1i}\, f_{2i})^{0.5}$ for these experiments vary between 0.09 and 0.43. The data are plotted against travel time (Fig. 3), and curve-fitting the field data results in a "best-fit" equation of

$$(f_{1i}\, f_{2i})^{0.5} = -0.1078 \ln(t) + 0.7898 \qquad (7)$$

with an R correlation factor of 0.5858. Also shown on the graph is the curve for Draxler's time-averaged function from Equation (3) for surface plumes under nonstable conditions. Overall, for this range of experimental data, our "instantaneous" curve and Draxler's "time-averaged" curve provide similar relationships with travel time, but as expected, the instantaneous factors are several times smaller than the time-averaged values. It should be noted that Equation (7) approaches zero for travel times on the order of 1500 s, so it would not be appropriate for receptors with source-to-receptor distances on the order of ≥1 km.

For near-source receptors, however, Equation (7) can be inserted into Equation (6) to estimate instantaneous diffusion coefficient as

$$\sigma_i = (\sigma_\theta\sigma_\phi)^{0.5} \, X \, [-0.1078 \ln(t) + 0.7898] \quad (8)$$

and minimal on-site input (i.e., X, U, σ_θ and σ_ϕ) are required for the calculation. Example results for the Galen data are given in Table 2. Note that the predicted values of σ_ι are within a factor of 2 of the observed values, and the average predicted-to-observed (P:O) ratio is 1.12.

Table 1. Galen 1997 Field Study - Test Conditions

Test	Date (D-M-YR)	Start Time(MDT)	X (m)	U (m s^{-1})	θ (deg)	σ_θ (deg)	σ_ϕ (deg)	Stability	T (K)	Q_{SF6} (g min^{-1})
S804c	04-08-97	1746	521	1.1	157	37	5	A	298	10.08
S804d	04-08-97	1906	521	1.9	163	56	7	A	296	10.01
S808c	08-08-97	1530	502	4.4	286	18	4	C	300	11.48
S808d	08-08-97	1638	478	4.0	303	19	5	C	298	11.41
S808e	08-08-97	1741	478	3.6	289	21	5	C	297	11.41
S808g	08-08-97	1924	520	4.1	360	11	4	D	293	11.27
S809b	09-08-97	1606	748	4.2	326	13	5	D	291	11.20
S8010c	10-08-97	1707	324	3.5	345	14	5	D	295	13.79

Test code – S: Galen fixed-point test
Test duration – 60 min
X – downwind distance
U – average wind speed
θ – average wind direction
σ_θ – standard deviation of horizontal wind fluctuations
σ_ϕ – standard deviation of vertical wind fluctuations
Stability – category based on the Sigma-A method (USEPA 1987).
T – ambient temperature
Q_{SF6} – release rate of tracer gas

Predicted values of σ_ι are plotted against observed values of σ_ι for the Galen 1997 experiments (Fig. 4). Also shown on the graph are results from applying the technique to field data from the Galen 1995/1996 study of Peterson et al. (1999), the Boardman tests of Peterson et at. (1999), the ERCB campaign of Peterson and Lamb (1995), and the Washington Desert Study of Peterson et al. (1990) and Peterson and Lamb (1992). This combined data set consists of 97 samples covering a range of terrain, meteorological conditions, and travel times. Overall, the method predicts observed values within a factor of 2, or better, for 94 percent of the cases, and within a factor of 3 for 100 percent of the experiments. In addition, the results are relatively unbiased with an average P:O ratio of 1.03 (with a standard deviation of 0.39).

In summary, we have developed and tested a simple way of predicting instantaneous plume spread for surface-level plumes from basic meteorological parameters. In the following section, we employ this technique in a meandering plume model to predict "real-time" concentration time series at fixed receptors.

The Meandering INstantaneous Diffusion (MIND) Model

While a diffusion coefficient is one component necessary to describe behavior of plumes in real time, another integral part is plume meander. To predict instantaneous concentrations downwind of a ground-level pollutant source, Peterson et al. (1990) and Peterson and Lamb (1992, 1995) developed a meandering plume model, and O'Neill (1996a, 1996b) packaged the approach into a program called the Meandering INstantaneous Diffusion (MIND) model. The core equation in MIND is

$$C_i = \frac{Q}{\pi \sigma_{yi} \sigma_{zi} u_i} e^{\frac{-(\theta_i - \theta_r)^2 (X\pi/180)^2}{2\sigma_{yi}^2}} \tag{9}$$

where C_i is instantaneous concentration (mg m^{-3}) at a ground-level receptor; Q is contaminant release rate (mg s^{-1}); σ_{yi} and σ_{zi} are the instantaneous diffusion coefficients (m); u_i is wind speed near plume height (ms^{-1}); θ_i is a horizontal meander component (deg); θ_r is a bearing from the source to the receptor (deg); X is source-to-receptor distance (m); and (π/180) is a unit conversion to change degrees to meters.

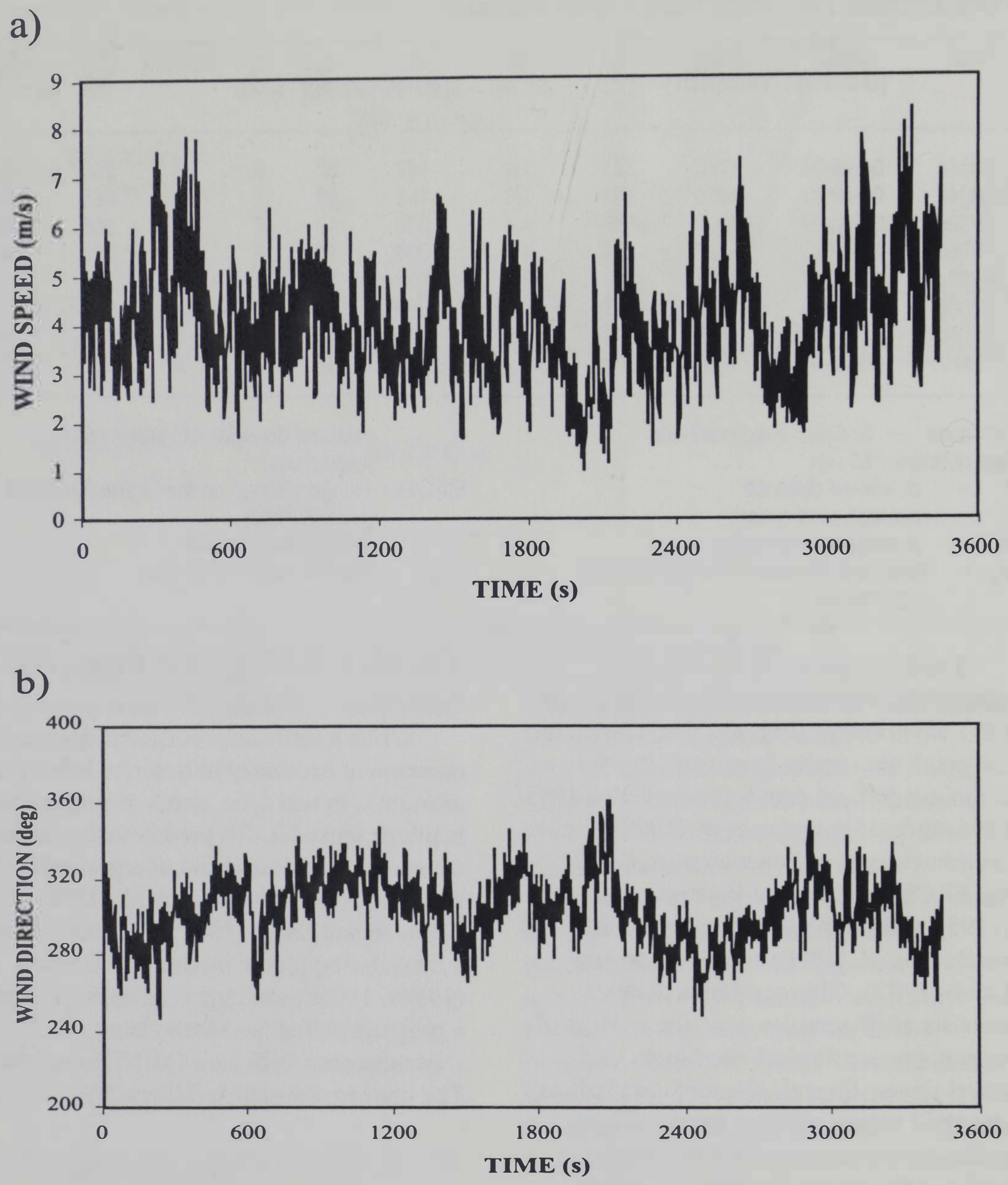

Figure 2. Time series of a) wind speed and b) wind direction for test S808d. Statistics include an average wind speed of 4 ms^{-1}, an average wind direction of 303°, and a standard deviation of wind azimuth of 19°.

The MIND model processes time series of uvw data from a propeller or sonic anemometer located near the source and near plume height. For each downwind distance, meander and wind speed components, θ_t and u_i, respectively, are resolved as running-average values using travel time for a smoothing time. Currently, several options are available in the model for instantaneous diffusion coefficients (σ_{yi} and σ_{zi}), including an option for user-specified entrees. Concentration time series are predicted for an array of receptors located downwind of the pollutant source. Corresponding concentration fluctuation statistics are calculated for each receptor, including mean concentration, intensity (ratio of concentration standard deviation to mean concentration), intermittency (fraction of time non-zero concentrations are

Table 2. Galen 1997 Study - Diffusion Data

Test	σ_t (m)	t (s)	$(f_{1i}\, f_{2i})^{0.5}$	σ_t^a (m)
S804c	23.9	453	0.200	15.6
S804d	15.7	282	0.090	31.7
S808c	17.0	115	0.216	21.9
S808d	19.7	119	0.241	22.4
S808e	16.2	133	0.185	23.0
S808g	18.3	127	0.281	17.9
S809b	31.5	179	0.284	25.6
S810c	20.0	94	0.429	14.0
Ratio P:O				1.12 (±0.45)

σ_t – observed diffusion coefficient

– travel time

$(f_{1i}\, f_{2i})^{0.5}$ – decay factor

σ_t^a – predicted value from Equation(8)
where $\sigma_t = (\sigma_\theta \sigma_\phi)^{0.5} \times [= -0.1078 \ln(t) + 0.7898]$

Ratio P:O – average ratio of predicted-to-observed (± standard deviation)

recorded at a receptor), and peak-to mean ratio.

As an example, Figure 5a shows field data for Test S808d. These data were collected by the fast-response analyzer located 478 m downwind of the SF_6 source with a source-to-receptor bearing of 282°. Figure 5b illustrates the predicted concentration time series for that receptor using the MIND model with on-site uvw data and a value of 22.4 m for the diffusion component as calculated by Equation (8). Both time series contain comparable temporal features caused by meander and similar concentration values in response to spread of the instantaneous plume.

Figures 6a-6d contain the corresponding modeled crosswind profiles of mean concentration, intensity, intermittency factor, and peak-to-mean ratio in addition to the field data for Test S808d. The profiles agree with data collected in previous field campaigns (i.e., Hanna 1984, Lewellen and Sykes 1986, Peterson and Lamb 1995, and Sawford 1985). Specifically, crosswind mean concentration profiles were nearly Gaussian (Peterson and Lamb 1995); intensity values on the mean plume axis were near 1.0, and at the plume edges they were of order 10 (Hanna 1984, Lewellen and Sykes 1986, Peterson and Lamb 1995, and Sawford 1985); intermittency factors ranged from 0.5 to 0.8 near the plume axis and from 0.1 to 0.3 at crosswind positions near $2\sigma_y$ (Hanna 1984, Peterson and Lamb 1995, and Sawford 1985); and peak-to-mean ratios were near 2-10 at the centerline and near 30-100, and higher, at plume edges (Csanady 1967, Hanna 1984, Peterson and Lamb 1995, and Sawford 1985).

The concentration fluctuation statistics for all Galen 1997 field experiments are presented in Table 3 in addition to predictions from the MIND model. The one-hour test period was chosen because it corresponds to the smallest averaging period in the regulatory models, and the sampling rate of 1 Hz gives us near-instantaneous fluctuation data on the order of human breathing rates. The fluctuation statistics are depicted in terms of one-to-one correspondence between the field data and the model (Fig. 7). Time series variability is particularly well represented by the method as evident from the model performance for intensity, intermittency, and peak-to-mean ratios. Regarding time-averaged exposure, the model is conservative with an average predicted-to-observed ratio of 1.82.

In terms of limitations of the MIND model, concentration fluctuation statistics in this work represent 1-Hz data throughout sampling periods of approximately one hour; thus, model data and field data do not resolve fluctuations with higher frequencies. Again, the one-hour sampling period was chosen because it corresponds to the smallest averaging period in existing regulatory models. Regarding the sampling rate, a few field campaigns in the literature utilize faster sampling rates (i.e., up to 270 Hz by Yee et al. 1994), but high-frequency concentration fluctuations are filtered in the lungs, and 1-Hz data are believed to adequately represent near-instantaneous exposure associated with human breathing

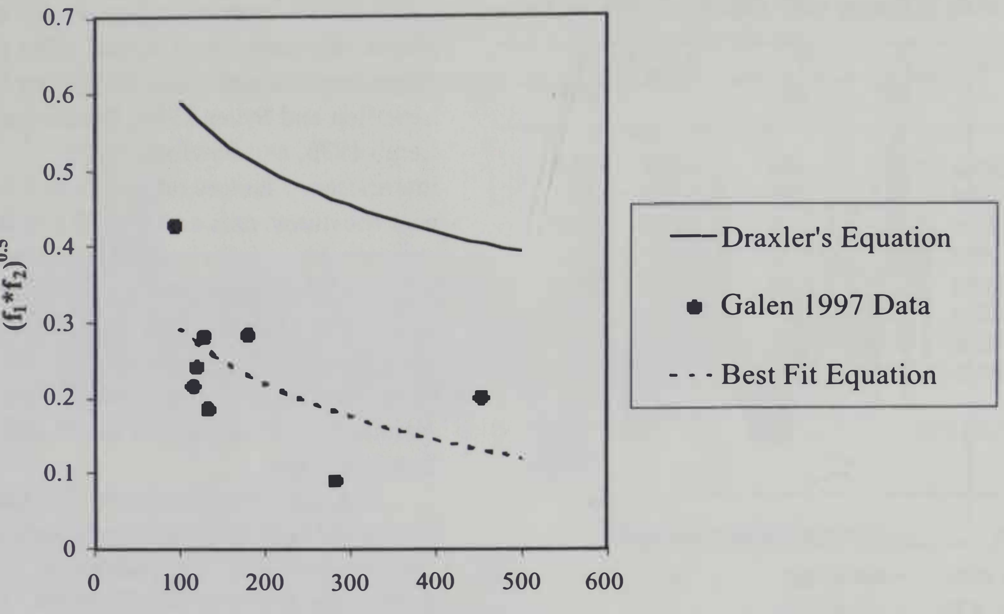

Figure 3. Instantaneous decay function versus travel time for the Galen 1997 data. A curve is shown representing a "best-fit" to the field data in addition to a "time-averaged" curve from Draxler (1976).

rates.

Other limitations involve source-to-receptor distance, plume profile, and wind speed. The MIND model has not been tested for receptors located farther than about 1 km from the source. Short-term plume behavior is most important for regulatory issues where the plume is narrow and concentrations are high, and other field campaigns will provide data for greater downwind distances in particular for stable conditions when instantaneous plume

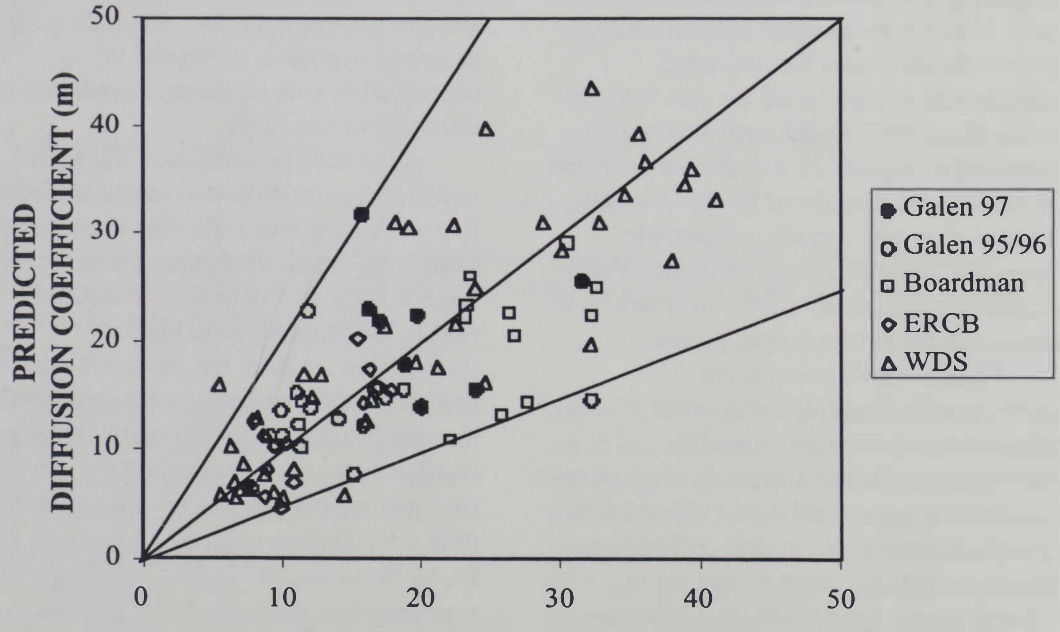

Figure 4. Predicted instantaneous diffusion coefficients versus observed values for five independent field campaigns.

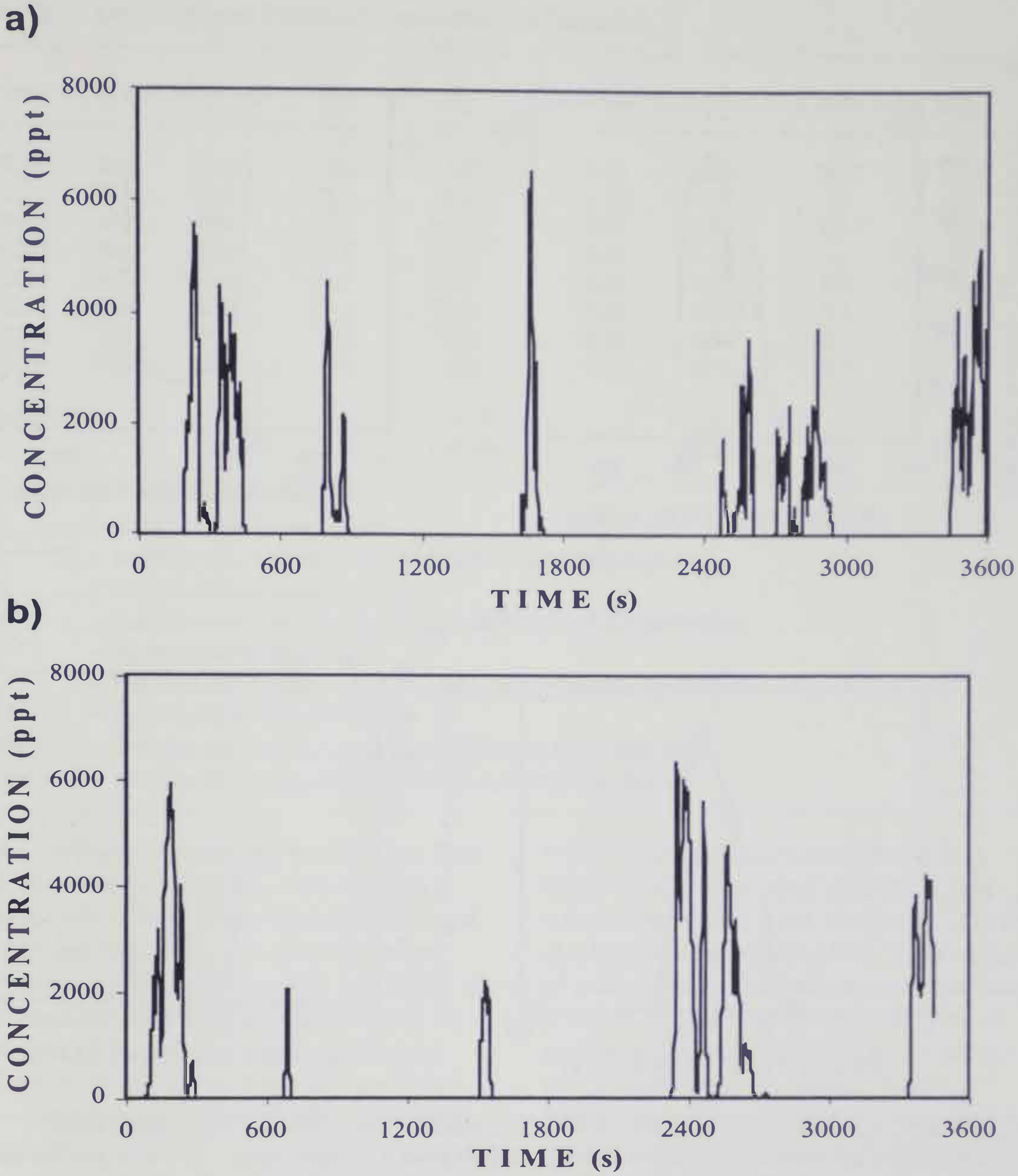

Figure 5. Concentration data for test S808d including a) time series of observations from the fast-response SF_6 analyzer at a receptor angle of 282°, b) predictions from the MIND model using Equation (8) for the diffusion coefficient. Also shown are 1:1, 1:2, and 2:1 lines-of-correspondence.

growth is slow and meander motions are large. In addition, vertical and horizontal profiles of the instantaneous plume are represented by smooth Gaussian functions; additional high-frequency fluctuations may result from patches of irregular internal plume structure. Finally, the largest uncertainties in the model correspond to conditions with weak winds. When wind speeds are less than about 1 ms^{-1}, variable wind directions may cause plume material to follow complicated paths between source and receptor. To date, few data have been collected under low-wind conditions to test and improve this aspect of the model, but in subsequent papers, we will address these uncertainties.

Normalized Peak Concentratrations

While the MIND model has been shown to reproduce field data under a range of meteorological conditions and amid a variety of roughness elements, the

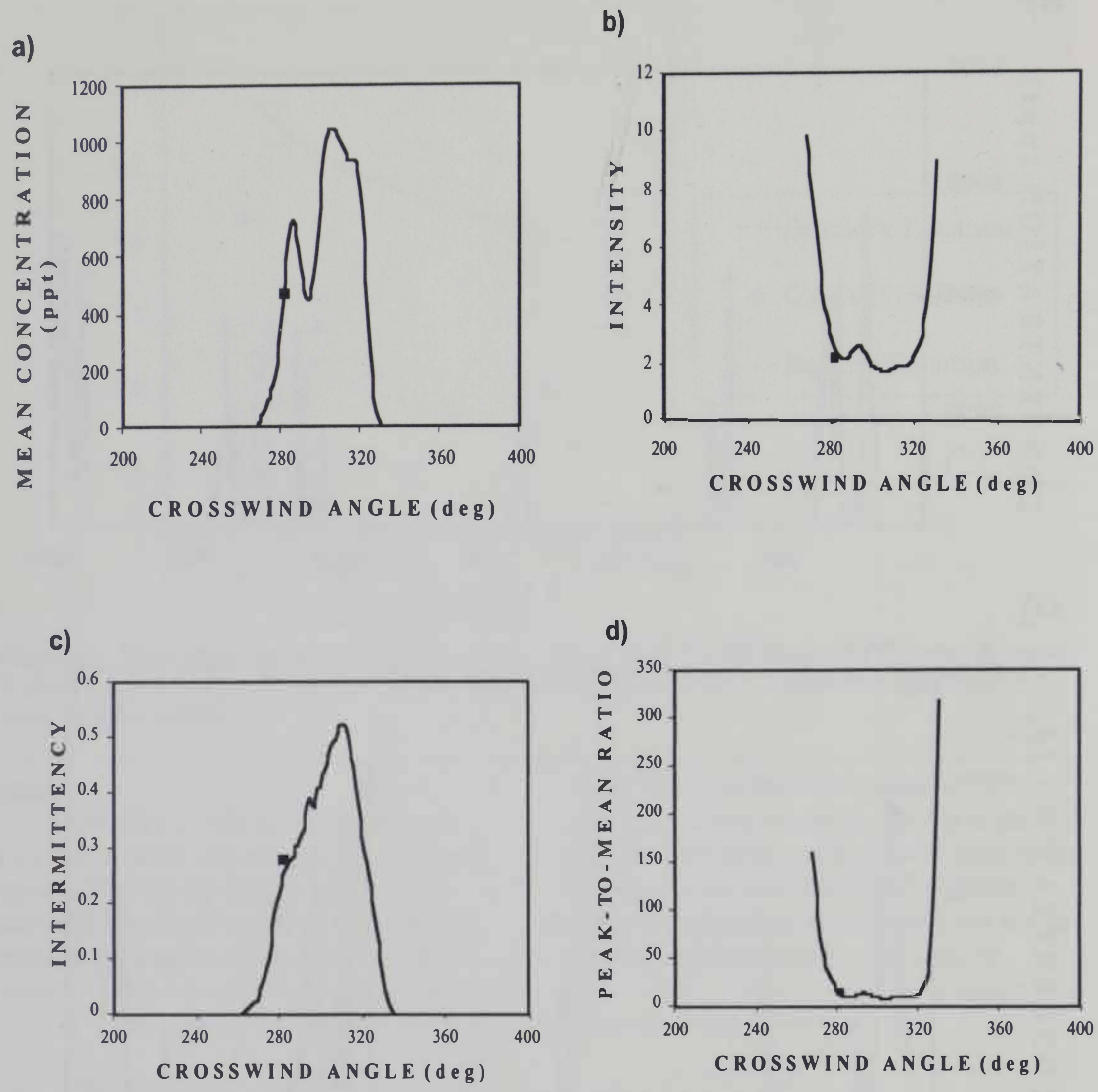

Figure 6. Crosswind profiles from the MIND model for test S808d, including a) mean concentration, b) intensity, c) intermittency, and d) peak-to-mean ratio. The statistic for the observed time series (shown in Figure 5a) is indicated by a "square".

"instantaneous" approach of predicting short-term exposure from real-time wind data is probably unrealistic for regulatory applications. The standard Gaussian model, however, could be used to predict a short-term peak concentration (C_p) for ground-level plumes as

$$C_p = \frac{Q}{\pi \sigma_{yi} \sigma_{zi} u} \qquad (10)$$

or in normalized form:

$$C_p \frac{u}{Q} = \frac{1}{\pi \sigma_{yi} \sigma_{zi}} \qquad (11)$$

where, again, Q is the mass release rate of pollutant; u is wind speed near source height; and instantaneous plume spread is determined by $\sigma_{yi}\sigma_{zi}$ or σ_i^2. For this work, normalized peak concentration in Equation (11) is assumed to represent a value with a time scale on the order of 1 sec if Equation (8) is used to estimate plume spread.

Table 4 contains normalized peak concentration ($C_p u/Q$) for the Galen 1997 experiments in addition to predictions from Equation (11) with Equation (8) for σ_i. For these data, the method produces an average P:O ratio of 1.19. Results are shown for

Table 3. Observed and Predicted Concentration Statistics

Test	C_o (ppt)	$C_p{}^a$ (ppt)	IN_o	$IN_p{}^a$	I_o	$I_p{}^a$	P/M_o	$P/M_p{}^a$
S804c	530	1314	3.5	4.5	0.35	0.09	25.9	32.2
S804d	2622	1024	1.9	2.0	0.43	0.29	7.5	6.1
S808c	603	794	2.1	1.9	0.47	0.45	13.7	10.6
S808d	465	507	2.2	2.5	0.28	0.25	14.1	12.5
S808e	1477	1300	1.5	1.6	0.66	0.55	6.8	10.3
S808g	1361	1856	1.2	1.6	0.65	0.54	5.1	6.4
S809b	221	953	1.8	1.4	0.39	0.59	10.7	4.9
S810c	1025	2772	1.6	2.0	0.51	0.46	8.7	9.0
Ratio P:O		1.82 (±1.27)		1.10 (±0.19)		0.86 (±0.35)		1.00 (±0.33)

Test Duration = approximately 60 min

C_o – observed mean concentration

$C_p{}^a$ – predicted mean concentration from MIND using Equation(8) for σ_i

IN_o – observed concentration intensity

$IN_p{}^a$ – predicted concentration intensity from MIND using Equation(8) for σ_i

I_o – observed intermittency factor

$I_p{}^a$ – predicted intermittency factor from MIND using Equation(8) for σ_i

P/M_o – observed peak-to-mean ratio

$P/M_p{}^a$ – predicted peak-to-mean ratio from MIND using Equation(8) for σ_i

Ratio P:O – average ratio of predicted-to-observed (± standard deviation)

the 1997 experiments and for the other four field campaigns (Fig. 8). The equation overpredicts in 60 percent of the cases, and underpredicts in 40 percent of the tests. Performance statistics include the effects of a few large outliers, but approximately 83 percent of the data are within a factor of three, or better, and the average predicted-to-observed ratio is 1.90 for the combined data set.

Similar to the limitations and uncertainties of the MIND model, this method of predicting normalized peak concentrations has not been tested for downwind distances greater than 1 km. Non-Gaussian plume profiles induce uncertainty to the results, and additional field data are required for stable meteorological conditions with low wind speeds. For the range of conditions tested, however, the simple approach is expected to provide realistic, yet conservative, estimates of peak concentration.

SUMMARY

In this paper, we presented results from recent field studies regarding short-term behavior of surface-level plumes. Eight tracer experiments were conducted in 1997 at a field site near Galen, MT. Time series of concentration fluctuations were collected at a rate of 1 Hz with fast-response tracer analyzers operating 324-748 m downwind of a ground-level SF_6 source. Wind conditions were monitored near the surface throughout the campaign, and stability categories ranged from neutral through extremely unstable.

Using the Galen field data, we developed a simple approach to estimate instantaneous spread for surface-level plumes. The approach was similar to the work by Draxler (1976) except an instantaneous time frame is represented instead of a time-averaged time frame. An empirical function was derived for s_i as a function of travel time, and the equation performed within a factor of 2, or better, for 94 percent of a dataset consisting of 97 samples covering a range of terrain types, meteorological conditions, and travel times. Furthermore, the results were nearly

Table 4. Normalized Peak Concentrations

Test	$C_pu/Q \times 10^6(m^{-2})$	$C_pu/Q^a \times 10^6(m^{-2})$
S804c	479	1314
S804d	1119	316
S808c	941	662
S808d	694	631
S808e	954	604
S808g	771	998
S809b	275	486
S8010c	681	1625
Ratio P:O		1.19(±0.84)

C_pu/Q – observed normalized peak concentration
C_pu/Q^a – predicted value from $(p\,\sigma_i^2)^{-1}$ using Equation (8) for σ_i
Ratio P:O – average ratio of predicted-to-observed (± standard deviation)

unbiased with an average predicted-to-observed (P:O) ratio of 1.03.

The field data were also used to test the Meandering INstantaneous Diffusion (MIND) model. We processed wind data into separate meander and diffusion components and predicted concentration time series for receptors corresponding to the location of the tracer analyzer in each experiment. The model predicted concentration patterns that were quite similar to the field data. In terms of concentration fluctuation statistics, the MIND model produced average predicted-to-observed ratios close to one for intensity, intermittency, and peak-to-mean ratio. The average P:O ratio for mean concentration was 1.82.

Finally, we proposed a simple approach to predict short-term peak concentrations. We modeled normalized peak concentration (C_pu/Q) for a ground-level source as $(\pi\sigma_{yi}\sigma_{zi})^{-1}$ or $(\pi\sigma_i^2)^{-1}$ with Equation (8) for σ_i. Values for the 1997 Galen experiments were combined with field data from Peterson et al. (1999), Peterson and Lamb (1995), Peterson et al. (1990) and Peterson and Lamb (1992). Overall, normalized peak concentrations were predicted within a factor of 3, or better, for 83 percent of the observed values, and the average P:O ratio was 1.90. Additional meteorological and terrain conditions should be tested, but this type of approach would be elementary to incorporate into a Gaussian-based

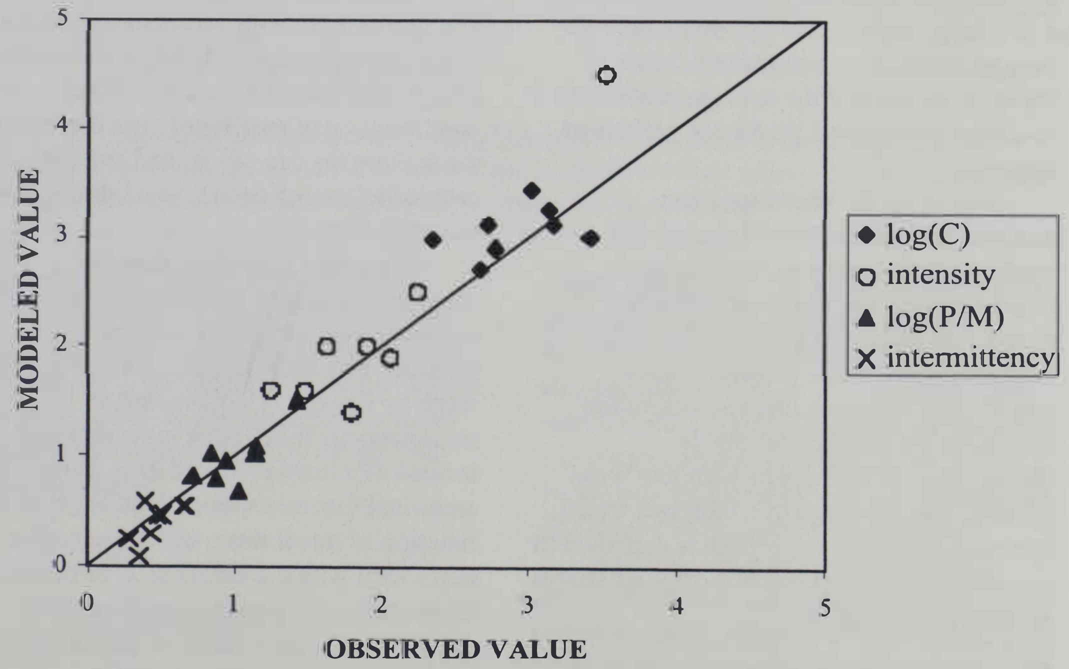

Figure 7. Predicted concentration fluctuation statistics from the MIND model versus observed values for the Galen 1997 experiments. Also shown is the 1:1 line-of-correspondence.

regulatory model such as ISC or SCREEN, and the end product would be hourly predictions of instantaneous peak concentration in addition to existing estimates of mean concentration.

ACKNOWLEDGEMENTS

This material is based upon work supported by the U. S. Army Research Office under contract/grant numbers DAAH04-94-G-0349 and DAAG55-98-0241. The authors specifically thank Dr. Walter Bach. Dione Mazzolini and Charles Mazzone are appreciated for assistance in fieldwork. Finally, landowners at the Galen site (Mr. Hans Lampert, Mr. Donald Beck, Dr. Elaine Stasney, and Dr. Mike Murnick) are also acknowledged.

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Received 19 July 2003
Accepted 11 December 2003

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Intermountain ournal of Sciences

Vol. 9, No. 2/3 - 2003

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