RIPARIAN ZONE CHANGES CAUSED BY STREAMFLOW AUGMENTATION

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ABSTRACT

A previously ephemeral watercourse in southeastern Wyoming has been used to convey water for the City of Cheyenne, Wyoming, since 1985. This water conveyance strategy was intended to partially mitigate the effects of the City's interbasin water diversions by creating a perennial stream along the pipeline diversion route. Since the effects of using this mitigation strategy are unknown, this study was initiated to evaluate the riparian vegetation response to flow augmentation, the rate of channel formation, and the depth-to-groundwater relationships for sedge (*Carex* spp.), tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.), and slimstem reedgrass (*Calamagrostis neglecta* [Ehrh.] Gaertn.). Above-ground biomass, density, basal cover, and below-ground biomass were measured for the riparian vegetation. Channel formation was evaluated with field surveys for channel length and cross section width, and measuring time-of-travel for a fluorescent dye. Depth-to-groundwater suitability curves for plants were based on the groundwater depth for 10, 50, and 90% (D_{10}, D_{50}, D_{90}) of the June through September growing season.

Streamflow augmentation elevated the groundwater level to within 0.21 m of the surface for 90% of the growing season in the unchannelized meadows. The elevated water level initially increased sedges (240 $g \cdot m^{-2}$ in 1986 to 350 $g \cdot m^{-2}$ in 1988), while tufted hairgrass decreased between 1986 and 1989 (18 to 3 $g \cdot m^{-2}$). Below-ground biomass decreased (4,900 to 3,400 $g \cdot m^{-2}$) during 4 years of flow augmentation. The proportion of channel increased from 24% (2,017 m) of the study area length before flow augmentation to 41% (3,446 m) by the sixth year of flow augmentation. Most of this channel formed by downcutting rather than by the upstream migration of abrupt

breaks in channel gradient (nick points).

The optimum depth-to-groundwater for sedge biomass was a nearly constant 0.15 m (D_{10} to D_{90}) of standing water. Tufted hairgrass response was optimized when the depth-to-groundwater was between 0.17 and 0.29 m for D_{10}, deeper than 1.23 m for D_{50}, and deeper than 1.79 m for D_{90}. The optimum depth-to-groundwater for slimstem reedgrass biomass was not well defined, but density appeared to decrease if the groundwater depths were shallower than 1.05 m for D_{10} , 1.34 m for D_{50} , and 1.81 m for D_{90} .

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

The City of Cheyenne, Wyoming, is attempting to create a perennial stream by releasing a controlled portion of their water supply from the Snowy Range in southeastern Wyoming into a previously ephemeral watercourse that flows 16 km into Cheyenne's storage reservoir, Crystal Lake. This streamflow augmentation was required by the U.S. Forest Service, under advisement from the U.S. Fish and Wildlife Service and the Wyoming Game and Fish Department, to partially mitigate the City's Stage II water development program. Stage II diverted water from perennial streams in the Sierra Madre to repay water diverted from perennial streams in the Snowy Range for use by the City. The South Fork of Middle Crow Creek (SFMCC) in the Laramie Range of southeastern Wyoming and one of its tributaries were selected to receive a controlled portion of this diverted flow. Flow augmentation has occurred since 1985 and was intended to enhance the aquatic and riparian resources along the SFMCC.

Since little information was available regarding the potential effects of using streamflow augmentation to mitigate water development projects, the Wyoming Water Resources Center initiated a multidisciplinary study in 1984 to evaluate the SFMCC project. From this study evolved two theses (Wolff 1987, Henszey 1988), one technical note (Henszey 1991), and two journal articles (Wolff et al. 1989, Henszey et al. 1991). Wolff (1987) and Wolff et al. (1989) evaluated the initial channel adjustments to flow augmentation and the developing brook trout (*Salvelinus fontinalis*) habitat. Henszey (1991) developed an electronic probe to facilitate the measurement of nearly 300 shallow alluvial wells installed on the SFMCC and adjacent ephemeral watercourses. Henszey (1988) and Henszey et al. (1991) evaluated the response of the herbaceous plant community to 2 years of streamflow augmentation, including the response of an assemblage of wetland sedges (*Carex* spp.), tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.), and slimstem reedgrass (*Calamagrostis neglecta* [Ehrh.] Gaertn.). Funding for these projects were provided by the Wyoming Water Resources Center, the Wyoming Game and Fish Department administered through the Wyoming Cooperative Fish and Wildlife Research Unit, and the Medicine Bow National Forest.

My dissertation was developed to address these following objectives:

1. Evaluate the herbaceous vegetation response to 4 years of streamflow augmentation.
2. Evaluate the below-ground biomass response to 4 years of streamflow augmentation.
3. Evaluate the length of developed channel and the time-of-travel for water moving through the SFMCC during 6 years of streamflow augmentation.
4. Develop depth-to-groundwater relationships for the SFMCC sedges, tufted hairgrass, and slimstem reedgrass.

From these objectives, the following null hypotheses were tested:

H_0: The amount (biomass, density, or cover) of sedge, tufted hairgrass, or slimstem reedgrass did not change as a result of an altered surface or groundwater level caused by streamflow augmentation on the SFMCC.

H_0: The below-ground biomass did not change as a result of an altered surface and groundwater level caused by streamflow augmentation on the SFMCC.

The length of channel, time-of-travel, and depth-to-groundwater relationships were not analyzed using inferential statistics, so strict null hypotheses could not be tested. Instead of testing null hypotheses, therefore, these following theoretical hypotheses were evaluated:

H: The length of channel did not change after streamflow augmentation began.

H: The time-of-travel did not change after streamflow augmentation began.

H: There is no relationship between the depth-to-groundwater and the response (biomass or density) of the SFMCC sedges, tufted hairgrass, or slimstem reedgrass.

Tests of these hypotheses are described in the following chapters. Chapter 2 evaluates the above-ground biomass, density, basal cover, and below-ground biomass response to 4 years of streamflow augmentation. The groundwater response to streamflow augmentation is also discussed in Chapter 2. Chapter 3 evaluates the length of channel and the time-of-travel during 6 years of streamflow augmentation. The groundwater regimes for the SFMCC and adjacent ephemeral watercourses are presented in Chapter 4. Chapter 4 also develops the depth-to-groundwater relationships for the SFMCC sedges, tufted hairgrass, and slimstem reedgrass. Each chapter was written to stand alone, so that they may be published as separate journal articles. This resulted in some duplication among chapters, but this format should benefit a larger audience by facilitating the publication of this information in more readily available journals. The articles will be co-authored by Quentin D. Skinner, Thomas A. Wesche, and myself. These co-authors are referred to as "we" in Chapters 2 through 4.

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CHAPTER 2

RESPONSE OF RIPARIAN VEGETATION TO FOUR YEARS OF STREAMFLOW AUGMENTATION IN SOUTHEASTERN WYOMING

ABSTRACT

Changes in above-ground biomass, density, basal cover, and below-ground biomass were examined in a previously ephemeral drainage that received flow augmentation as mitigation for an interbasin water diversion in southeastern Wyoming. In unchannelized meadows, the groundwater level was elevated to within 0.21 m of the ground surface for 90% of the time during the June through September growing season. For 10% of the time during the growing season the water level was $\geq$0.03 m above the ground surface in these meadows, while 10% of the time the water level in similar meadows without flow augmentation was 0.05-0.37 m below the ground surface. After 4 years of elevated surface and groundwater levels, the herbaceous vegetation shifted toward more water-tolerant species. Sedge (*Carex* spp.) biomass increased from 240 to 350 $g \cdot m^{-2}$ by the third year of flow augmentation, and then declined to an intermediate value (285 $g \cdot m^{-2}$) by the fourth year. Tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.) biomass declined steadily from 18 to 3 $g \cdot m^{-2}$ by the fourth year. Slimstem reedgrass (*Calamagrostis neglecta* [Ehrh.] Gaertn.) showed no consistent trend for biomass, density, or basal cover. The proportion of bare ground in the unchannelized meadows increased as much as 56% (1 to 57%) by the third year, and then declined to an intermediate value by the fourth year. Below-ground biomass (roots, rhizomes, and other organic material) for the 0-15 cm zone below the ground surface decreased from 4,900 $g \cdot m^{-2}$ before flow augmentation to 3,400 $g \cdot m^{-2}$ by the fourth year. The biomass under the developing channel was 53% of the biomass under the adjacent vegetation

(3,900 g·m^{-2}), but ranged from nearly the same as the adjacent vegetation to a minimum of 570 g·m^{-2}.

INTRODUCTION

Water is often diverted from streams and rivers in the western United States for agricultural, industrial, and municipal use. These diversions may alter aquatic and riparian resources by reducing or eliminating instream flow. Since more water transfers are likely in the future, these new projects should be designed to maximize their benefits while minimizing problems (National Research Council 1992). One potential benefit from diverting water that has seldom been considered is the method used for water conveyance. Diverted water is usually conveyed through pipelines or open channels. If a natural watercourse were used to convey this water, then new aquatic and riparian habitat may be created. This unusual method has been used by the City of Cheyenne, Wyoming, since 1985 to partially mitigate its interbasin water development program. The City is attempting to create a perennial stream by releasing a controlled portion of their water supply from the Snowy Range in southeastern Wyoming into a previously ephemeral watercourse that flows 16 km into Cheyenne's storage reservoir, Crystal Lake. The South Fork of Middle Crow Creek (SFMCC) in the Laramie Range and one of its tributaries were selected to receive this enhanced streamflow.

Few studies have examined aquatic or riparian habitat changes caused by streamflow augmentation (Kellerhals et al. 1979). Bergman and Sullivan (1963) observed the establishment of permanent vegetation following flow augmentation, but Williams and Hynes (1977) suggest that biota adapted to an ephemeral stream will probably be eliminated with flow augmentation. Excessive or irregular flow augmentation also may be detrimental to aquatic and riparian habitat (Maddock 1960, Kellerhals et al. 1979). After 2 years of flow augmentation on the SFMCC, however, plant species composition shifted toward more water tolerant species and no species were eliminated (Henszey et al. 1991). Brook trout (*Salvelinus fontinalis*) habitat also increased during this period (Wolff et al. 1989).

Part of our overall evaluation of the SFMCC streamflow augmentation project was to evaluate the riparian vegetation response to altered surface and groundwater levels caused by flow augmentation. The response of the herbaceous vegetation to 2 years of streamflow augmentation was discussed by Henszey et al. (1991). This paper describes the changes in above-ground biomass, density, and basal cover for an additional 2 years of streamflow augmentation, and the below-ground biomass response to the first 4 years of streamflow augmentation. We theorized that the vegetation should shift toward more water-tolerant species because streamflow augmentation would elevate the natural groundwater level. The response of an assemblage of wetland sedges (*Carex* spp.), tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.), and slimstem reedgrass (*Calamagrostis neglecta* [Ehrh.] Gaertn.) was evaluated because they were the most abundant herbaceous species and they appeared to be adapted to different soil moisture regimes. We expected many of the sedges, such as beaked sedge (*Carex rostrata* Stokes), Nebraska sedge (*Carex nebrascensis* Dewey) and water sedge (*Carex aquatilis* Wahl.), to increase with flow augmentation because they tolerate high water levels (Bernard 1974 and 1976, Cronquist et al. 1977, Sjöberg and Danell 1983, Grootjans and van Tooren 1984). We also expected less water tolerant species, such as tufted hairgrass, slimstem reedgrass, fieldclustered sedge (*Carex praegracilis* W. Boot) and smallwing sedge (*Carex microptera* Mack.), to decrease with flow augmentation (Weaver 1960, Walker and Coupland 1968, Herman 1970, Davy and Taylor 1974, Gomm 1978 and 1979, Rahman and Rutter 1980, Seliskar 1983). The proportion of the meadows covered by bryophyte mosses, litter, and bare ground were also examined. Below-ground biomass (e.g., roots, rhizomes, and other organic material) was sampled because we theorized that it might change with flow augmentation. The soil binding capability of below-ground biomass is generally accepted (e.g., Troughton 1957, Weaver 1963, Hathaway and Penny 1975, Waldron 1977, Sidle 1991) and occasionally has been evaluated for its ability to protect the soil from flowing water (Kramer 1936, Ree 1976, Smith 1976, Garofalo 1980, Thorne 1981, Eerdt 1985). Little information, however, is available regarding the below-ground biomass response to streamflow augmentation.

METHODS

STUDY AREA. The South Fork of Middle Crow Creek originates at an elevation of 2506 m in the Medicine Bow National Forest, and flows east 7.8 km to the lower limit of the 830 ha study area at an elevation of 2361 m (Figure 1). The upper 40% of the SFMCC is a steep (3.2-4.6%), narrow, geologically-controlled valley dominated by aspen (*Populus tremuloides* Michx.) and outcrops of Sherman granite. Meadows dominated by sedge and tufted hairgrass occur along the occasional lower gradient sections. About 1% of this steep reach was channelized before flow augmentation and the remainder consisted of an unchannelized valley bottom approximately 16 m wide. The lower 60% of the SFMCC is characterized by a wider, lower-gradient valley (0.8-1.4%) with deeper alluvial soils, and vegetation dominated by sedge meadows. Aspen and shrubby cinquefoil (*Pentaphylloides floribunda* [Pursh] Löve) formed a transition between these meadows and the upland, and occurred in the infrequent areas where a developed channel was present before flow augmentation. About 23% of the lower area was channelized before flow augmentation with nearly all of this channel occurring along the last 1.9 km of the SFMCC within the study area. The remainder of the lower area was an unchannelized valley bottom approximately 45 m wide. Four nearby watersheds were used to compare the effects of flow augmentation with similar non-augmented ephemeral watercourses (Figure 1). These comparison watersheds were chosen because of their similarity and proximity to the

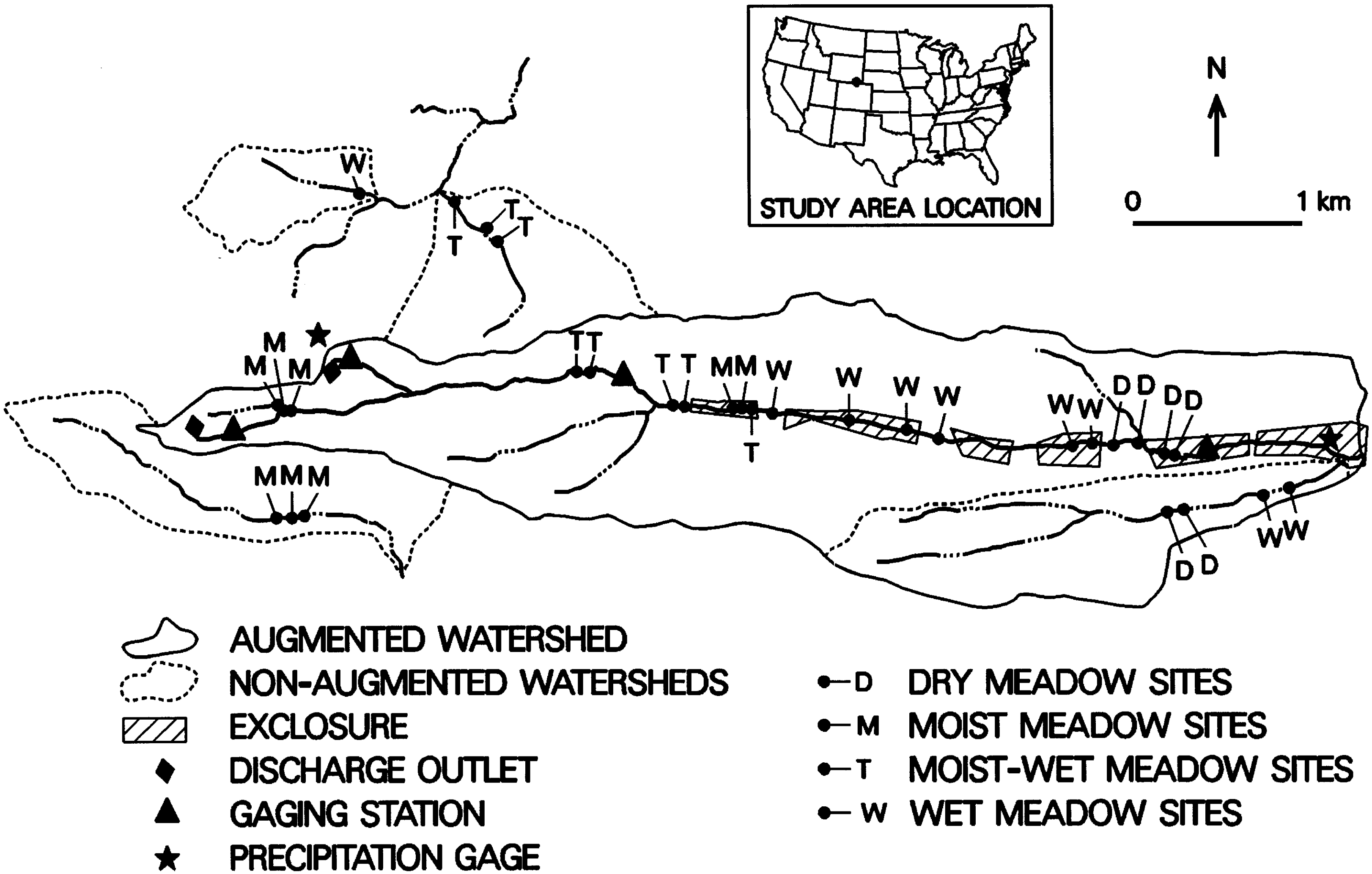

Figure 1. Map of the South Fork of Middle Crow Creek Study Area, Wyoming, and adjacent non-augmented watersheds, showing the location of the herbaceous vegetation study sites.

SFMCC plant communities.

Six livestock grazing exclosures (Figure 1) were constructed in the fall of 1984 to provide protection for the developing riparian and aquatic habitat. These exclosures included 48% (26 ha) of the total riparian habitat along the SFMCC. Parts of 2 cattle allotments were included in the study area, with the allotment boundary heading north to south through the study area and crossing the SFMCC 85 m upstream from the middle gaging station. Both allotments were managed under a three-pasture deferred rotational grazing system with a 1 June through 15 October grazing season (U.S.D.A. Forest Service 1991ab). Part of 1 pasture (1993 ha total) from the upstream allotment was in the study area. This pasture had a 42 day grazing period and a stocking rate of 0.45 $AUM \cdot ha^{-1}$. The downstream allotment was divided into 2 pastures with the boundary crossing the SFMCC at the upstream end of the fourth exclosure from the discharge outlet. The stocking rate for the upstream pasture (507 ha total, 37 days) was 0.56 $AUM \cdot ha^{-1}$, and the stocking rate for the downstream pasture (514 ha total, 41 days) was 0.62 $AUM \cdot ha^{-1}$. Pasture rotation for both allotments was based on a utilization standard of 45-55% for the meadows or aspen. Livestock were moved to the next pasture when this level was exceeded, regardless of the specified grazing period.

Four meadow types were described by Henszey et al. (1991) for the SFMCC: dry, moist, moist-wet, and wet. Dry meadows were dominated by shrubby cinquefoil, Kentucky bluegrass (*Poa pratensis* L.), mat muhly (*Muhlenbergia richardsonis* [Trin.] Rydb.), and Western iris (*Iris missouriensis* Nutt.). Moist meadows were characterized by an abundance of tufted hairgrass and an equal or slightly greater amount of sedge, including water sedge and smallwing sedge. Meadows almost entirely dominated by a mixture of beaked sedge, Nebraska sedge, water sedge, or fieldclustered sedge were considered to be either moist-wet or wet meadows. The moist-wet meadows had a minor component of tufted hairgrass, while the wet meadows had almost no tufted hairgrass. Sites dominated by aspen were also included in the below-ground biomass portion of this study. Other communities examined were named for the most characteristic plant species or physical feature of the riparian area (e.g., aspen-willow {*Populus tremuloides*-*Salix* spp.}, boulders). The groundwater dynamics for the meadow types are detailed in Chapter 4.

The study area was in a 38-48 cm precipitation zone (U.S.D.A. Soil Conservation Service 1982). From 1986 through 1989 the 2 SFMCC precipitation gages (Figure 1) recorded a low of 39 cm for the 1986 water year (October through September) and a high of 52 cm for the 1987 water year. Total monthly precipitation during the June-through-September growing season ranged from a low of 0.9 cm in August of 1988 to a high of 10.1 cm after an intense July thunderstorm in 1987.

Before streamflow augmentation the SFMCC was an ephemeral watercourse that flowed in response to spring snow melt and intense summer thunderstorms. Runoff from snowmelt typically began in March, peaked in mid April, and decreased to little or no flow by late June or early July. Scattered springs and seeps throughout the drainage provided limited areas of surface flow during non-runoff periods. Four Parshall flumes equipped with continuous recorders were installed on the SFMCC between 1985 and 1986 to gage streamflow (Figure 1). Data collected in 1985 before these gages were installed suggests that the mean flow near the lower gaging station (Figure 1) during April was about 17 Ls^{-1} ($n = 4$, $s_{\bar{x}} = 2$ Ls^{-1}). A maximum of 38 Ls^{-1} was measured near the lower gage on 1 May 1985. By mid July of 1985 there was no surface flow near the lower gage. Augmented flow was first released into the SFMCC in August of 1985. This flow was piped from the Snowy Range 60 km west of the study site and represented nearly 100% of the SFMCC streamflow in the study area from mid summer until spring runoff. A combined average total of 57 Ls^{-1} was released from the 2 discharge outlets throughout the year (Figure 1), except when the augmented flow was suspended for 1 month during peak runoff and for occasional maintenance on the supply system.

SAMPLING PROCEDURES. Suitable sites were not available for all combinations of grazing levels (i.e., inside and outside livestock grazing exclosures) with plant community types and flow augmentation levels (i.e., natural and flow augmentation), so we did not attempt to stratify by grazing level. This may have introduced some added variation in our data, but this variation appeared to be minimal because the livestock were managed under a deferred rotation grazing system that minimized the impacts from grazing.

Groundwater Hydrology. Each site typically had 4 shallow alluvial wells cased with 5 cm diameter polyvinyl chloride (PVC) pipe. Since these wells were located along a cross-valley transect, it was not possible to consistently have all 4 wells located in the plant communities represented by the sampling scheme. Each site, however, had at least 2 wells located in the selected plant communities, except for 4 below-ground biomass sites that had 1 well (1 aspen and 1 moist-wet meadow with flow augmentation, and 2 aspen without flow augmentation). Below-ground biomass was collected near the lowest point on the cross-valley transect, so fewer wells were available to represent this location. The wells were perforated below the surface at approximately 15 cm intervals and open at the bottom. Water levels were measured with an electronic probe (Henszey 1991) at least once a month during the ice-free months. More frequent measurements (daily to biweekly) were taken during the spring runoff on the ephemeral channels and following interrupted flow augmentation on the SFMCC. A transect for each community type that was accessible during the winter, and that had few wells freeze, was measured monthly throughout the winter to monitor changes during the winter.

Above-ground Herbaceous Vegetation. Sampling followed Henszey et al. (1991), except 2 SFMCC sites (1 moist meadow and 1 moist-wet meadow) were discontinued because they were flooded by beaver (*Castor canadensis*) ponds. Thirty-one study sites (Figure 1) were selected from 72 valley-bottom/groundwater-well transects established between 1984 and 1986. These transects were established to evaluate channel adjustments to flow augmentation, and were located based upon channel gradient, vegetation type, type of channel control (geologic, beaver or vegetative), and presence of livestock grazing exclosures. Sites on the SFMCC with the widest meadows were chosen first (4 dry, 5 moist, 5 moist-wet, and 6 wet meadow sites). The nearby non-augmented ephemeral stream sites were selected to represent sites similar to the SFMCC (2 dry, 3 moist, 3 moist-wet, and 3 wet meadow sites).

Above-ground biomass, basal cover, and density were sampled annually during the first 2 weeks of August from 1986 through 1989. Each site had 10 equally-spaced, 0.125 m^2, permanent quadrats located along a transect perpendicular to the general direction of the valley. Quadrats were located within the distinct boundaries of the meadow and permanently marked with steel stakes. Five additional 0.125 m^2, annual-production plots per site were destructively sampled each year to obtain above-ground biomass. The annual-production plots were rotated on a four-year cycle, with the plots located 3 m up or down stream from the permanent quadrats and opposite every other permanent quadrat. Large ungulate grazing was prevented by placing a 1.3 m^2 cage around each production plot. Production plots were sampled for above-ground biomass, while both the production plots and the permanent quadrats were sampled for basal cover and density. The species or categories sampled included sedges, tufted hairgrass, slimstem reedgrass, all other herbaceous species combined, bryophyte mosses, litter, and bare ground. Above-ground biomass samples were dried at 65°C until 2 consecutive measurements, taken a minimum of 6 hours apart, were within 0.1 g of each other. Percent basal cover was determined by taking one, 10-pin point frame sample per quadrat. Density was determined by counting the number of stems per quadrat for sedge and reedgrass, and the number of bunches per quadrat for tufted hairgrass.

Below-ground Biomass. Below-ground biomass sites were stratified by plant community type (Figure 2). Baseline sites were selected from 47 valley-bottom transects established in the fall of 1984 to evaluate channel adjustments to flow augmentation. Twenty-six baseline sites were sampled in 1984 before the ground froze for the winter, but only 12 sites (2 moist meadow, 4 moist-wet meadow, 4 wet meadow, and 2 aspen) were used for the baseline analysis. The discontinued sites were either not located in the 5 primary plant communities described above or were flooded in subsequent years by beaver ponds. In 1986 the above-ground biomass sampling scheme was expanded to evaluate the long-term response to flow augmentation (Henszey et al. 1991). These additional sites were included in the below-ground biomass sampling scheme beginning in 1987. This expanded design (n=37, including the 12 baseline sites) consisted of 24 sites on the SFMCC (2 dry meadow, 5 moist meadow, 8 moist-wet meadow, 6 wet meadow, and 3 aspen), plus 13 sites on nearby non-augmented ephemeral watercourses (2 dry meadow, 3 moist meadow, 3 moist-wet meadow, 3 wet meadow, and 2 aspen). Except for the 2 SFMCC dry meadow sites, none of these sites had a concise channel before flow augmentation. Surface flow typically traveled as sheet flow through the sites. Five 0-15 cm core samples were extracted from each baseline site in November 1984 using a heavy-walled 6.2 cm diameter core sampler. One sample was taken from near the base of a permanently located steel stake, while the other 4 samples were taken at right angles from each other approximately 1 m from the stake. The steel stake was located at the lowest elevation on the cross-valley transect or where it was assumed a channel would develop with flow augmentation due to controlling factors up-gradient (e.g., breached beaver dams). The SFMCC dry meadows (D in Figure 2) were an exception to this sampling design because a channel was already present. This channel before flow augmentation was vegetated with sedges similar to the wet meadows, so the dry meadow portion of the cross-valley transect was divided into 5 equidistant points and the 5 samples were taken

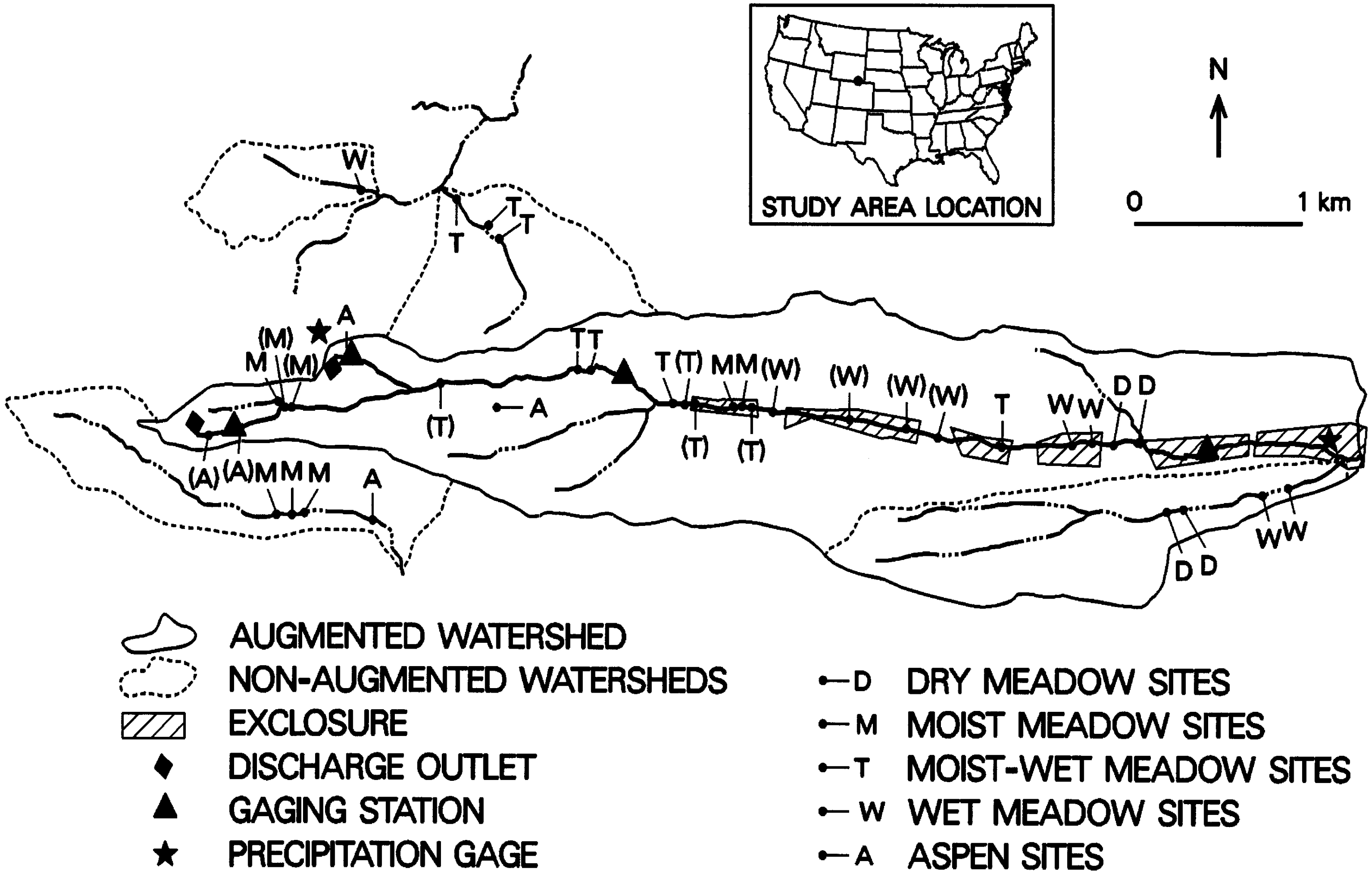

Figure 2. Map of the South Fork of Middle Crow Creek Study Area, Wyoming, and adjacent non-augmented watersheds, showing the location of the below-ground biomass study sites. The 12 baseline sites sampled in 1984 are shown in parentheses. Note that one aspen site without flow augmentation was located on an ephemeral watercourse within the SFMCC watershed that was too small to show on the map.

at these points.

When a channel began to develop and the steel stake was not in the channel, 3 additional samples were taken in the channel at 1 m intervals with the center sample located on the transect. Samples from the developing channel were not adjusted for the change in surface elevation caused by channel formation, since the objective was to determine the below-ground biomass in the 0-15 cm below the developing channel bed. This had the effect of progressively lowering the sampling depth each year as the channel developed.

Five 15-30 cm core samples were also taken at 11 of the 26 baseline sites in 1984 (3 aspen, 4 aspen-willow, 1 boulder, 2 moist meadow, and 1 wet meadow). The other 15 sites were either too rocky or too liquefied (wet meadows) to obtain adequate samples. Four of the 15-30 cm sites (2 aspen, 2 moist meadow) were also part of the 0-15 cm baseline and expanded design. The other 7 sites were not included in the 0-15 cm designs because they were either not located in the 5 primary plant communities described above or were flooded in subsequent years by beaver ponds.

The 37 sites for the expanded design were sampled using the procedures described above between late October and early November of 1987 and 1989, except a thin-walled 6.3 cm diameter copper pipe was used in the flooded areas because the heavy-walled sampler pushed the roots and rhizomes down into the soft substrate. All samples were placed in sealed plastic bags and frozen until analyzed.

ANALYSES: Groundwater Hydrology. Box-and-whisker plots (Ott 1988, SAS Institute Inc. 1990a) were used to describe the groundwater hydrograph. The periodic measurements were summarized by month, except during the spring when additional measurements were taken so May and June could be divided into 2 periods per month. Boxes were constructed to represent the median (connected by a line through each month), the middle 50% of the observations (the box), the lower 10-25% and the upper 75-90% of the observations (the whiskers), and the lower 0-10% and upper 90-100% of the observations (individual data points). These plots allow examination of the groundwater level variation within months as well as between months.

Depth-to-groundwater duration curves were generated from estimated continuous daily mean groundwater depths. These curves are cumulative frequency distributions that show the percent of time that a particular depth was equaled or above that level for the period specified, and require continuous data or at least regular periodic data. Groundwater-level recorders provide the most accurate data, but a reasonable estimate of daily values can also be obtained by regression with nearby stream gages. Linear regression with nearby stream gages was used to estimate continuous groundwater levels for the SFMCC wells. A different technique was used to estimate continuous data for the SFMCC wells with poor regressions ($p > 0.10$) and for the wells in plant communities without flow augmentation. This technique used PROC EXPAND (SAS Institute Inc. 1988) to estimate daily values between sampling points by linear interpolation. Linear interpolation provides good estimated data when the period between sample points is short and the influence from external factors (e.g., response from precipitation) is small. Without continuous data for comparison, it was difficult to judge the quality of our estimated data. We believe, however, that our data was reasonably accurate for this area based on over 6 years of experience working with continuous groundwater data from responsive sandy riparian soils in Nebraska and relatively constant subalpine riparian soils in Wyoming (Wesche et al. 1990, Peacock 1992, Henszey and Wesche 1993). Groundwater depths were calculated by subtracting the groundwater elevation from the surface elevation. Duration curves were calculated using procedures similar to those used to calculate a typical flow duration curve for streamflow analysis (Searcy 1959). PROC FREQ (SAS Institute Inc. 1985a) was used to generate the duration data and PROC GPLOT (SAS Institute Inc. 1990b) was used to graph the data. Graphical data were based upon 0.3 cm (0.01 ft) size classes.

To compare depth-to-groundwater levels between plant communities, 3 values were selected from the duration curves. These 3 values (D_{10}, D_{50}, D_{90}) show the percent of time (10, 50, 90%) that the water was at a specific level or higher, and represent the "typical" shallowest (D_{10}), median (D_{50}), and deepest (D_{90}) groundwater levels for a plant community. The actual deepest and shallowest groundwater levels for each community during the study, however, were the values for D_{100} and D_s (D_s, for shallowest, varies with the data but the duration value is usually less than 1%). A four-way analysis of variance (ANOVA) among plant communities, treatments (augmented and non-augmented), and repeated measures for years and groundwater durations was used to evaluate the groundwater response to flow augmentation. Sites were considered the experimental unit, with 36 of the 37 below-ground biomass sites used for the analysis. One moist-wet meadow site without flow augmentation was excluded from the groundwater analysis, because the wells did not represent the site. PROC GLM with the Greenhouse and Geisser adjustment for *p* (SAS Institute Inc. 1985b) was used to perform the ANOVA. Bonferroni *t* tests (Miller 1981, SAS Institute Inc. 1985b) were used to suggest which means differed when a significant effect ($p \leq 0.05$) was detected.

Above-ground Herbaceous Vegetation. The response of the above-ground herbaceous vegetation to flow augmentation was evaluated with a three-way ANOVA among meadow types, treatments (augmented and non-augmented), and repeated measures for years. A separate analysis was performed for each combination of species (or category) and biomass, density, or basal cover. Sites ($n = 31$) were considered the experimental unit. Standard deviations were dependent upon the site means for biomass, density, and basal cover. A square root transformation $[(x + 0.5)^{0.5}]$ was used to decrease this dependence for biomass and density, while an arcsine transformation (Sokal and Rohlf 1981) was used to decrease this dependence for basal cover. All analyses were performed with the transformed site means and the results presented as back-transformed values. PROC GLM with the Greenhouse and Geisser adjustment for p (SAS Institute Inc. 1985b) was used to perform the ANOVA. Bonferroni t tests (Miller 1981, SAS Institute Inc. 1985b) were used to suggest which means differed when a significant effect ($p \leq 0.05$) was detected. Differences between augmented and non-augmented sites were not tested, since they were not tested before flow augmentation.

Below-ground Biomass. Soil was washed from the samples following Lauenroth and Whitman (1971). The below-ground biomass was not separated into living and dead material, since dead roots, rhizomes, and a small amount of organic material should also provide some resistance to soil erosion. The vast majority of roots and rhizomes, however, appeared to be structurally sound without having to separate the living from the dead. Washed samples were dried at 65°C and then ashed at 500°C to determine the ash-free weight.

Two separate analyses were used to evaluate the response to flow augmentation: one using the baseline sites (1984-89) and the other using the expanded study design that included the baseline sites (1987-89). Sites were considered the experimental unit. The subsampling scheme for each site was initially intended to collect samples at the location of the developing channel. Unfortunately a channel did not always develop at this location, or only some of the subsamples were included in the developing channel. Since pooling subsamples from the developing channel and the adjacent vegetation would introduce added variation to the site mean, only the subsamples extracted from outside the developing channel (if present) were used for these 2 analyses. This maintained consistency with the 1984 samples, which were all collected in unchannelized areas. The 12 baseline sites were analyzed as a two-way ANOVA among plant communities and repeated measures for years. A three-way ANOVA ($n=37$) among plant communities, treatments (augmented and non-augmented), and repeated measures for years was used for the expanded design.

The differences between in and out of the developing channel, and between the 0-15 cm and 15-30 cm samples collected in 1984 were also examined. For the developing channel analysis, subsamples for the SFMCC sites were redistributed into 2 groups based upon location (vegetated or developing channel), then analyzed as a three-way ANOVA (n=16) among plant communities and repeated measures for location and years. The difference between the 0-15 cm and 15-30 cm samples was analyzed as a two-way ANOVA (n=11) among plant communities and repeated measures for depths.

All ANOVAs were performed using the GLM procedure, with the Greenhouse and Geisser adjustment for p (SAS Institute Inc. 1985b). Bonferroni t tests (Miller 1981, SAS Institute Inc. 1985b) were used to suggest which means differed when a significant effect ($p \leq 0.05$) was detected. Means not tested with an ANOVA are presented as the mean plus-or-minus the standard error of the mean ($\bar{x} \pm s_{\bar{x}}$).

RESULTS

GROUNDWATER HYDROLOGY. Streamflow augmentation elevated the natural groundwater level at the aspen sites along the SFMCC (Figure 3). Without a channel to convey the augmented flow, much of the adjacent vegetation became flooded with a relatively constant level of standing water throughout the year (Figure 3b). The meadows responded similarly (Chapter 4). The median groundwater level for the aspen sites without flow augmentation ranged from a low of 2.00 m below the surface in February to a high of 0.13 m below the surface in early June (Figure 3a). Although recharge usually occurred between April and May, early snow melt probably caused recharge to begin as early as January about 25% of the time and late snow melt probably delayed recharge until late May about 10% of the time. The median groundwater level was within 0.14 m of the surface from May through early June, and then dropped 0.21 to 0.76 m per month throughout the growing season (June through

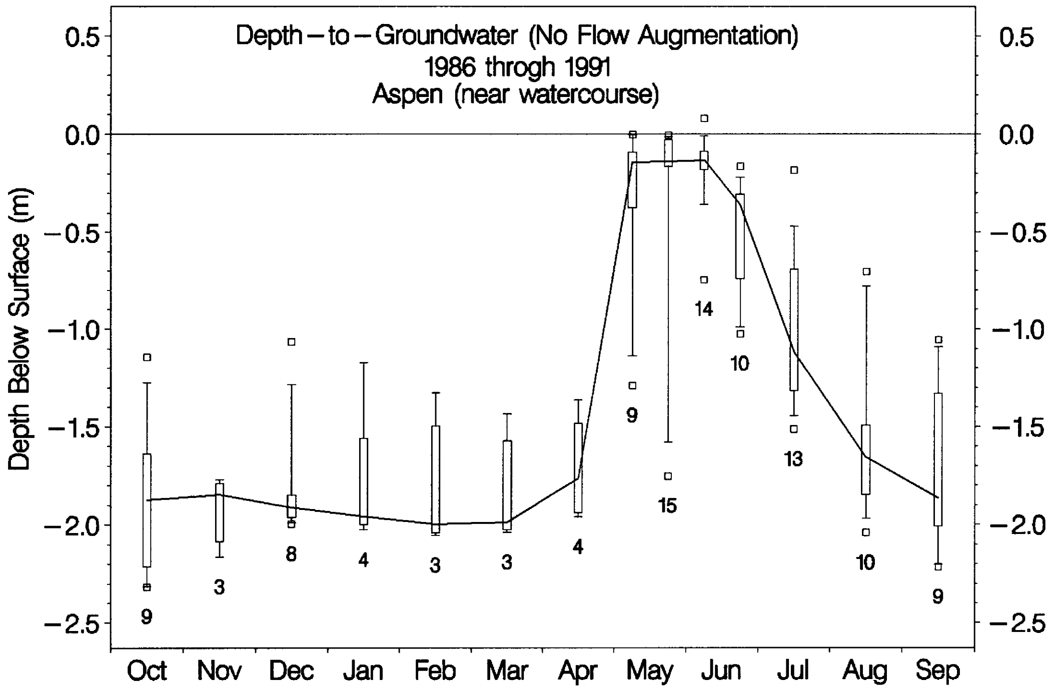

Figure 3a. Groundwater hydrograph for the aspen sites without flow augmentation, showing the variation within each month (or half month). The number of observations for each box is shown below the deepest observation. The groundwater wells were located near the lowest point on the cross-valley transect.

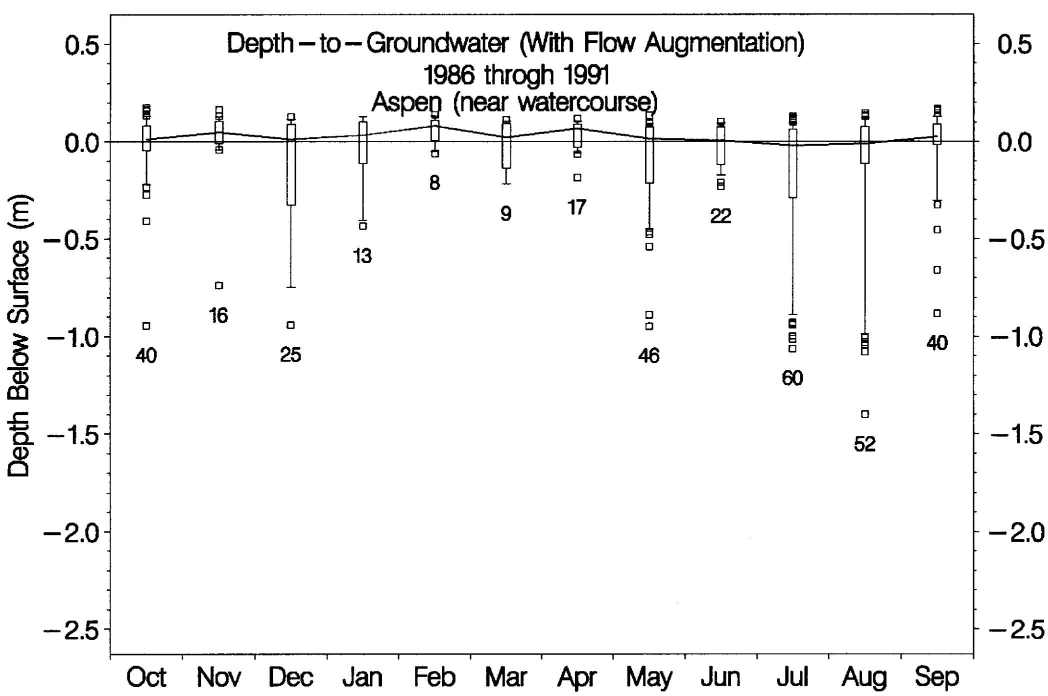

Figure 3b. Groundwater hydrograph for the aspen sites with flow augmentation, showing the variation within each month. The number of observations for each box is shown below the deepest observation. The groundwater wells were located near the lowest point on the cross-valley transect.

September). Water levels in the aspen sites without flow augmentation were never observed to be more than 0.08 m above the surface (early June), or deeper than 2.31 m below the surface (October). When the augmented flow was suspended for extended periods (e.g., 19 July through 29 August 1988), the water level in the SFMCC aspen sites approached the levels observed in the sites without flow augmentation (0-10% range for July and August, Figure 3b).

The depth-to-groundwater duration curves for the aspen sites show the proportion of time that a specific depth was equaled or above that level for the June-though-September growing season (Figure 4). Water levels varied from a high of 0.08 m above the surface to a low of 2.23 m below the surface. Water was above the surface 2% of the time for 1 of the 2 wells. Mean daily groundwater depths were within 0.5 m of the surface from 18-24% of the time, and were deeper than 1.0 m below the surface from 49-62% of the time.

Mean depth-to-groundwater for each plant community type with and without flow augmentation is presented in Table 1. The groundwater well network was not completed until 2 weeks into the 1986 growing season, so it was not possible to develop duration values for 1986. There was a difference among treatments, plant community types, and depth-to-groundwater durations ($p < 0.0001$). Wet meadows without flow augmentation had groundwater levels closer to the surface (D_{10} = -0.05 m, D_{50} = -0.44 m, D_{90} = -0.65 m) than the other 4 community types without flow augmentation. Dry meadows had the deepest D_{10} value (-0.98 m), while the aspen had the deepest D_{50} (-1.53 m) and D_{90} (-2.02 m) values for plant communities without flow augmentation. The difference between treatments was not tested before flow augmentation, but limited data collected before flow augmentation and when flow augmentation was suspended suggest that the flow augmented communities were similar to the communities without flow augmentation and that flow augmentation has elevated the groundwater levels. All flow-augmented communities had a D_{10} water level from 0.02 m below the surface to

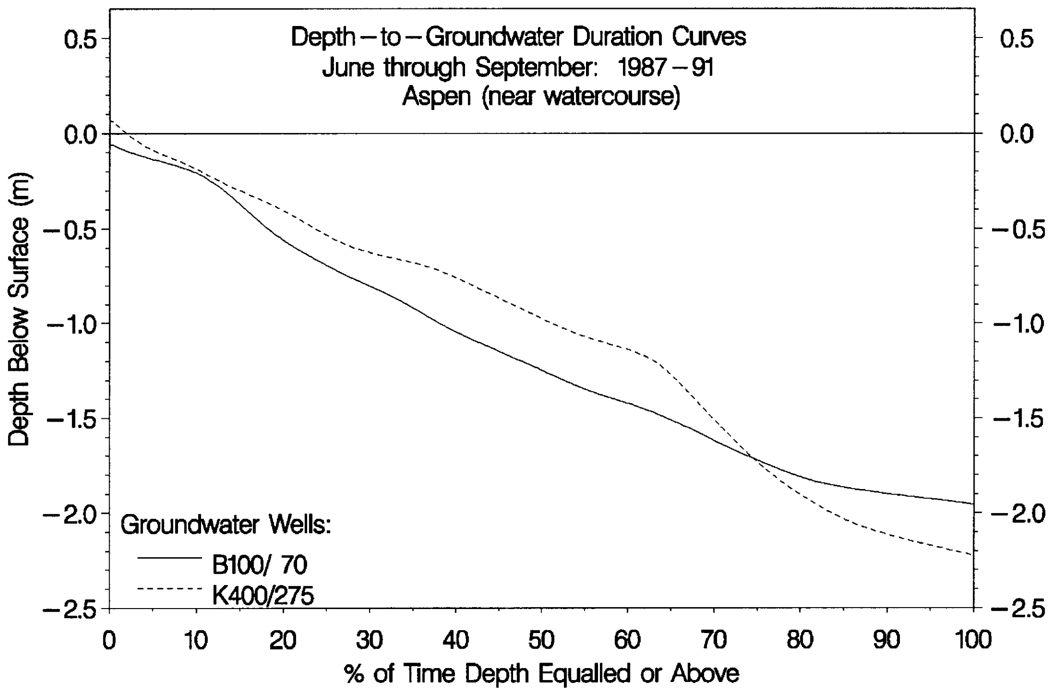

Figure 4. Depth-to-groundwater duration curves for the aspen sites without flow augmentation. Curves are for the June through September growing season for the years 1987 through 1991. The groundwater wells were located near the lowest point on the cross-valley transect. Wells are labeled by reach (letter), cross section (number before "/"), and distance across the valley bottom (number after "/").

Table 1. Mean depth-to-groundwater (m) for 10, 50, and 90% of the time (D_{10}, D_{50}, and D_{90}) by plant community type. Values shown are the mean depths that were equaled or above for each treatment (flow, or no flow augmentation) during June through September 1987-89. Means within a column followed by the same letter were not significantly different ($p > 0.05$) according to the Bonferroni *t* test.

Plant Community Type	D_{10}		D_{50}		D_{90}	
	Flow	No flow	Flow	No flow	Flow	No flow
Aspen (near watercourse)	-0.02[ab]	-0.55[b]	-0.20[bc]	-1.53[d]	-0.34[bc]	-2.02[d]
Dry meadow	-0.20[b]	-0.98[c]	-0.35[c]	-1.22[c]	-0.45[c]	-1.28[b]
Moist meadow	0.03[a]	-0.37[b]	-0.09[ab]	-1.11[bc]	-0.21[ab]	-1.58[c]
Moist-wet meadow	0.06[a]	-0.37[b]	-0.01[a]	-0.95[b]	-0.09[a]	-1.21[b]
Wet meadow	0.05[a]	-0.05[a]	-0.05[ab]	-0.44[a]	-0.18[ab]	-0.65[a]

Table 2. Mean depth-to-groundwater (m) for 10, 50, and 90% of the time (D_{10}, D_{50}, and D_{90}) by year. Values shown are the mean depths that were equaled or above for all plant communities with (flow) and without (no flow) flow augmentation during June through September. Means within a column followed by the same letter were not significantly different ($p > 0.05$) according to the Bonferroni *t* test.

Year	D_{10}		D_{50}		D_{90}	
	Flow	No flow	Flow	No flow	Flow	No flow
1987	0.02[a]	-0.53[b]	-0.01[a]	-1.04[b]	-0.03[a]	-1.28[a]
1988	0.00[a]	-0.20[a]	-0.25[b]	-0.88[a]	-0.51[b]	-1.28[a]
1989	0.03[a]	-0.53[b]	0.00[a]	-1.08[b]	-0.04[a]	-1.37[b]

0.06 m above the surface, except for the dry meadows (D_{10} = -0.20 m). The SFMCC dry meadows had a channel before flow augmentation, so the groundwater levels (D_{10}, D_{50}, and D_{90}) tended to be deeper than the other SFMCC plant communities with little or no channel. There was also a difference among treatments, years, and depth-to-groundwater durations ($p < 0.05$, Table 2). Groundwater depths for the SFMCC in 1988 were 0.25 m (D_{50}) and 0.48 m (D_{90}) deeper than were observed in 1987 or 1989, because flow augmentation was suspended from 19 July to 29 August 1988. D_{10} depths for the SFMCC were similar for all 3 years (0.00-0.03 m), because most of the highest groundwater levels occurred between May and early June (Figure 3a) before the augmented flow was suspended in 1988.

ABOVE-GROUND HERBACEOUS VEGETATION. Slimstem reedgrass remained relatively unaffected by the first 4 years of streamflow augmentation (Figure 5). Above-ground biomass differed among treatments, meadow types, and years ($p < 0.05$). Biomass increased from 4 to 31 $g \cdot m^{-2}$ between 1986 and 1987, but returned to the 1986 level in 1988 and 1989. Stem density differed among treatments and years ($p < 0.0001$), but the flow-augmented sites remained unchanged while the sites without flow augmentation varied by year.

Sedge biomass for all meadow types and density in the dry meadows tended to increase, while sedge basal cover declined with flow augmentation. Above-ground biomass ($p < 0.01$) and basal cover ($p < 0.01$) differed among treatments and years, and stem density differed among treatments, meadow types, and years ($p < 0.001$). The mean biomass for all meadows with flow augmentation increased from 240 $g \cdot m^{-2}$ in 1986 to 350 $g \cdot m^{-2}$ in 1988, but then returned to the 1986 level (285 $g \cdot m^{-2}$) in 1989. Stem density increased consistently from 1986 to 1989 (160 to 580 $stems \cdot m^{-2}$) in the dry meadows with flow augmentation, but showed no consistent trend in the other 3 meadow types. Mean basal cover for all meadows with flow augmentation declined from 14% in 1986 to 4% in 1989.

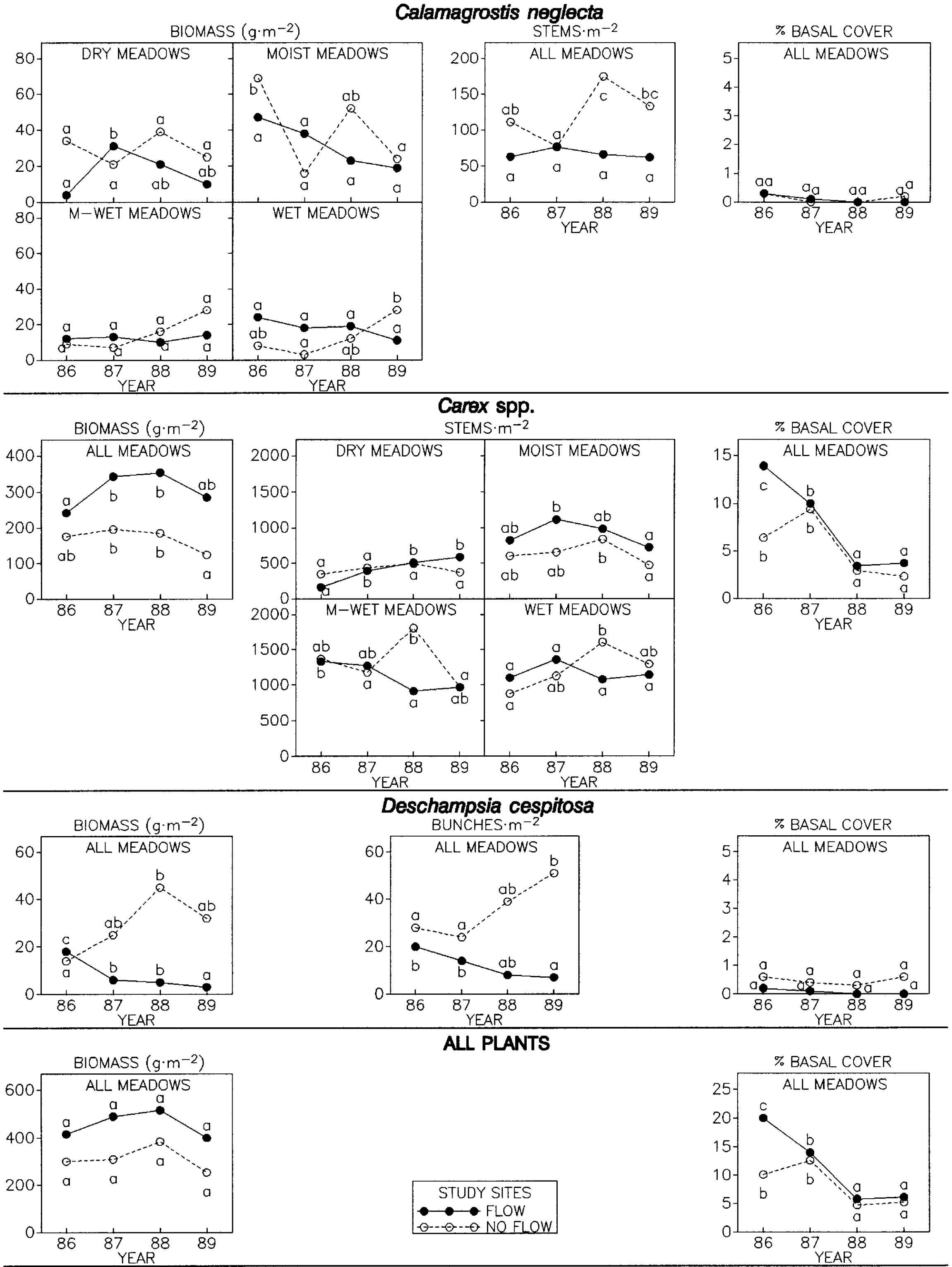

Figure 5. Slimstem reedgrass, sedge, tufted hairgrass, and total plant response to streamflow augmentation (flow) and adjacent ephemeral streams without flow augmentation (no flow). Flow augmentation began August 1985. Means on the same line with an identical letter were not significantly different ($p > 0.05$) according to the Bonferroni t test.

Tufted hairgrass biomass and density declined consistently during the first 4 years of streamflow augmentation (Figure 5). Above-ground biomass ($p < 0.0001$) and bunch density ($p < 0.0001$) differed among treatments and years. Mean biomass for all meadows with flow augmentation decreased between 1986 and 1989 (18 to 3 $g \cdot m^{-2}$). The mean density for all meadows with flow augmentation also decreased between 1986 and 1989 (20 to 7 bunches$\cdot m^{-2}$).

The category for other plant species remained unchanged, showing no differences among treatments and years, or among treatments, meadow types, and years for either above-ground biomass ($p > 0.22$) or basal cover ($p > 0.24$). Total plant response was similar to the sedges (Figure 5), but only the basal cover showed a difference among treatments and years ($p < 0.001$). The mean basal cover for all plants combined in the meadows with flow augmentation decreased from 20 to 6% between 1986 and 1989. Moss cover differed among treatments, meadow types, and years ($p < 0.05$). Moss cover in the flow augmented moist-wet meadows decreased from 25 to 4% between 1986 and 1987, while the other meadow types remained unchanged (Figure 6). Litter differed among treatments and years ($p < 0.05$), but the flow augmented sites showed no consistent trend (Figure 6). The proportion of bare ground differed among treatments, meadow types, and years ($p < 0.01$). Bare ground increased in the meadows with standing water ($D_{10} > 0$, Table 1), and remained unchanged in the channelized dry meadows (Figure 6). Very little bare ground was present in 1986 (4% moist, 1% moist-wet, and <1% wet meadows). Bare ground peaked in 1988 (27% moist, 57% moist-wet, and 55% wet meadows), and declined to a level that was still greater than 1986 by 1989 (19% moist, 23% moist-wet, and 24% wet meadows).

BELOW-GROUND BIOMASS. Below-ground biomass (0-15 cm) was different among plant communities, and decreased with flow augmentation. Both the baseline ($p < 0.05$) and the expanded ($p < 0.001$) designs showed a difference among

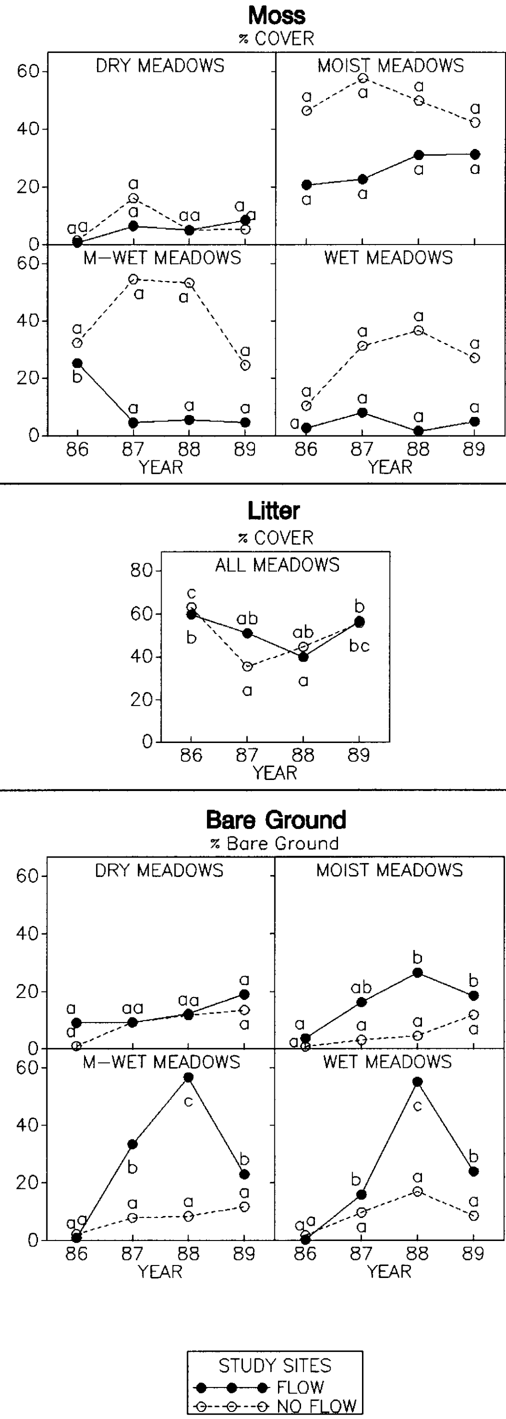

Figure 6. Moss, litter, and bare-ground response to streamflow augmentation (flow) and adjacent ephemeral streams without flow augmentation (no flow). Flow augmentation began August 1985. Means on the same line with an identical letter were not significantly different ($p > 0.05$) according to the Bonferroni t test.

plant communities. The 4 meadow types were similar, but the aspen community had less biomass than the moist-wet and wet meadow types (Figure 7). Below-ground biomass for the baseline sites decreased ($p < 0.001$) from 4,900 $g \cdot m^{-2}$ in 1984 to 3,950 $g \cdot m^{-2}$ in 1987 following the initiation of flow augmentation in 1985, and tended to decline through 1989 (Figure 8). The expanded design confirmed ($p < 0.05$) that the flow augmented sites continued to decline from 1987 (3,970 $g \cdot m^{-2}$) to 1989 (3,550 $g \cdot m^{-2}$) while the non-augmented sites remained unchanged. The slight difference between the baseline and flow augmented sites in 1987 and 1989 was because 12 additional sites were added to the original 12 baseline sites for the expanded design. There was a difference ($p \leq 0.0001$) between the flow augmented (3,760 $g \cdot m^{-2}$) and the non-augmented (5,700 $g \cdot m^{-2}$) sites, but this difference was not tested before flow augmentation began. The baseline sites before flow augmentation, however, appeared to be similar to the non-augmented sites (Figure 8).

The below-ground biomass decreased ($p < 0.05$) with depth, based on the 11 sites in 1984 where deeper samples were taken. Biomass in the 0-15 cm zone was 3,500 $g \cdot m^{-2}$, while the 15-30 cm zone was 1,300 $g \cdot m^{-2}$. These samples were mainly collected at the drier sites (aspen and aspen-willow) where it was easier to obtain deeper samples. The soils at the wetter sites became liquefied when disturbed, making deeper samples difficult to obtain. The wetter sites also appeared to have few roots below 15 cm. Although there was no interaction among community types and depth ($p > 0.85$), it is interesting that the wetter sites sampled in 1984 (2 moist and 1 wet meadow) had only 6% (226$\pm$27 $g \cdot m^{-2}$) of the 0-30 cm biomass in the 15-30 cm zone. Since the 15-30 cm increment had so little biomass and this biomass was not directly involved in protecting the surface from erosion, this increment was discontinued in subsequent years.

A channel was developing at 16 of 26 SFMCC sites (4 dry meadow, 1 moist meadow, 6 moist-wet meadow, 3 wet meadow, 2 aspen) in both 1987 and 1989. Two

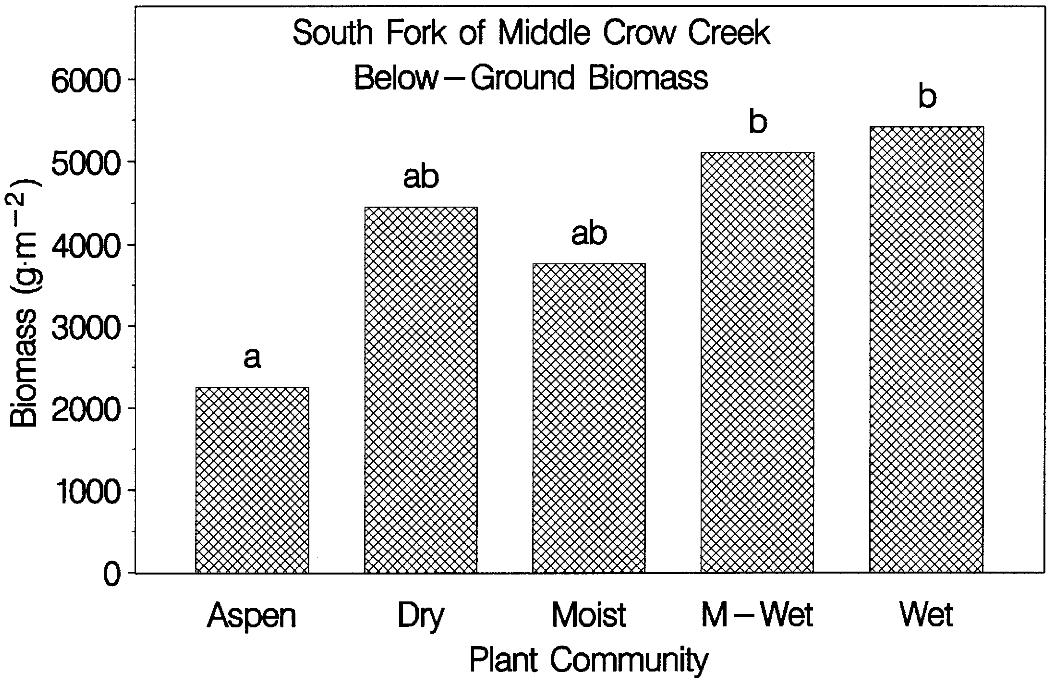

Figure 7. Mean below-ground biomass for the 5 plant communities investigated on the South Fork of Middle Crow Creek and adjacent watersheds for 1987 and 1989. Means with the same letter were not significantly different ($p > 0.05$) according to the Bonferroni t test.

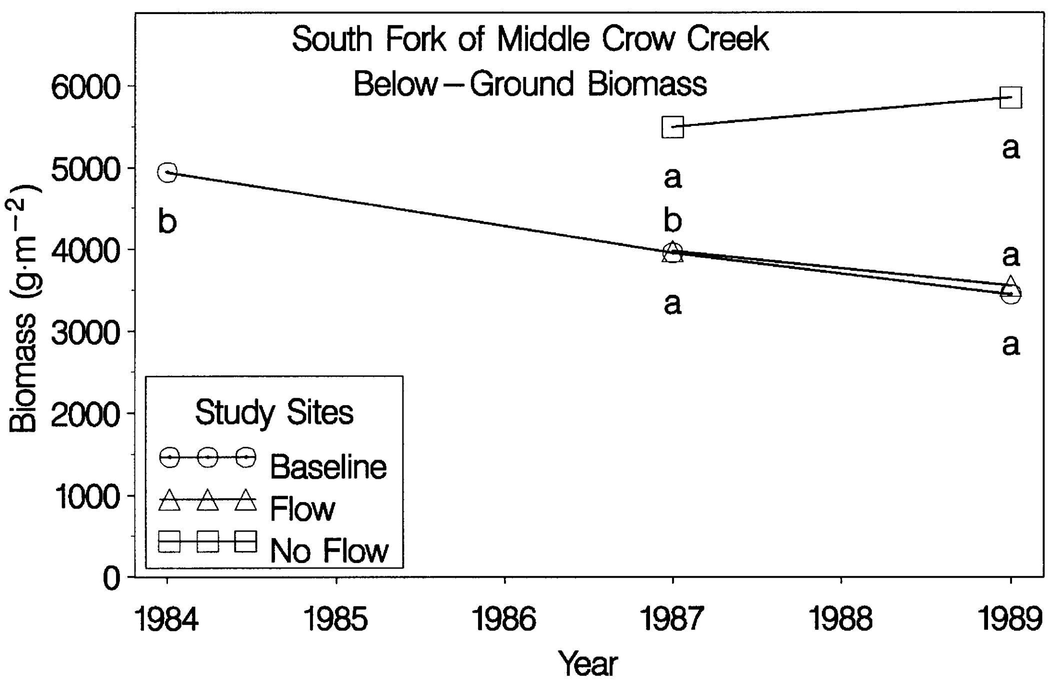

Figure 8. Below-ground biomass response to streamflow augmentation. Flow augmentation began August 1985. Baseline sites were sampled in 1984, 1987, and 1989. The study design was expanded in 1987 by adding sites to the baseline sites (now called flow augmented sites) and by sampling adjacent ephemeral streams with no flow augmentation. Means on the same line with an identical letter were not significantly different ($p > 0.05$) according to the Bonferroni t test.

of the 4 dry meadow sites were collected in the downstream livestock exclosure, and were not included in the expanded design discussed above because the subsamples were collected around the steel stake instead of the pattern used for the dry meadows. The below-ground biomass in the developing channel (2,060 $g \cdot m^{-2}$) was 53% ($p < 0.001$) of the biomass in the adjacent vegetation (3,900 $g \cdot m^{-2}$). Values for below-ground biomass in the developing channel ranged from nearly the same as the adjacent vegetation, to a minimum of 570 $g \cdot m^{-2}$ at 1 dry meadow site. The dry meadows, which all had a channel vegetated with sedges similar to the wet meadows before flow augmentation, tended to have less biomass (1,080$\pm$110 $g \cdot m^{-2}$) under the developing channel than the other plant communities (2,400$\pm$250 $g \cdot m^{-2}$), but the interaction ($p > 0.15$) among plant communities and location was not significant.

DISCUSSION AND CONCLUSIONS

As expected, 4 years of streamflow augmentation elevated the groundwater level, shifted the composition of the SFMCC meadows toward more water-tolerant species, and changed (decreased) the below-ground biomass. Since these community types were already present before flow augmentation, we did not observe the expansion of riparian vegetation reported by Bergman and Sullivan (1963). Their perennial flow came from reservoir seepage, while the SFMCC received augmented flow as a mitigation for water diversions.

GROUNDWATER HYDROLOGY. Without a channel to convey the augmented flow, water spread across the valley bottom in the aspen, moist meadows, moist-wet meadows, and wet meadows. This caused the water level to be near ($\geq$-0.02 m) or above the surface ($\geq$0.06 m) for 10% of the growing season. The dry meadows with flow augmentation also had elevated water levels, but this was less pronounced because there was a channel to convey the water. Ninety percent of the time during the growing season the water levels in the flow augmented sites were from

0.47 m (wet meadows) to 1.68 m (aspen) above the water levels in similar sites without flow augmentation. These elevated water levels were constant among years, except when the augmented flow was suspended for extended periods (e.g., 1988).

When a channel eventually forms in these previously unchannelized areas, the water levels will probably be lower. The magnitude of this potential decline will depend upon the type of channel that develops. If a channel similar to the dry meadows forms, then the water levels may still be higher than before flow augmentation. If the channel downcuts too much, however, then the water levels may be deeper than before flow augmentation. After 6 years of flow augmentation the SFMCC channel length increased from 24 to 41% (Chapter 3). Most of this channel formed by downcutting from 0 to about 0.40 m. Before the long-term effects of flow augmentation on the SFMCC groundwater levels can be fully evaluated, however, more time will be needed for the channel and groundwater levels to adjust to the augmented streamflow.

ABOVE-GROUND HERBACEOUS VEGETATION. The response of the above-ground herbaceous vegetation to 4 years of streamflow augmentation was similar to the response observed for the first 2 years of streamflow augmentation (Henszey et al. 1991), although there were some differences. The initial increase in sedge biomass observed in the wet meadows between 1986 and 1987 was maintained through 1989 for the mean biomass in all meadow types. No changes in the dry meadows were observed for sedges in the initial study, but after 4 years of flow augmentation the density of sedges in the dry meadows increased. An initial trend toward decreased basal cover for the sedges continued, and led to a decline in the mean basal cover for sedges in all the meadows from 1986 to 1989. Sedge basal cover was apparently inversely related to sedge biomass, suggesting that the sedges may have become taller with flow augmentation while becoming narrower at the base. This inverse relationship conflicts with Bernard (1975), who noted a positive relationship between shoot length and basal diameter for *Carex lacustris*. Henszey (Chapter 4) found that the optimum depth-to-groundwater for sedge biomass in the study area was a nearly constant 0.15 m (D_{10} to D_{90}) of standing water, while the optimum depth-to-groundwater for sedge density was 0.18 m (D_{10}), 0.43±0.26 m (D_{50}±95% CI), and 0.76±0.45 m (D_{90}±95% CI) below the surface. Given the current conditions in the SFMCC moist, moist-wet, and wet meadows (0.03 to 0.06 m for D_{10}, -0.09 to -0.01 m for D_{50}, and -0.21 to -0.09 m for D_{90}), it appears that the hydric sedges (e.g., beaked sedge, Nebraska sedge, water sedge, and fieldclustered sedge) are growing in nearly optimal conditions for above ground biomass.

Tufted hairgrass continued the decline observed for the first 2 years of streamflow augmentation in the moist-wet meadows (Henszey et al. 1991), by showing a consistent decline in the mean biomass and mean density for all meadow types combined from 1986 to 1989. The optimum depth-to-groundwater for tufted hairgrass was between 0.17 and 0.29 m for D_{10}, deeper than 1.23 m for D_{50}, and deeper than 1.79 m for D_{90} (Chapter 4). Since none of the SFMCC community types had depth-to-groundwater durations similar to these optimum levels, the tufted hairgrass declined with flow augmentation.

The initial increase in slimstem reedgrass observed in the dry meadows between 1986 and 1987 (Henszey et al. 1991) was temporary. Slimstem reedgrass biomass in the dry meadows returned to the 1986 level by 1988, and remained unchanged from 1986 to 1989 for biomass in the other meadow types. Mean density and mean basal cover for all meadow types also remained unchanged from 1986 to 1989. Slimstem reedgrass had the least well defined relationship for depth-to-groundwater (Chapter 4), but slimstem reedgrass density appeared to decrease if the groundwater depths were shallower than 1.05 m for D_{10}, 1.34 m for D_{50}, and 1.81 m for D_{90}. None of the SFMCC communities had depth-to-groundwater durations similar to these optimum levels, yet slimstem reedgrass appeared to be relatively unaffected by streamflow augmentation. Apparently slimstem reedgrass has a fairly broad ecological tolerance for groundwater levels.

The above-ground vegetation response to flow augmentation has so far been dominated by elevated water levels because there has been little or no channel to convey the water. This may change when a channel develops, however. If the channel downcuts too much and drains the groundwater from the riparian plant communities, then tufted hairgrass may increase while sedges may decrease.

BELOW-GROUND BIOMASS. Four years of streamflow augmentation decreased the below-ground biomass averaged over the 5 plant communities on the SFMCC. The decrease may have been more pronounced between 1985 and 1986 following the initiation of flow augmentation in August of 1985, but samples were not collected for those years. Although the below-ground biomass decreased following flow augmentation, the total above-ground biomass for the meadows remained unchanged (400-516 $g \cdot m^{-2}$, $p > 0.30$) during this period. Above-ground biomass in the aspen was not sampled, but field observations suggest that the aspen were apparently healthy for at least 3 years (through 1988) of flow augmentation. By 1991 (Year 6) nearly all the aspen in shallow standing water were dead, however. Mature aspen in the SFMCC study area generally die within a year after being flooded in beaver ponds, so it is interesting that it took 4-6 years of nearly constant elevated water levels before they died. Krasny et al. (1988) suggest that aspen are unable to tolerate flooding because they do not readily form adventitious roots. Adventitious roots are an important adaptation for survival in saturated, anaerobic soil. We suspect that aspen on the SFMCC were able to tolerate shallow flooding longer than aspen in beaver ponds, because the flowing water may have provided better gas exchange with the roots.

Below-ground biomass was generally higher in the SFMCC sedge meadows than reported for other sedge meadows (Bernard 1974, Manning et al. 1989). Our values were probably higher because we included dead material in the below-ground biomass. Anaerobic conditions retard decomposition, causing the buildup of considerable dead material (Bernard and Fiala 1986). When Bernard and Fiala (1986) included dead material, their total below-ground biomass (2,237-4,948 $g \cdot m^{-2}$) was similar to the SFMCC (3,760-5,400 $g \cdot m^{-2}$). The mean below-ground biomass for aspen in the SFMCC and adjacent watersheds for 1987 and 1989 (2,100 $g \cdot m^{-2}$) was similar to the total aspen and understory biomass for roots ≤ 3.0 cm in diameter (2,040-2,180 $g \cdot m^{-2}$) found by Ruark and Bockheim (1988). This suggests that a buildup of below-ground biomass due to anaerobic conditions did not occur in the SFMCC aspen meadow types.

Although the below-ground samples were collected and analyzed in 15 cm increments, most of the roots and rhizomes in the samples appeared to be concentrated within 8 cm of the surface in 1989. In contrast, the roots and rhizomes appeared to be more evenly distributed throughout the 0-15 cm samples collected in 1984 and 1987. Mörnsjö (1969) found that most active roots were just above the anaerobic zone, although species with aerenchyma (e.g., beaked sedge) had roots penetrating deep into the anaerobic zone. Bernard and Gorham (1978) noted similar rooting characteristics and described 2 major root types. One type was a fibrous root that grows nearly horizontal and is more plentiful in aerated soils. The second type was an unbranched root that grows nearly straight down and seems more common in waterlogged, anaerobic soils. If permanent shallow flooding has established an anaerobic zone close to the soil surface and shifted the SFMCC sedges from fibrous to unbranched roots, then there may be less intertwined roots to bind the soil and fewer roots overall to protect the soil from erosion. This shift in root type might have been tested more adequately by measuring the root length density (Manning et al. 1989). Not all sedges, however, respond to anaerobic soils by decreasing their root biomass. Moog and Janiesch (1990) found that both *Carex remota* and *Carex pseudocyperus* increased their root biomass and density in anaerobic soils.

The developing channel had less below-ground biomass than the adjacent vegetation. Whether this was true before flow augmentation could not be tested, since the channel did not always form at the permanent sampling points. Most likely there was less biomass under the developing channel because the channel was beginning to downcut (0 to about 40 cm) into the root mass and the 0-15 cm samples were essentially collected at a greater depth than the adjacent vegetation. The flowing water apparently removed the exposed roots and rhizomes as the channel downcut, because this material was seldom observed above the developing channel bottom. Although the developing channel had less biomass, it was surprising to find that even the most developed channels (dry meadows) had at least 570 $g \cdot m^{-2}$. Most of these roots and rhizomes still appeared to be structurally sound, if not living.

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CHAPTER 3

CHANNEL RESPONSE AND TIME-OF-TRAVEL IN AN EPHEMERAL WATERCOURSE ADJUSTING TO STREAMFLOW AUGMENTATION

ABSTRACT

Channel adjustments to 6 years of streamflow augmentation and changes in the time-of-travel for water moving downstream were examined in a previously ephemeral watercourse that received flow augmentation as mitigation for an interbasin water diversion in southeastern Wyoming. The time-of-travel was used to examine the rate of channel formation by measuring the traveltime of an introduced fluorescent dye. As the channel developed, the leading edge and peak dye concentrations typically arrived earlier than the previous year. Decreased traveltime showed that water was moving more efficiently through the watercourse, even in areas where a channel was not evident. The proportion of channel increased from 24% (2,017 m) of the study area length before flow augmentation to 41% (3,446 m) by the sixth year of flow augmentation. Most of this channel formed by downcutting rather than by the upstream migration of abrupt breaks in channel gradient (nick points). Channel roughness (Manning's n) was used as an index to compare the state of channel development with similar natural perennial streams. Initial channel roughness values were high, ranging from 0.446 for the steeper reaches to 1.181 for the lower-gradient meadows. Channel roughness decreased over 6 years but remained high, suggesting that the channel was still adjusting to flow augmentation.

INTRODUCTION

Riparian zones in the western United States are important focal points for the management of recreation, livestock, water quality, and fish and wildlife resources (Kauffman and Krueger 1984). These zones are often recognized as areas occupying the transition between water in a defined stream channel and the adjoining upland ecosystem (Brown et al. 1978). Since water is important to riparian zones, the removal of water for other uses has caused significant controversy (Reisner 1986, National Research Council 1992). In contrast adding water to the normal flow has seldom been considered, so little is known about this action (Kellerhals et al. 1979). Streamflow augmentation, however, may provide an opportunity to improve aquatic and riparian habitat with water that would normally be transported through pipelines or open channels. If a suitable watercourse along the pipeline diversion route is available, then streamflow augmentation may provide a viable option when considering mitigation for water development projects.

Streamflow augmentation may be detrimental to aquatic and riparian habitat if the flow is excessive or interrupted (Maddock 1960, Kellerhals et al. 1979). Favorable results may be obtained, however, if the augmented flow is within the capacity of the existing channel or the channel is allowed to adjust by controlled releases into the channel (Bergman and Sullivan 1963). Improving aquatic and riparian resources was the intention of a streamflow augmentation project used by the City of Cheyenne, Wyoming, since 1985. This project was designed to partially mitigate an interbasin water development project by releasing a controlled portion of the diverted flow into a previously ephemeral watercourse along the pipeline diversion route. The South Fork of Middle Crow Creek (SFMCC), a mostly unchannelized montane ephemeral watercourse in southeastern Wyoming, was selected to receive this enhanced streamflow.

The initial adjustments to flow augmentation of the stream channel, fish habitat, and meadow vegetation were described by Wolff et al. (1989), and Henszey et al. (1991). This paper describes the rate of channel formation on the SFMCC for the first 6 years of flow augmentation. We theorized that the time-of-travel for water moving through the SFMCC would decrease as a channel formed, because the augmented flow would initially be obstructed by litter and vegetation in the flooded, unchannelized valley. As an unobstructed channel formed and the flow became consolidated into a defined channel with an increased velocity, the traveltime should decrease. To compare our results with natural perennial streams we used the Manning roughness coefficient *n*. This coefficient is inversely related to streamflow velocity and should indicate when the SFMCC channel has adjusted to the streamflow augmentation.

METHODS

<u>**STUDY AREA**</u>. The South Fork of Middle Crow Creek originates at an elevation of 2506 m in the Medicine Bow National Forest, and flows east 7.8 km to the lower limit of the 830 ha study area at an elevation of 2361 m (Figure 9). The upper 40% of the SFMCC is a steep (3.2-4.6%), narrow, geologically-controlled valley dominated by aspen (*Populus tremuloides* Michx.) and outcrops of Sherman granite. Meadows dominated by sedge (*Carex* spp.) and tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.) occur along the occasional lower gradient sections. About 1% of this steep reach was channelized before flow augmentation and the remainder consisted of an unchannelized valley bottom approximately 16 m wide. The lower 60% of the SFMCC is characterized by a wider, lower-gradient valley (0.8-1.4%) with deeper alluvial soils, and vegetation dominated by sedge meadows. About 23% of the lower area was channelized before flow augmentation with nearly all of this channel occurring along the last 1.9 km of the SFMCC within the study area. The remainder of the lower area was an unchannelized valley bottom approximately 45 m wide.

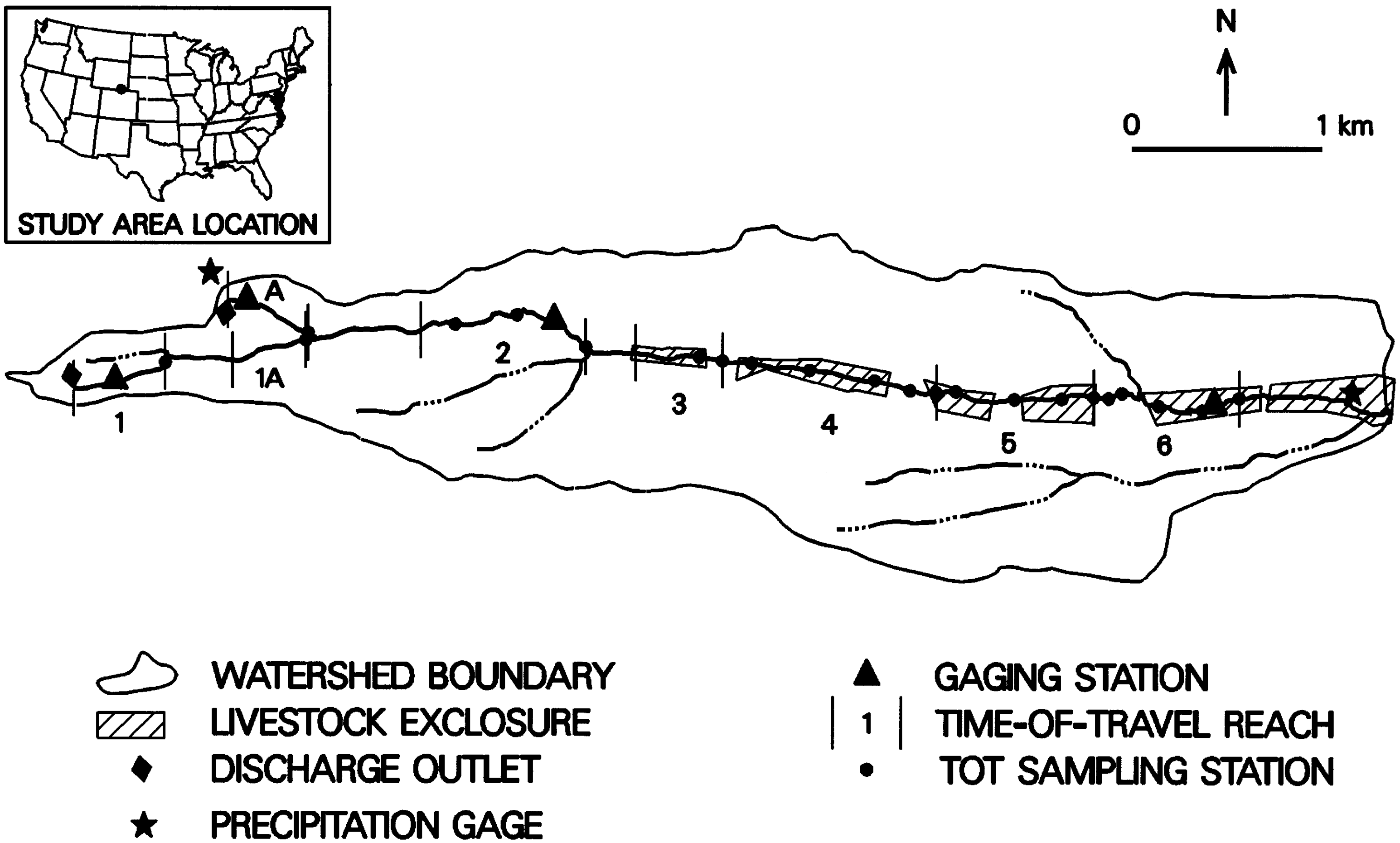

Figure 9. Map of the South Fork of Middle Crow Creek Study Area, Wyoming, and the time-of-travel (TOT) study reaches.

Six livestock grazing exclosures (Figure 9) were constructed in the fall of 1984 to provide protection for the developing riparian and aquatic habitat. These exclosures included 48% (26 ha) of the total riparian habitat along the SFMCC. Parts of 2 cattle allotments were included in the study area, with the allotment boundary heading north to south through the study area and crossing the SFMCC 85 m upstream from the middle gaging station. Both allotments were managed under a three-pasture deferred rotational grazing system with a 1 June through 15 October grazing season (U.S.D.A. Forest Service 1991ab). Part of 1 pasture (1993 ha total) from the upstream allotment was in the study area. This pasture had a 42 day grazing period and a stocking rate of 0.45 $AUM \cdot ha^{-1}$. The downstream allotment was divided into 2 pastures with the boundary crossing the SFMCC at the upstream end of the fourth exclosure from the discharge outlet. The stocking rate for the upstream pasture (507 ha total, 37 days) was 0.56 $AUM \cdot ha^{-1}$, and the stocking rate for the downstream pasture (514 ha total, 41 days) was 0.62 $AUM \cdot ha^{-1}$. Pasture rotation for both allotments was based on a utilization standard of 45-55% for the meadows or aspen. Livestock were moved to the next pasture when this level was exceeded, regardless of the specified grazing period.

Four meadow types were described by Henszey et al. (1991) for the study area: dry, moist, moist-wet, and wet. Dry meadows were dominated by shrubby cinquefoil (*Pentaphylloides floribunda* [Pursh] Löve), Kentucky bluegrass (*Poa pratensis* L.), mat muhly (*Muhlenbergia richardsonis* [Trin.] Rydb.), and Western iris (*Iris missouriensis* Nutt.). Moist meadows were characterized by an abundance of tufted hairgrass and an equal or slightly greater amount of sedge. Meadows almost entirely dominated by sedge were considered to be either moist-wet or wet meadows. The moist-wet meadows had a minor component of tufted hairgrass, while the wet meadows had almost no tufted hairgrass. Other communities (cottonwood {*Populus angustifolia* James}, aspen, aspen-willow, willow {*Salix* spp.}, and boulders) were named for the most characteristic plant species or physical feature of the riparian area.

The study area was in a 38-48 cm precipitation zone (U.S.D.A. Soil Conservation Service 1982). From 1986 through 1991 the 2 SFMCC precipitation gages (Figure 9) recorded a low of 39 cm for the 1986 water year (October through September) and a high of 63 cm for the 1990 water year. Total monthly precipitation during the June-through-September growing season ranged from a low of 0.9 cm in August of 1988 to a high of 11.0 cm in July of 1990.

Before streamflow augmentation the SFMCC was an ephemeral watercourse that flowed in response to spring snow melt and intense summer thunderstorms. Runoff from snowmelt typically began in March, peaked in mid April, and decreased to little or no flow by late June or early July. Scattered springs and seeps throughout the drainage provided limited areas of surface flow during non-runoff periods. Four Parshall flumes equipped with continuous recorders were installed on the SFMCC between 1985 and 1986 to gage streamflow (Figure 9). Data collected in 1985 before these gages were installed suggest that the mean flow near the lower gaging station (Figure 9) during April was about 17 Ls^{-1} ($n = 4$, $s_{\bar{x}} = 2$ Ls^{-1}). A maximum of 38 Ls^{-1} was measured near the lower gage on 1 May 1985. By mid July of 1985 there was no surface flow near the lower gage. Augmented flow was first released into the SFMCC in August of 1985. This flow was piped from the Snowy Range 60 km west of the study site and represented nearly 100% of the SFMCC streamflow in the study area from mid summer until spring runoff. A combined average total of 57 Ls^{-1} was released from the 2 discharge outlets throughout the year (Figure 9), except when the augmented flow was suspended for 1 month during peak runoff and for occasional maintenance on the supply system.

STUDY REACHES. The watercourse within the study area was divided into 8 reaches denoted by numbers and letters in Figure 9. Reach lengths were adjusted to avoid beaver ponds or provide suitable dye injection points between adjacent reaches. Reach 1A was initially part of Reach 1, but was separated from Reach 1 in 1988 to avoid a newly established beaver-pond complex.

For each reach the length, slope, proportion of developed channel, and hydraulic geometry were determined. Reach length and slope were determined from a grade line survey conducted in 1985 using standard engineering techniques. The proportion of developed channel was estimated from field observations in 1984, 1989, and 1991 (Years 0, 4, and 6). A channel was considered fully formed when all the augmented flow was confined within defined banks with little or no water spread across the valley floor. Channel geometry was quantified each fall at 41 permanently located cross-valley transects where the wetted perimeter, cross-sectional area, and hydraulic radius were determined. These transects were located based upon channel gradient, vegetation type, type of channel control (geologic, beaver or vegetative), and presence of livestock grazing exclosures.

TIME-OF-TRAVEL. Rhodamine WT, a harmless fluorescent dye (Kilpatrick and Wilson 1989), was used to measure the time-of-travel. The change in traveltime was determined by comparing the arrival time at selected downstream locations with the previous year. Fluorescent dyes have been used to investigate other hydrologic properties including: the traveltime for noxious substances, discharge, reaeration rates, water uptake by plants, and Manning's *n* (Shih and Rahi 1982, Wesche et al. 1983, Wilson et al. 1986, Kilpatrick and Wilson 1989), but has never been used to investigate channel response to flow augmentation.

Our time-of-travel procedures followed Kilpatrick and Wilson (1989) and Wilson et al. (1986). Reaches were sampled in succession starting with the downstream reach (Reach 6), so that residual dye from upstream reaches would not interfere with subsequent tests. A single slug of rhodamine WT fluorescent dye was injected into the center of flow at the upstream end of the reach. The dye concentration was measured at one or more stations (locations) downstream from the injection point using a Turner Designs model 10 fluorometer. Samples were collected from the center of flow at each station, and taken as often as necessary (30 s to $\geq$20 min) to detect the leading edge and peak dye concentration. Sampling continued until the peak concentration was detected, or until it became obvious that the dye had become too dispersed to detect a peak. Dye concentrations were not unitized (Kilpatrick and Taylor 1986) to adjust for the quantity of dye injected, dye lost, or stream discharge, since the objective of this study was to monitor the arrival of the leading edge and peak. Unitizing requires observations until the dye concentration returns to 10% of the peak, and is more important for studies investigating the dispersion of a soluble contaminant.

Time-of-travel tests were conducted once a year between the first week of July and the first week of August. This sampling period occurred after spring runoff and coincided with the peak standing crop of vegetation. Streamflow was monitored during the tests at each of the 4 gaging stations (Figure 9).

CHANNEL ROUGHNESS. The time-of-travel was used to make comparisons among years for the same SFMCC reaches, but the channel roughness provides a more universal value for comparison with other streams. An estimate of channel roughness was determined by rearranging Manning's equation (Barnes 1977) to:

$$n = v^{-1}\, R^{2/3}\, S^{1/2} \qquad \textbf{(1)}$$

where n is a dimensionless roughness coefficient, v is the mean velocity ($m \cdot s^{-1}$) for the reach, R is the mean hydraulic radius (m) for the reach, and S is the reach slope ($m \cdot m^{-1}$). The velocity was determined from the time-of-travel, and R and S were calculated from the cross-valley transects and the gradeline survey. Manning's roughness coefficient was used solely to provide an index for comparison with other streams, and not as a test of its underlying theory. Two estimates for channel roughness were calculated: one based on the leading-edge velocity and the second based on the peak-concentration velocity. The faster leading-edge velocity underestimates n, while the peak-concentration velocity more closely approximates the true value for n since this velocity is closer to the mean reach velocity (Kilpatrick and

Wilson 1989). The leading-edge values were included because the peak was not always detected early in the study. A weighted mean of 2-7 transects per reach was used to calculate R. Weights were based on the proportion of each reach that a transect represented. The transects detailed the channel profile, but the cross-sectional area of the wetted channel had to be estimated from indefinite locations for the left and right edge of water. The values for R, therefore, should be considered rough estimates.

Equation 1 has been used to calculate *n* for vegetated waterways (Ree and Palmer 1949, Ree and Crow 1977), and for a marsh (Shih and Rahi 1982). Some factors affecting the value of *n* include: size and shape of side and bottom material, height of channel vegetation, channel cross section, channel curvature, size and types of obstructions, and stage (Wesche et al. 1983). Additional factors affecting *n* for heavily vegetated waterways include: the product of the velocity and hydraulic radius, water depth or degree of submergence, and the size, shape, flexibility and density of the vegetation (Ree and Palmer 1949, Petryk and Bosmajian 1975, Thompson and Roberson 1976).

RESULTS

CHANNEL FORMATION. Study reaches were mostly unchannelized before flow augmentation (Table 3). Only the downstream reach (Reach 6) was completely channelized before flow augmentation. Reach 6 was the upstream end of the developed channel for the SFMCC. The remaining reaches had little (10%) or no channel. When flow augmentation began in 1985, the water flooded the valley floor in the unchannelized areas and traveled as sheet-flow down valley. Channel formation occurred first where the flow was confined by geologic controls (Reach 2), by vegetative controls (aspen and willow in Reach 5), or by abandoned beaver dams (Reach 3). Steeper slopes also encouraged channel formation (Reaches 1A and 2), but not consistently (Reach A).

Table 3. Physical and biological characteristics for the South Fork of Middle Crow Creek time-of-travel study reaches.

			Developed Channel (%)			Plant Communities[1] (% of reach)								
Reach	Length (m)	Slope (%)	Year 0	Year 4	Year 6	1	2	3	4	5	6	7	8	9
A	549	3.5	0	10	27	0	44	56	0	0	0	0	0	0
1	679	1.7	0	9	29	0	96	0	0	0	4	0	0	0
1A	432	4.8	0	40	44	43	19	38	0	0	0	0	0	0
2	1127	3.2	3	63	69	0	15	47	0	0	0	31	0	7
3	464	1.4	0	50	71	0	0	0	3	0	0	40	57	0
4	1154	1.1	0	3	5	0	0	0	0	0	0	0	100	0
5	888	1.2	10	50	69	0	17	0	13	0	0	8	62	0
6	969	0.8	100	100	100	0	0	0	16	84	0	0	0	0
Total[2]	8405	1.7	24	35	41	1	39	10	11	17	6	4	12	T[3]

1. Plant communities: 1) cottonwood, 2) aspen, 3) aspen-willow, 4) willow, 5) dry meadow, 6) moist meadow, 7) moist-wet meadow, 8) wet meadow, 9) boulders.
2. Total flow augmented watercourse within the SFMCC study area, including portions excluded from the time-of-travel study reaches.
3. Values less than 0.5 and greater than 0.0 are labeled as trace (T).

By Year 6 (1991), 41% of the SFMCC watercourse was channelized (Table 3), and about 16% was beaver ponds. All reaches had at least 27% of their watercourse with a channel, except Reach 4. Reach 4 was a low gradient, relatively wide sedge meadow that provided little energy to form a channel. Although only 5% of Reach 4 was channelized by Year 6, about 60% of the reach had the majority of flow concentrated in one general path. The concentrated flow had not yet formed a channel, so standing water was still spread across the valley floor.

Most of the SFMCC channel formed by downcutting, rather than by the upstream migration of nick points (abrupt breaks in channel gradient). Out of 23 nick points monitored between 1985 and 1989, the furthest any one nick point moved was 1.9 m. Most channels appeared to develop by confining their flow and then downcutting (Figures 10 and 11). The flow of water through the flooded valley eventually became concentrated in localized areas (Figure 11b). As the above-ground vegetation diminished, the velocity increased, and the water downcut through the root zone (Figures 10b and 11c).

TIME-OF-TRAVEL. Each year the leading edge and peak typically arrived earlier than the previous year, and the time for the dye to pass through a station decreased (Figure 12). The dye dispersed as it passed through each reach (Figure 13), resulting in diminished peak concentrations and an elongation of the time-concentration curves. Dispersal was especially noticeable as the dye passed through unchannelized meadows (Reaches 3-5).

Figure 14 presents a summary of the time-of-travel for the leading edge through 4 reaches representing the different combinations of vegetation type and channel slope on the SFMCC. The time-of-travel for the peak concentrations followed a similar pattern, but more time was required for the dye to reach each station. Flow through trees and willows (Reaches 1, A, 1A, 2) generally took less traveltime than flow through meadows (Reaches 3-6). Steeper gradient channels (Reaches A, 1A, 2) also

Figure 10. Evolution of a channel created by flow augmentation at the upstream end of Reach 3 (Station 0 m). Two months before flow augmentation (a), and 6 years after flow augmentation began (b).

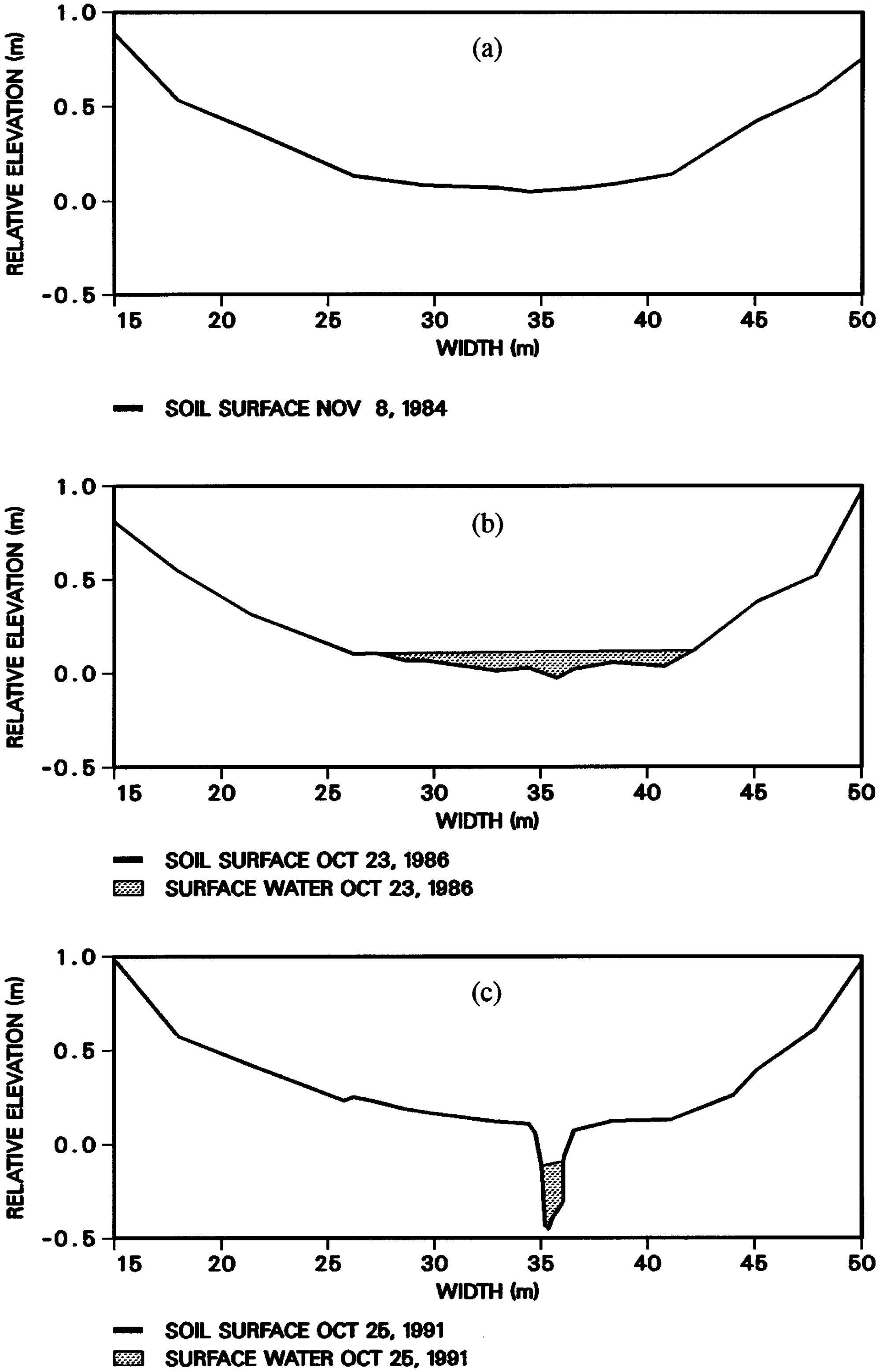

Figure 11. Cross-section profiles for Figure 10, showing the profile 1 year before (a), 1 year after (b), and 6 years (c) after flow augmentation began. Note that a channel is beginning to downcut at the 36 m position after 1 year of flow augmentation.

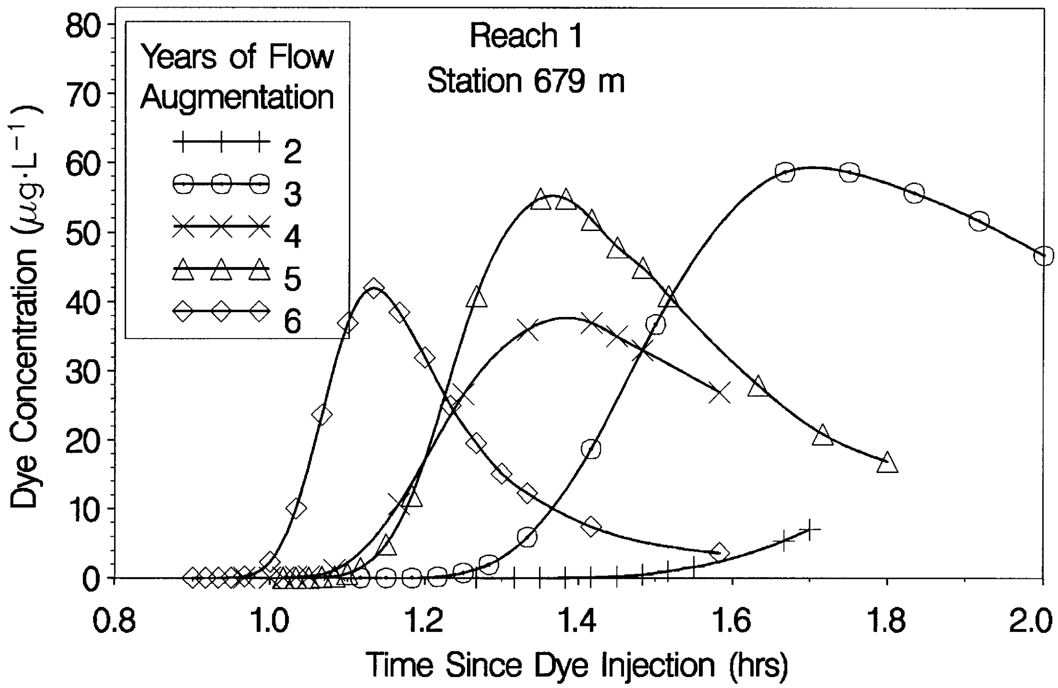

Figure 12. Time-concentration curves at the downstream end of Reach 1 (Station 679 m) for the second through sixth year of flow augmentation.

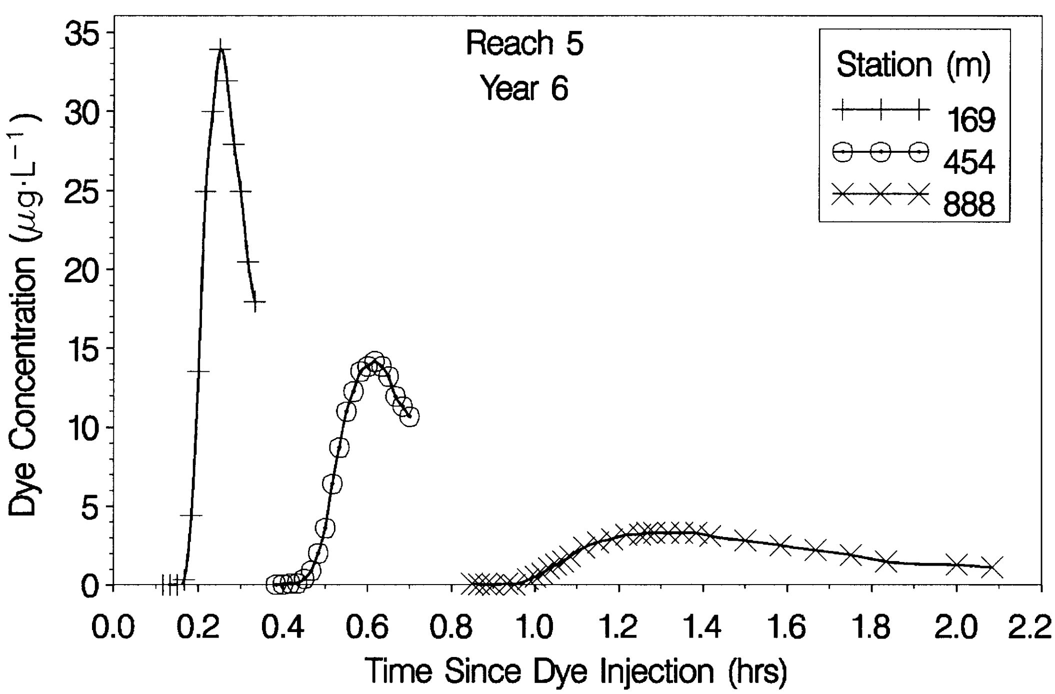

Figure 13. Reach 5 time-concentration curves for 3 locations (Stations 169, 454, 888 m) downstream from the injection point 6 years after flow augmentation began.

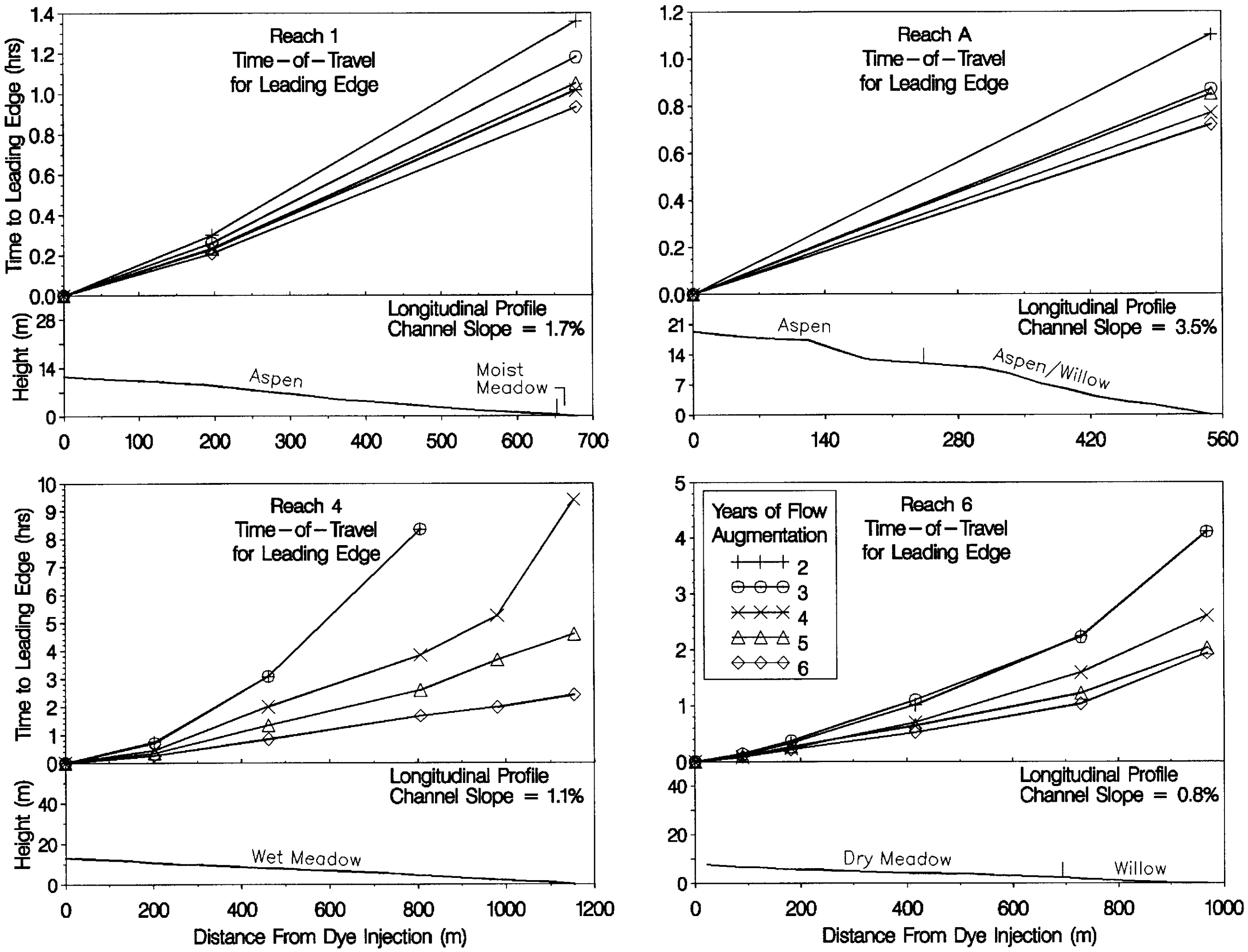

Figure 14. Time-of-travel for the leading edge, and the longitudinal profile of 4 representative reaches for the second through sixth year of flow augmentation. Symbols show the sampling stations used for each year. Reaches 1 and A were dominated by trees and willows with a low or high gradient channel respectively. Reaches 4 and 6 had low gradient channels with unchannelized or channelized meadows before flow augmentation respectively.

took less traveltime. With few exceptions, the time-of-travel for the leading edge decreased consistently from one year to the next. Notable exceptions were Reaches 4 and 6 where the time-of-travel remained unchanged between the second and third years of flow augmentation, and Reach 3 where a series of beaver ponds were established between the fifth and sixth years of flow augmentation. A substantial decrease in the time-of-travel for Reach 4 was still occurring between Years 5 and 6. Reach 4 was originally an unchannelized wet meadow (Table 3). The time-of-travel for the remaining reaches, however, was stabilizing by the end of the study.

Streamflow tended to increase each year (Table 4). Since the time-of-travel is inversely related to discharge (time = {area × length} ÷ discharge), the observed decreases in the time-of-travel may have been due solely to an increase in discharge. This may have been true for the fully formed channels (e.g., Reach 6), but some of the largest decreases in the time-of-travel occurred among years when the change in discharge was minimal. For example, the time-of-travel decreased while the discharge varied 3 Ls^{-1} or less among years for Reach A (Year 2 to 3), Reach 1 (Year 2 to 4), and Reach 4 (Year 4 to 5). At the same time the length of channel for these reaches increased less than 10% (Table 3), suggesting that the time-of-travel was influenced by water moving more efficiently through the system as well as by channel formation and discharge. More efficient streamflow was observed at many locations when most of the streamflow became concentrated in localized areas while there were still wide areas of standing water (e.g., Figure 11b).

CHANNEL ROUGHNESS. Channel roughness generally decreased each year (Table 5). The leading-edge velocity consistently estimated a smaller channel roughness value than the peak-concentration velocity, because channel roughness is inversely related to velocity. The true value for n is more closely approximated when the peak-concentration velocity is used, but the peak was not always detected early in the study because the dye became too dispersed. The leading-edge values were

Table 4. Mean discharge (Ls^{-1}) and total precipitation (mm) for the day when the time-of-travel was measured. Discharge (Q) and precipitation (P) were obtained from the gage closest to the upstream end of each reach.

	Year 2		Year 3		Year 4		Year 5		Year 6	
Reach	Q	P	Q	P	Q	P	Q	P	Q	P
A	21	T[1]	19	10	28	0	24	0	32	1
1	27	T	28	10	28	0	24	0	34	0
1A	27	T	28	T	28	0	24	0	34	1
2	37	T	39	10	51	0	51	0	70	1
3	39	T	33	0	51	0	51	0	77	9
4	39	0	37	1	57	1	59	1	73	0
5	18	0	23	1	30	0	33	14	173[2]	13
6	18	0	17	2	31	0	51	1	97	40

1. Precipitation less than 0.5 mm and greater than 0.0 mm is labeled as trace (T).
2. Discharge for Reach 5, Year 6 was high because there was 40 mm of precipitation on the previous day.

Table 5. Mean hydraulic radius (m), velocity ($m \cdot s^{-1}$), and channel roughness (Manning's *n*) for the first 6 years of streamflow augmentation. The slope used to calculate the channel roughness was presented in Table 3.

Reach	Year [1]	Hydraulic Radius [2]	Leading Edge Velocity	Leading Edge *n*	Peak Concentration Velocity	Peak Concentration *n*
A	2	0.098 (6)	0.139	0.287	0.091	0.435
	3	0.058 (6)	0.175	0.160	0.124	0.226
	4	0.064 (6)	0.198	0.151	0.154	0.195
	5	0.052 (6)	0.179	0.145	0.137	0.190
	6	0.070 (6)	0.212	0.151	0.170	0.188
1	2	0.076 (2)	0.139	0.169	-	-
	3	0.061 (2)	0.160	0.127	0.111	0.183
	4	0.082 (2)	0.185	0.133	0.136	0.181
	5	0.098 (2)	0.180	0.154	0.138	0.200
	6	0.098 (3)	0.202	0.137	0.167	0.166
1A	2	-	-	-	-	-
	3	0.088 (2)	0.133	0.327	0.098	0.446
	4	0.107 (2)	0.174	0.284	0.130	0.379
	5	0.088 (2)	0.171	0.254	0.124	0.350
	6	0.128 (2)	0.194	0.287	0.150	0.372
2	2	0.094 (6)	0.130	0.285	-	-
	3	0.064 (6)	0.133	0.215	-	-
	4	0.094 (6)	0.177	0.210	0.121	0.307
	5	0.101 (6)	0.191	0.203	0.151	0.258
	6	0.119 (6)	0.215	0.202	0.163	0.266
3	2	0.073 (6)	0.051	0.407	-	-
	3	0.073 (6)	0.077	0.268	-	-
	4	0.098 (6)	0.103	0.242	0.063	0.395
	5	0.116 (6)	0.136	0.206	0.085	0.328
	6 [3]	0.113 (6)	0.084	0.327	0.051	0.539
4 [4]	2	0.101 (4)	0.027	0.839	-	-
	3	0.067 (4)	0.027	0.640	-	-
	4	0.098 (4)	0.058	0.379	-	-
	5	0.140 (4)	0.086	0.325	-	-
	6	0.085 (4)	0.134	0.151	0.088	0.229
5	2 [5]	0.104 (7)	0.078	0.310	0.021	1.181
	3	0.085 (7)	0.063	0.338	0.044	0.489
	4	0.119 (7)	0.078	0.341	-	-
	5	0.107 (7)	0.138	0.179	0.078	0.317
	6	0.110 (7)	0.263	0.096	0.187	0.135
6	2	0.171 (7)	0.066	0.421	0.046	0.598
	3	0.155 (7)	0.066	0.395	0.049	0.530
	4	0.122 (7)	0.103	0.213	0.081	0.272
	5	0.149 (7)	0.133	0.190	0.102	0.249
	6	0.195 (7)	0.139	0.216	0.113	0.268

1. Number of years after streamflow augmentation began (1985).
2. The number of cross sections used to calculate the mean hydraulic radius is shown in parentheses.
3. Reach 3, Year 6 was affected by newly established beaver ponds.
4. Reach 4 includes data for the first 806 m. The leading edge was not detected at the lower end of Reach 4 (Station 1154 m) until Year 4.
5. Reach 5, Year 2 was sampled at Station 850 m instead of at the lower end of the Reach (Station 888 m).

included to provide a more complete record of channel roughness changes, even though the values underestimate the true value of n. Leading-edge channel roughness values ranged from a maximum of 0.839 (Reach 4, Year 2) to a minimum of 0.096 (Reach 5, Year 6), while the peak-concentration channel roughness values ranged from a maximum of 1.181 (Reach 5, Year 2) to a minimum of 0.135 (Reach 5, Year 6). Channel roughness based on the peak-concentration may have been greater in Reach 4, but the peak was not detected until Year 6 when the water flow became more confined in the wet meadow.

Channel roughness calculated from the leading-edge decreased consistently each year in Reaches 2 and 4, and in Reaches A and 5 when calculated from the peak-concentration velocity. Channel roughness also decreased consistently each year in Reach 3 if Year 6 is excluded because of the newly established beaver ponds. Reaches 5 and 6 remained relatively unchanged until Year 4 or 5, while Reaches A, 1A, 2, and 3 began to stabilize by Year 3 or 4. Channel roughness in Reach 1 decreased somewhat, but remained mostly unchanged from Year 2 to Year 6. Reach 4 was still adjusting its channel roughness in Year 6.

DISCUSSION AND CONCLUSIONS

The previously ephemeral South Fork of Middle Crow Creek was still adjusting to flow augmentation 6 years after augmentation began, and as we expected the time-of-travel decreased as a channel formed. Low gradient sedge meadows were highly resistant to channel formation. The previously unchannelized sedge meadow in Reach 4 was only 5% channelized by Year 6. The soil in these meadows was protected from flowing water by a dense, 8-15 cm mat of below-ground biomass (Chapter 2). This mat was slowly being removed by the streamflow. If this rate of channel formation continues, we believe there will be little or no undesirable adjustments to flow augmentation before the SFMCC channel is fully developed. Bergman and

Sullivan (1963) also noted favorable channel adjustments and vegetation establishment following sustained seepage into a previously intermittent watercourse from upstream floodwater-retarding structures. Excessive flows, however, can produce undesirable physical and biological adjustments to flow augmentation (Maddock 1960, Kellerhals et al. 1979), and should be avoided if a mitigation project similar to the SFMCC is contemplated.

Since our design included areas both inside and outside the livestock grazing exclosures, our results may be somewhat more variable. This variability could not be removed, because suitable reaches both inside and outside exclosures were not available for all plant community types. Any variability introduced by the exclosures appeared to be minimal, however, because the livestock were managed under a deferred rotation grazing system that minimized the impacts from grazing.

The proportion of the SFMCC watercourse with a channel increased from 24% in 1984 to 41% by 1991 (Year 6), with an additional 16% included within beaver ponds. Most of this channel formed by downcutting rather than by the upstream migration of nick points. Much of the remaining 43% of the SFMCC had flow confined in localized areas, and appeared ready to form a channel. Bare ground in the moist (4-19%), moist-wet (1-23%), and wet (<1-24%) meadows increased from 1986-89, and temporarily peaked at 27, 57, and 55% in these meadow types respectively in 1988 (Chapter 2). These data were an average for each meadow type. Field observations, however, suggest that there was nearly 100% bare ground in long, narrow (typically <1 m) corridors just before a channel formed in these areas. Once the above-ground vegetation was removed, the streamflow velocity increased (e.g., 0.027 to 0.134 $m \cdot s^{-1}$ in Reach 4) and a channel began to form by downcutting in place. Apparently the below-ground biomass (Chapter 2) was unable to prevent channel formation without the benefit of the above-ground biomass reducing streamflow velocity.

Sediment transport and deposition were not sampled intensively, but observation and limited sampling with a U.S. DH-48 suspended sediment sampler (Dendy et al. 1979) during high flows suggests that most of the sediment created by channel formation was redistributed throughout the system rather than flushed out of the study site. Limited deposition was observed in the vegetation next to the channel and on an occasional point bar, but no substantial accumulation of sediment was observed at any one location.

The time-of-travel was useful for making comparisons among years for the same SFMCC reaches, but the time-of-travel was also affected by the trend toward greater discharges each year. Adjusting the time-of-travel for a selected flow duration (e.g., 50%) would have accounted for discharge, but this procedure requires at least two sampling periods per year at different discharges (Kilpatrick and Taylor 1986, Kilpatrick and Wilson 1989). The effect of minor changes in discharge is minimal for channel roughness, however, since the channel roughness remains about the same until the discharge is sufficient to change the roughness characteristics of the channel (e.g., over top the vegetation). Channel roughness also includes the slope and hydraulic radius besides the velocity derived from the time-of-travel, so the channel roughness provides a more universal value for comparing the SFMCC to other streams. Normally Manning's n is calculated for a homogeneous reach. Most of our reaches were not homogeneous, however, so our values represent the average roughness for the entire reach. These values for channel roughness, therefore, should be considered as an index for comparison rather than as a precise value for Manning's n.

Channel roughness in the steeper reaches (A, 1A, 2) decreased from 0.435-0.446 in Year 2 and 3, to 0.188-0.372 in Year 6. A typical mountain stream has 0.100 for a maximum value of Manning's n (Van Haveren 1986). Low-gradient sections included within these steep reaches may have increased n somewhat, but it appears the steeper SFMCC reaches are still adjusting to flow augmentation. The initial channel roughness in the flooded meadows ranged from a conservative estimate of 0.407 in Reach 3 to 1.181 in Reach 5. These values were similar to other vegetated watercourses: 0.300 in a good stand of 30-60 cm tall grass (Van Haveren 1986), 0.75 in a splitbeard bluestem stand (Ree et al. 1977), and 1.2 in a south Florida marsh (Shih et al. 1979). Once a channel forms in these meadows, however, Van Haveren (1986) suggests that the maximum value for Manning's *n* should be 0.045 for a clean, winding minor stream on the plains with some pools and bars. Since *n* ranged from 0.135 to 0.229 in Year 6, it appears that the watercourse in these low-gradient meadows is still adjusting to streamflow augmentation.

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CHAPTER 4

DEPTH-TO-GROUNDWATER RELATIONSHIPS FOR THREE RIPARIAN SPECIES/ASSEMBLAGES IN SOUTHEASTERN WYOMING

ABSTRACT

Few quantitative data are available relating the underlying hydrology of riparian wetlands to the riparian plant species. Future riparian mitigation projects will require more specific hydrologic relationships than were available from most environmental gradient analyses. This paper details the surface and groundwater hydrology of 4 montane meadow types in southeastern Wyoming, and the depth-to-groundwater relationships for an assemblage of wetland sedges (*Carex* spp.), tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.), and slimstem reedgrass (*Calamagrostis neglecta* [Ehrh.] Gaertn.). Depth-to-groundwater hydrographs and duration curves were used to describe the water-level regime for dry, moist, moist-wet, and wet meadows. The hydrologic regimes were related to the plants with depth-to-groundwater suitability curves. These curves were adapted from the Habitat Suitability Index (HSI) models used by the U.S. Fish and Wildlife Service, and suggest the expected plant response (biomass and density) to groundwater depths that occur at a specific level or above for 10, 50 and 90% (D_{10}, D_{50}, D_{90}) of the growing season. The optimum depth-to-groundwater for sedge biomass was a nearly constant 0.15 m (D_{10} to D_{90}) of standing water, while the optimum depth-to-groundwater for sedge density was 0.18 m (D_{10}), 0.43±0.26 m (D_{50}±95% CI), and 0.76±0.45 m (D_{90}±95% CI) below the surface. Tufted hairgrass response was optimized when the depth-to-groundwater was between 0.17 and 0.29 m for D_{10}, deeper than 1.23 m for D_{50}, and deeper than 1.79 m for D_{90}. The relationship between slimstem reedgrass biomass and the depth-to-groundwater was

too poor to develop suitability curves, but slimstem reedgrass density appeared to decrease if the groundwater depths were shallower than 1.05 m for D_{10}, 1.34 m for D_{50}, and 1.81 m for D_{90}. Data for these analyses were obtained from a long-term mitigation project that converted an ephemeral watercourse to a perennial stream with flow augmentation, and from nearby natural ephemeral watercourses.

INTRODUCTION

The value of healthy riparian wetlands to wildlife, fisheries, agriculture, and nonpoint pollution control is well established (Johnson and McCormick 1978, Johnson et al. 1985, Gresswell et al. 1989), yet few quantitative data are available relating the underlying hydrology to the riparian plant species that support these wetlands. Kusler and Kentula (1990) note that the most critical gap in our wetland knowledge is "The hydrologic needs and relationships of various plants and animals, minima water depths, hydroperiod, . . ., and the role of large scale but infrequent hydrologic events such as floods and long term fluctuations in water levels." Only 5.3% of the U.S. Fish and Wildlife Service's wetland creation/restoration data base contains citations for stream/riparian creation or restoration projects in the western United States (Ischinger and Schneller-McDonald 1988), suggesting that riparian-wetland research lags behind research in other wetland types. Ischinger and Schneller-McDonald (1988) also emphasize the pressing need for research describing the interrelationships between surface and groundwater hydrology and wetland plant communities.

Riparian mitigation projects should consider the hydrologic requirements necessary to maintain healthy riparian plant communities. Instream flows have been used to mitigate damage to fish and wildlife habitat caused by water development projects (Raley et al. 1988, Reiser et al. 1989). These flows are based on specific relationships to maintain fish populations (e.g., Bovee 1986). Similar relationships will be needed if flows regimens will be managed for maintaining riparian plant communities. Studies detailing riparian hydrology beyond a simple description of the average water level are few (Peacock 1992, Henszey and Wesche 1993). Even more infrequent are studies describing the frequency and duration of water levels for more than 1 or 2 seasons, and then relating this hydrology to specific water-level relationships for riparian plants. Environmental gradients (Barbour et al. 1980) have been used to separate the effects of selected environmental variables on wetland plants, but these gradients are usually labeled qualitatively, such as moist to dry. Most management decisions require more precise values, such as the water table depth is less than 1.0 feet from the surface for usually 1 week or more during the growing season (Federal Interagency Committee for Wetland Delineation 1989).

The goal for this study was to describe the surface and groundwater hydrology of 4 montane meadow types in southeastern Wyoming, and the depth-to-groundwater relationships for 3 riparian species/assemblages in these meadows. Meadow types were arranged along a moisture gradient from dry to wet, and the hydrology was defined with depth-to-groundwater hydrographs and depth-to-groundwater duration curves. Depth-to-groundwater suitability curves were used to relate the hydrology to the plant species. These curves include the water-level duration information required by current and proposed government regulations for delineating wetlands (U.S. Army Corps of Engineers 1987, Federal Interagency Committee for Wetland Delineation 1989, General Services Administration 1991), and are especially useful for predicting plant response to different groundwater-level regimes. The depth-to-groundwater suitability curves were adapted from the Habitat Suitability Index (HSI) models used by the U.S. Fish and Wildlife Service (Bovee 1986). Suitability curves were developed for an assemblage of wetland sedges (*Carex* spp.), tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.), and slimstem reedgrass (*Calamagrostis neglecta* [Ehrh.] Gaertn.). A more precise analysis for sedges may have been achieved by separating the sedges into species, but most of the species studied had similar hydrologic relationships and they served to illustrate the techniques presented. Data for these analyses were obtained from a long-term mitigation project that converted an ephemeral watercourse to a perennial stream with flow augmentation, and from nearby natural ephemeral watercourses (Wolff et al. 1989, Henszey et al. 1991).

METHODS

STUDY AREA. The study area was located 45 km west of Cheyenne, Wyoming in the Medicine Bow National Forest, and ranges from 2361 to 2506 m above sea level (Figure 15). This study area was established in 1984 to evaluate a mitigation project that diverts a nearly constant 57 Ls^{-1} into a previously ephemeral stream (Wolff et al. 1989, Henszey et al. 1991). Five watersheds comprise the study area. The largest watershed (830 ha) includes the South Fork of Middle Crow Creek (SFMCC), and has received flow augmentation since August 1985. The additional water spread as sheet flow across the valley in areas lacking a developed channel, and caused many lower gradient areas to be flooded with 5-10 cm of standing water. Before flow augmentation the SFMCC was similar to the adjacent ephemeral watercourses, and flowed in response to spring snow melt and intense summer thunderstorms. The upper 40% of the SFMCC is a steep (3.2-4.6%), narrow, geologically-controlled valley dominated by aspen (*Populus tremuloides* Michx.) and outcrops of Sherman granite. Meadows dominated by sedge and tufted hairgrass occur along the occasional lower gradient sections. About 1% of this steep reach was channelized before flow augmentation and the remainder consisted of an unchannelized valley bottom approximately 16 m wide. The lower 60% of the SFMCC is characterized by a wider, lower-gradient valley (0.8-1.4%) with deeper alluvial soils, and vegetation dominated by sedge meadows. Aspen and shrubby cinquefoil (*Pentaphylloides floribunda* [Pursh] Löve) form a transition between these meadows and the upland, and occurred in the infrequent areas where a developed channel was

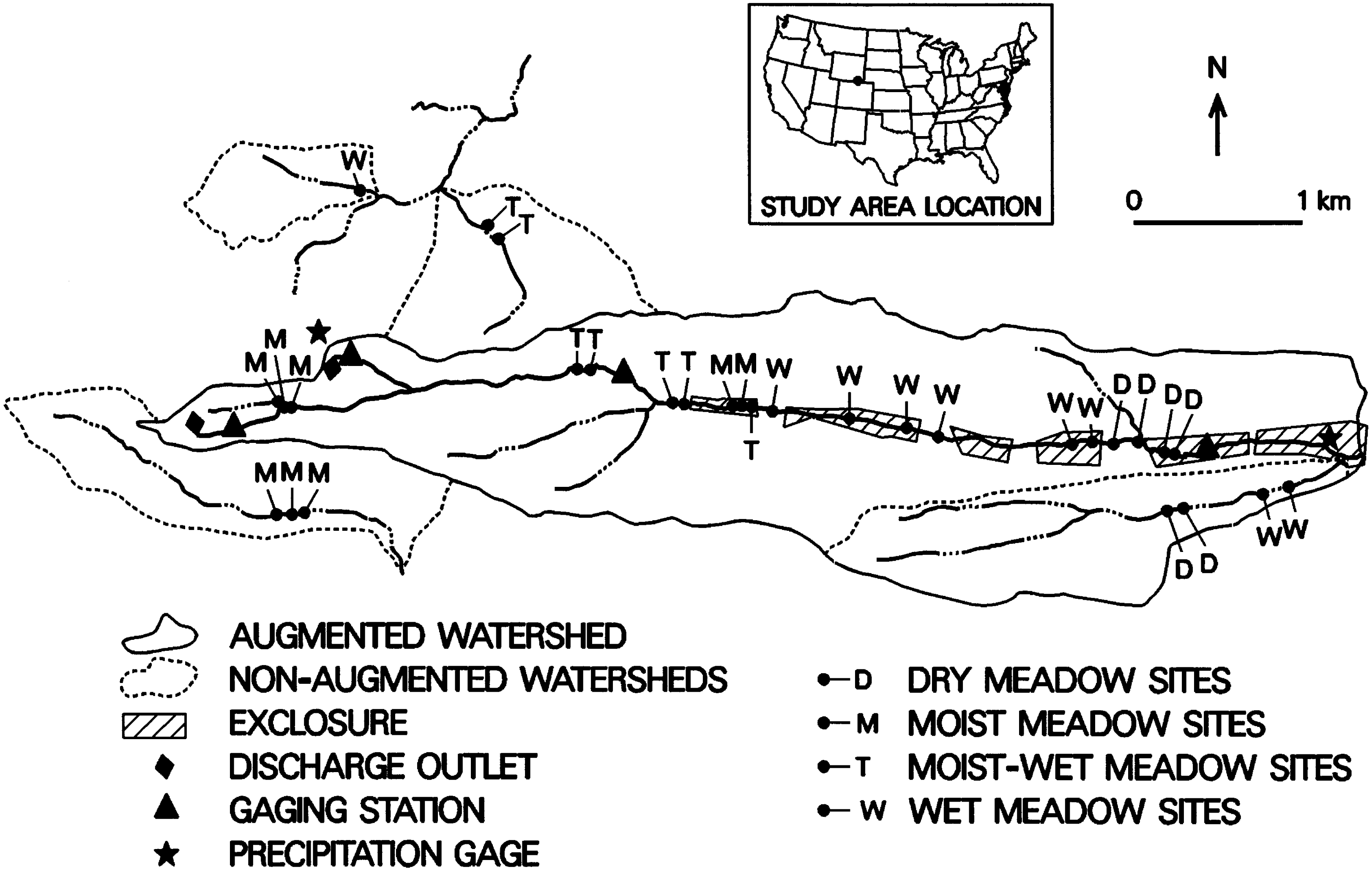

Figure 15. Map of the South Fork of Middle Crow Creek Study Area, Wyoming, and adjacent non-augmented watersheds, showing the location of the herbaceous vegetation study sites used for the depth-to-groundwater study.

present before flow augmentation. About 23% of the lower area was channelized before flow augmentation with nearly all of this channel occurring along the last 1.9 km of the SFMCC within the study area. The remainder of the lower area was an unchannelized valley bottom approximately 45 m wide.

Six livestock grazing exclosures (Figure 15) were constructed in the fall of 1984 to provide protection for the developing riparian and aquatic habitat. These exclosures included 48% (26 ha) of the total riparian habitat along the SFMCC. Parts of 2 cattle allotments were included in the study area, with the allotment boundary heading north to south through the study area and crossing the SFMCC 85 m upstream from the middle gaging station. Both allotments were managed under a 3 pasture deferred rotational grazing system with a 1 June through 15 October grazing season (U.S.D.A. Forest Service 1991ab). Part of 1 pasture (1993 ha total) from the upstream allotment was in the study area. This pasture had a 42 day grazing period and a stocking rate of 0.45 $AUM \cdot ha^{-1}$. The downstream allotment was divided into 2 pastures with the boundary crossing the SFMCC at the upstream end of the fourth exclosure from the discharge outlet. The stocking rate for the upstream pasture (507 ha total, 37 days) was 0.56 $AUM \cdot ha^{-1}$, and the stocking rate for the downstream pasture (514 ha total, 41 days) was 0.62 $AUM \cdot ha^{-1}$. Pasture rotation for both allotments was based on a utilization standard of 45-55% for the meadows or aspen. Livestock were moved to the next pasture when this level was exceeded, regardless of the specified grazing period.

The study area was in a 38-48 cm precipitation zone (U.S.D.A. Soil Conservation Service 1982). From 1986 through 1989 the 2 SFMCC precipitation gages (Figure 15) recorded a low of 39 cm for the 1986 water year (October through September) and a high of 52 cm for the 1987 water year. Total monthly precipitation during the June-through-September growing season ranged from a low of 0.9 cm in August of 1988 to a high of 10.1 cm after an intense July thunderstorm in 1987.

Four meadow types were described by Henszey et al. (1991) for the study area: dry, moist, moist-wet, and wet. Dry meadows were dominated by shrubby cinquefoil, Kentucky bluegrass (*Poa pratensis* L.), mat muhly (*Muhlenbergia richardsonis* [Trin.] Rydb.), and Western iris (*Iris missouriensis* Nutt.). Moist meadows were characterized by an abundance of tufted hairgrass and an equal or slightly greater amount of sedge, including water sedge (*Carex aquatilis* Wahl.) and smallwing sedge (*Carex microptera* Mack.). Meadows almost entirely dominated by a mixture of beaked sedge (*Carex rostrata* Stokes), Nebraska sedge (*Carex nebrascensis* Dewey), water sedge, or fieldclustered sedge (*Carex praegracilis* W. Boott) were considered to be either moist-wet or wet meadows. The moist-wet meadows had a minor component of tufted hairgrass, while the wet meadows had almost no tufted hairgrass.

SAMPLING PROCEDURES. Sampling followed Henszey et al. (1991). Thirty study sites (Figure 15) were selected from 72 previously established valley-bottom/groundwater-well transects. Sites on the SFMCC with the widest meadows were chosen first (4 dry, 5 moist, 5 moist-wet, and 6 wet meadow sites). These transects were located based upon channel gradient, vegetation type, type of channel control (geologic, beaver or vegetative), and presence of livestock grazing exclosures. The nearby non-augmented ephemeral stream sites were selected to represent sites similar to the SFMCC (2 dry, 3 moist, 2 moist-wet, and 3 wet meadow sites).

Each site typically had 4 shallow alluvial wells cased with 5 cm diameter polyvinyl chloride (PVC) pipe. Since these wells were located along a transect perpendicular to the general direction of the valley, it was not possible to consistently have all 4 wells located in the meadow types used for this study. Each site had at least 2 wells located in the meadows, however. The wells were perforated below the surface at approximately 15 cm intervals and open at the bottom. Water levels were measured with an electronic probe (Henszey 1991) at least once a month during the ice-free months. More frequent measurements (daily to biweekly) were taken during the spring runoff on the ephemeral channels and following interrupted flow augmentation on the SFMCC. A transect for each community type that was accessible during the winter, and that had few wells freeze, was measured monthly throughout the winter to monitor changes during the winter.

Above-ground biomass and density were sampled annually during the first 2 weeks of August from 1987 through 1989. Each site had 10 equally-spaced, 0.125 m^2, permanent quadrats located along a transect perpendicular to the general direction of the valley. Quadrats were located within the distinct boundaries of the meadow and permanently marked with steel stakes. Five additional 0.125 m^2, annual-production plots per site were destructively sampled each year to obtain above-ground biomass. The annual-production plots were rotated on a 4 year cycle, with the plots located 3 m up or down stream from the permanent quadrats and opposite every other permanent quadrat. Large ungulate grazing was prevented by placing a 1.3 m^2 cage around each production plot. The production plots were sampled for above-ground biomass, while both the production plots and the permanent quadrats were sampled for density. Above-ground biomass samples were dried at 65°C until 2 consecutive measurements, taken a minimum of 6 hours apart, were within 0.1 g of each other. Density was determined by counting the number of stems per quadrat for sedge and reedgrass, and the number of bunches per quadrat for tufted hairgrass.

ANALYSES: Groundwater Hydrology. Box-and-whisker plots (Ott 1988, SAS Institute Inc. 1990a) were used to describe the groundwater hydrograph for each meadow type. The periodic measurements were summarized by month, except during the spring when additional measurements were taken so May and June could be divided into 2 periods per month. Boxes were constructed to represent the median (connected by a line through each month), the middle 50% of the observations (the box), the lower 10-25% and the upper 75-90% of the observations (the whiskers), and the lower 0-10% and upper 90-100% of the observations (individual data points). These plots allow examination of the groundwater level variation within months as well as between months.

Depth-to-groundwater duration curves were generated from estimated continuous daily mean groundwater depths. These curves are cumulative frequency distributions that show the percent of time that a particular depth was equaled or above that level for the period specified, and require continuous data or at least regular periodic data. Groundwater-level recorders provide the most accurate data, but a reasonable estimate of daily values can also be obtained by regression with nearby stream gages. Linear regression with nearby stream gages was used to estimate continuous groundwater levels for the SFMCC wells. A different technique was used to estimate continuous data for the SFMCC wells with poor regressions ($p > 0.10$) and for the wells in the meadows without flow augmentation. This technique used PROC EXPAND (SAS Institute Inc. 1988) to estimate daily values between sampling points by linear interpolation. Linear interpolation provides good estimated data when the period between sample points is short and the influence from external factors (e.g., response from precipitation) is small. Without continuous data for comparison, it was difficult to judge the quality of our estimated data. We believe, however, that our data were reasonably accurate for this area based on over 6 years of experience working with continuous groundwater data from responsive sandy riparian soils in Nebraska and relatively constant subalpine riparian soils in Wyoming (Wesche et al. 1990, Peacock 1992, Henszey and Wesche 1993). Groundwater depths were calculated by subtracting the groundwater elevation from the land-surface elevation. Duration curves were calculated using procedures similar to those used to calculate a typical flow duration curve for streamflow analysis (Searcy 1959). PROC FREQ (SAS Institute Inc. 1985a) was used to generate the duration data and PROC GPLOT (SAS Institute Inc. 1990b) was used to graph the data. Graphical data were based upon 0.3 cm (0.01 ft) size classes.

Vegetation Response. Site means were used to evaluate the vegetation response. These means were based upon 5 subsamples for above-ground biomass and 15 subsamples for density at each site. The 3 year mean (1987-89) for each site was used for the meadows without flow augmentation, while the 1989 sample was used for the SFMCC. Only 1 year was used for the SFMCC because the vegetation was adjusting to flow augmentation during the early years of the study (Henszey et al. 1991). By 1989 the plant species response to flow augmentation had stabilized (Chapter 2), except for tufted hairgrass biomass. Tufted hairgrass biomass was expected to decrease with flow augmentation and it decreased from 18 $g{\cdot}m^2$ in 1986 to 3 $g{\cdot}m^2$ in 1989, so it was also probably very close to equilibrium by 1989. Although the hydrology for the SFMCC sites was no longer natural, these sites were included in the analysis because they showed the plant species response to very wet (often standing water) conditions.

Depth-to-Groundwater Suitability Curves. Depth-to-groundwater suitability curves for each species were developed by plotting the depth-to-groundwater at each site versus the plant species response (biomass or density) for the site. Three different duration values (D_{10}, D_{50}, D_{90}) obtained from the depth-to-groundwater duration curves were plotted for each site. These 3 values show the percent of time (10, 50, 90%) that the water was at a specific level or higher, and represent the "typical" shallowest (D_{10}), median (D_{50}), and deepest (D_{90}) groundwater levels for a site. The actual deepest and shallowest groundwater levels for each site during the study, however, were the values for D_{100} and D_s (D_s, for shallowest, varies with the data but the duration value is usually less than 1%).

A curve was fitted through the data for each duration series (D_{10}, D_{50}, D_{90}) with PROC NLIN (SAS Institute Inc. 1985b). Several curves suggested by Bovee (1986) that appeared to fit the data were tested, but the generalized Poisson, logistic, and exponential (Equations 1-3, respectively) provided the best fit to the data.

$$f(x,a,b,c,d) = \left[\frac{b-x}{b-a}\right]^{c} \cdot e^{\left(\frac{c}{d}\right) \cdot \left[1 - \left(\frac{b-x}{b-a}\right)^{d}\right]} \qquad \textbf{(1)}$$

were:
a = value of "x" where f(x) = 1.0
b = value of "x" where f(x) = 0.0, (x < b)
c = shape parameter for part of the curve to the right of x = a
d = shape parameter for part of the curve to the left of x = a
e = base of the natural logarithm ≅ 2.71828

$$f(x,a,b,c) = \frac{a}{1 + b \cdot e^{-cx}} \qquad \textbf{(2)}$$

were:
a = the maximum value of f(x), f(x) = $\frac{a}{2}$ at the inflection point of the curve
b = control parameter for the value of f(x) when x = 0.0
c = control parameter for the value of "x" at the inflection point of the curve

$$f(x,a,b) = a \cdot e^{(bx)} \qquad \textbf{(3)}$$

were:
a = the value of f(x) when "x" = 0.0
b = parameter that controls the rate of increase (b > 0), or decrease (b < 0)

The effects of each coefficient on the generalized Poisson and logistic curves are described by Parton and Innis (1972, reprinted in Bovee 1986), and the effects of each coefficient on the exponential curve are described by Olinick (1978). Curves were fit to the data measured in English units (ft), and then converted to metric units (m) for presentation. The sign of x (groundwater depth) was reversed by subtracting x from zero to make the groundwater levels negative, and the response variable (biomass or density) was normalized to facilitate comparison between species and response variables. Normalizing the curves provides the same scale (0 to 1.0) for all comparisons. The generalized Poisson and logistic curves were normalized by dividing the predicted values by the maximum predicted value for each curve. The exponential curves were normalized by dividing the predicted values by the maximum predicted value within the range of the observed data, since the theoretical maximum value for the exponential curve is infinity. If more than 1 exponential curve was included in a figure, then all exponential curves for the figure were normalized based on the maximum predicted value from the observed data of the inner most curve (e.g., D_{90} for exponential decay, and D_{10} for exponential growth).

RESULTS

GROUNDWATER HYDROGRAPHS. The depth-to-groundwater hydrographs for the 4 meadow types without flow augmentation are presented in Figures 16a through 19a, and the same meadow types with flow augmentation are presented in Figures 16b through 19b. In the meadows without flow augmentation the peak median groundwater level occurred in May or early June, and the lowest median groundwater level occurred during or after August. Recharge occurred after August and varied between a gradual recharge over the winter (dry meadows, Figure 16a), to a rapid recharge during snow melt in the spring (moist meadows, Figure 17a).

Meadow types differed in the duration and elevation of the highest median water levels, the deepest median groundwater level during the June through September growing season, and the timing of groundwater recharge. Dry meadows (Figure 16a) were characterized by a relatively constant hydrograph throughout the year, with the highest median groundwater water levels (-0.60 to -0.51 m) occurring from May through mid June. Elevated median groundwater levels occurred from May through June in both the moist (Figure 17a) and the moist-wet meadows (Figure 18a), but the median water levels were below the surface (-0.18 to -0.05 m) in the moist meadows and mostly above the surface in the moist-wet meadows (-0.09 to 0.06 m). The elevated median water levels in the wet meadows (-0.08 to 0.02 m, Figure 19a) were not as high as the moist-wet meadows, but they occurred for a much longer period (April through July). The deepest median groundwater depth during the growing season for the wet meadows was -0.52 m, while the dry (-1.12 m), moist (-1.29 m),

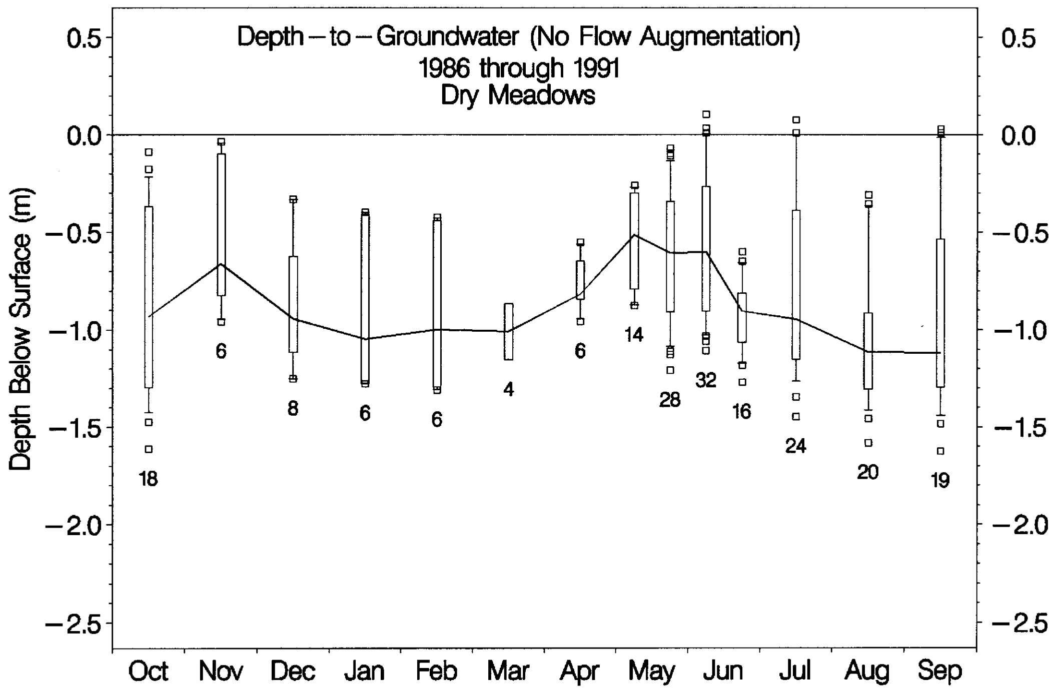

Figure 16a. Groundwater hydrograph for the dry meadows without flow augmentation, showing the variation within each month (or half month). The number of observations for each box is shown below the deepest observation.

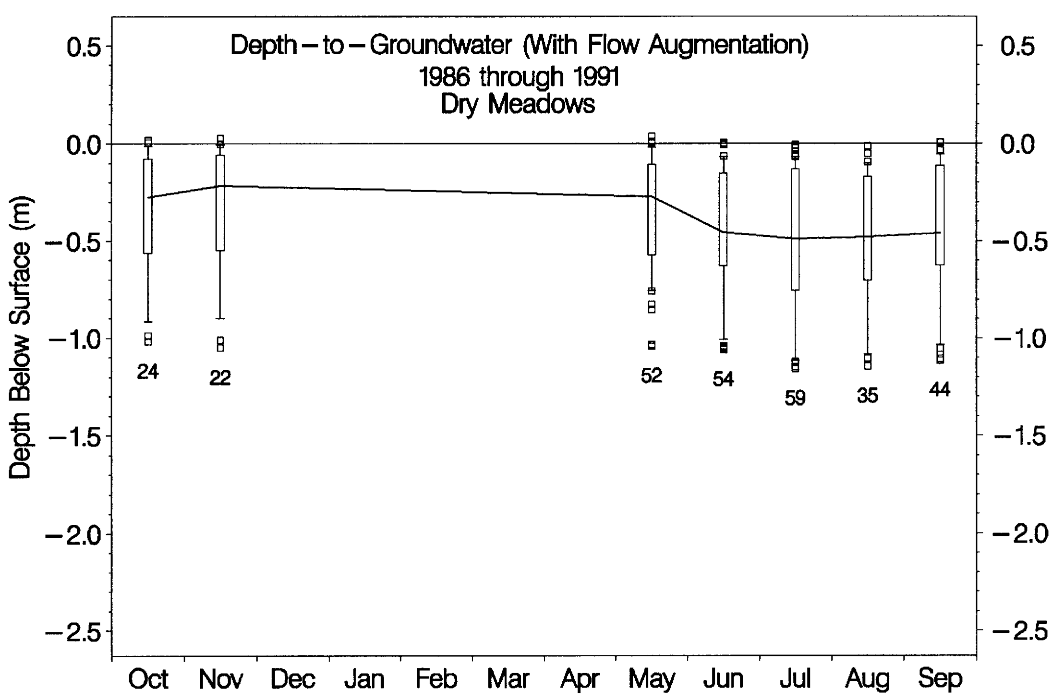

Figure 16b. Groundwater hydrograph for the dry meadows with flow augmentation, showing the variation within each month. The number of observations for each box is shown below the deepest observation.

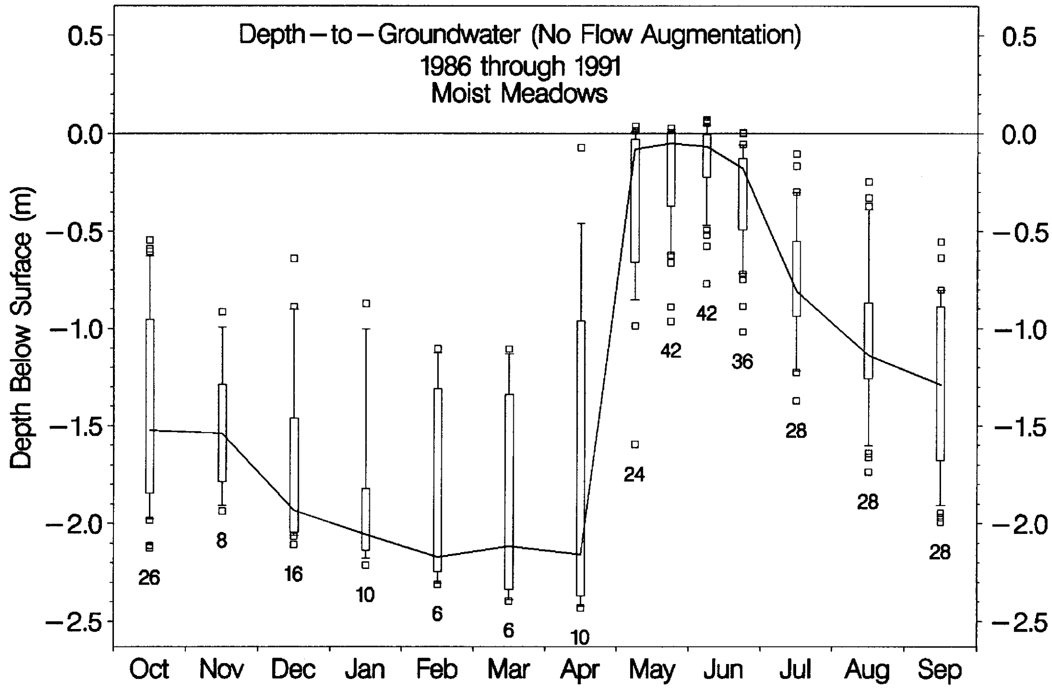

Figure 17a. Groundwater hydrograph for the moist meadows without flow augmentation, showing the variation within each month (or half month). The number of observations for each box is shown below the deepest observation.

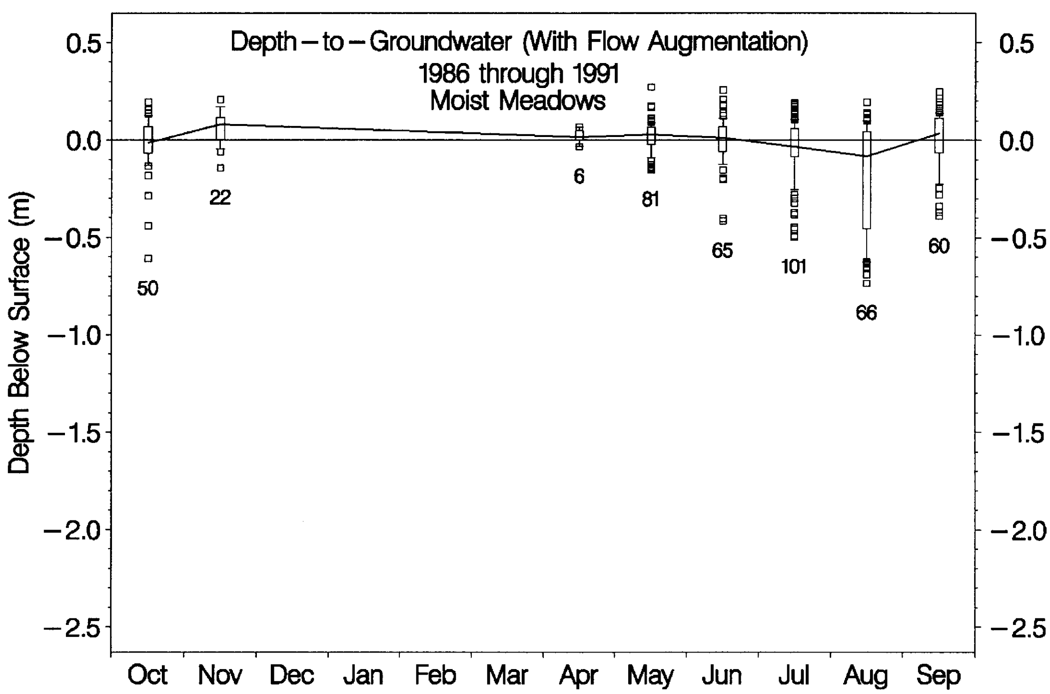

Figure 17b. Groundwater hydrograph for the moist meadows with flow augmentation, showing the variation within each month. The number of observations for each box is shown below the deepest observation.

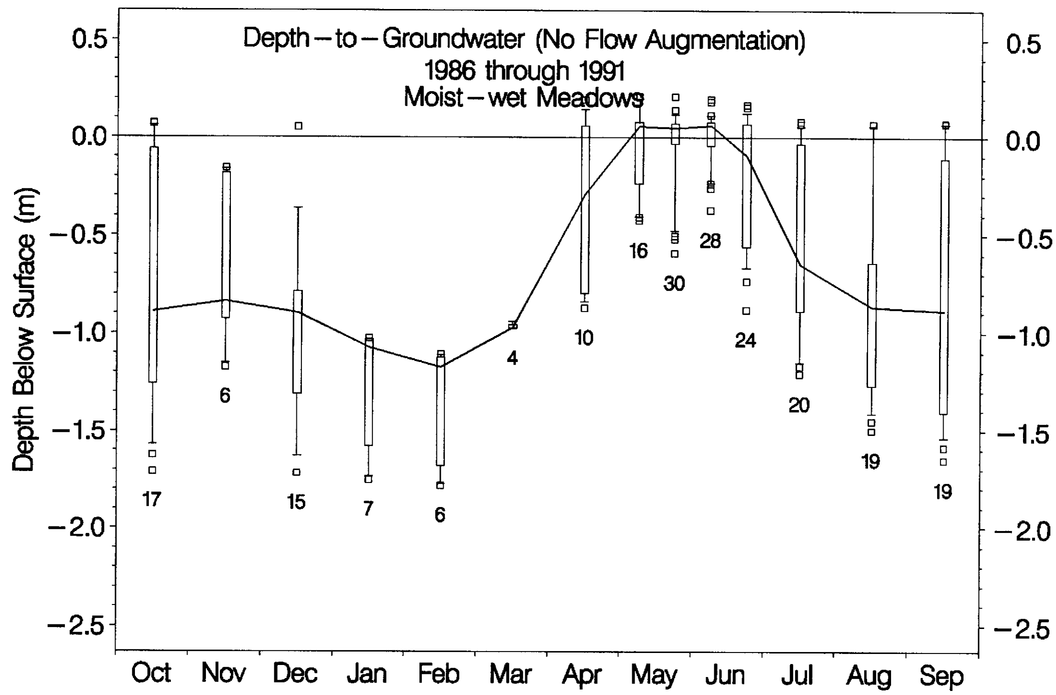

Figure 18a. Groundwater hydrograph for the moist-wet meadows without flow augmentation, showing the variation within each month (or half month). The number of observations for each box is shown below the deepest observation.

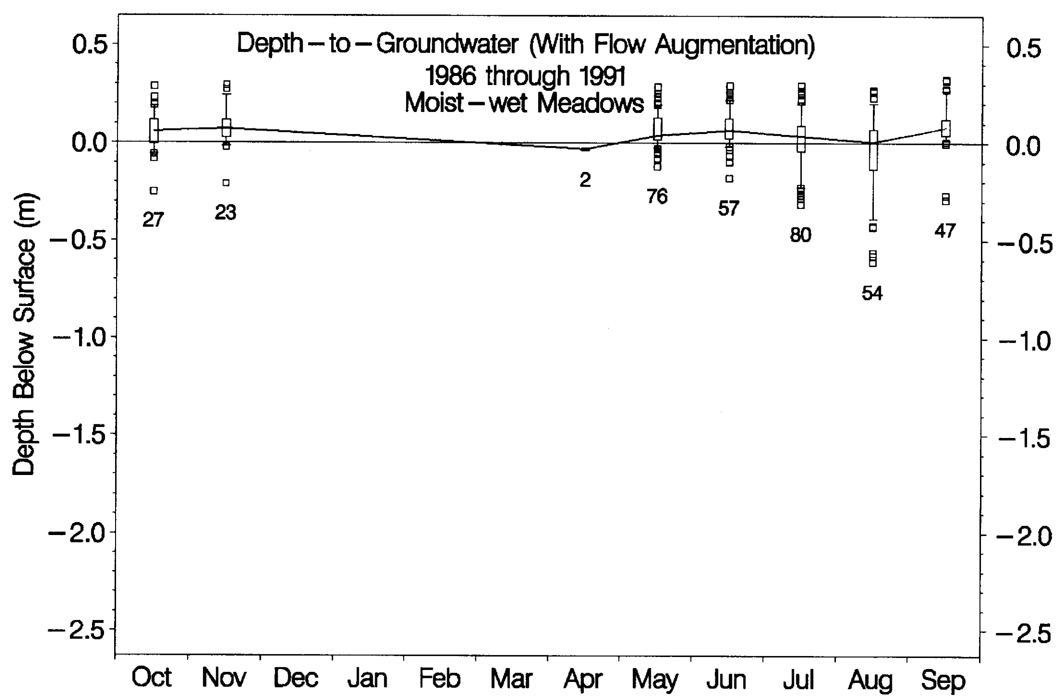

Figure 18b. Groundwater hydrograph for the moist-wet meadows with flow augmentation, showing the variation within each month. The number of observations for each box is shown below the deepest observation.

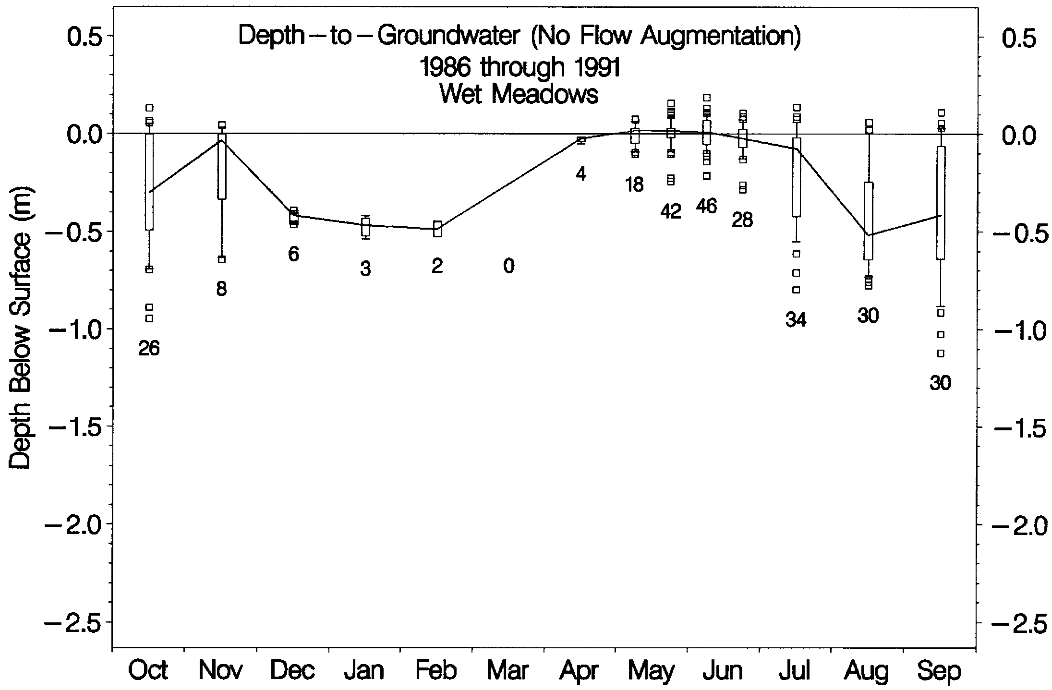

Figure 19a. Groundwater hydrograph for the wet meadows without flow augmentation, showing the variation within each month (or half month). The number of observations for each box is shown below the deepest observation.

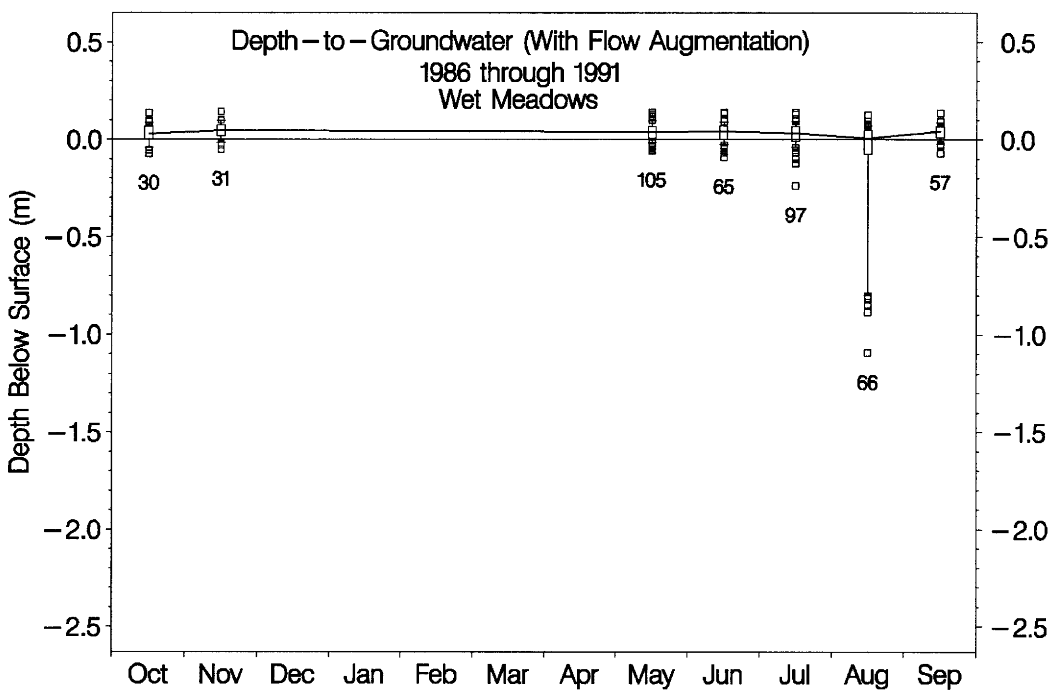

Figure 19b. Groundwater hydrograph for the wet meadows with flow augmentation, showing the variation within each month. The number of observations for each box is shown below the deepest observation.

and moist-wet (-0.89 m) meadows all had their deepest median groundwater depth during the growing season below -0.85 m.

Groundwater recharge began in September before the end of the growing season in the wet meadows, and at the end of the growing season (October) in the dry and moist-wet meadows. Recharge throughout the winter was difficult to detect in these meadows because the wells froze when the water came close to the surface. Since only the deeper groundwater levels could be measured during the winter, the winter groundwater levels in the dry, moist-wet, and wet meadows were probably biased toward deeper values. Groundwater levels declined throughout the winter in the moist meadows, so there was no problem with frozen wells. Although recharge usually occurred between April and May in the moist meadows, early snow melt probably caused recharge to begin as early as February about 25% of the time.

Flow augmentation caused the median hydrograph to be closer to, or above the surface, as well as relatively constant throughout the year (Figures 16b through 19b). The wells were frozen during the winter, so no data were obtained for the winter months. Maintenance on the water supply system occasionally interrupted the augmented flow, which introduced some variability in the hydrographs. This variability was especially noticeable for August in the moist, moist-wet, and wet meadows (Figures 17b through 19b), when the interrupted augmented flow caused the difference between the median and the deepest observation to be greater than the difference between the median and the highest observation. The dry meadows (Figure 16b) were apparently less susceptible to interrupted flow augmentation, possibly because these sites were located furthest downstream and discharge from upstream bank storage minimized the interrupted flow.

DEPTH-TO-GROUNDWATER DURATION CURVES. The depth-to-groundwater duration curves for the 4 meadow types without flow augmentation are presented in Figures 20 through 23. These curves show the percent of time that a

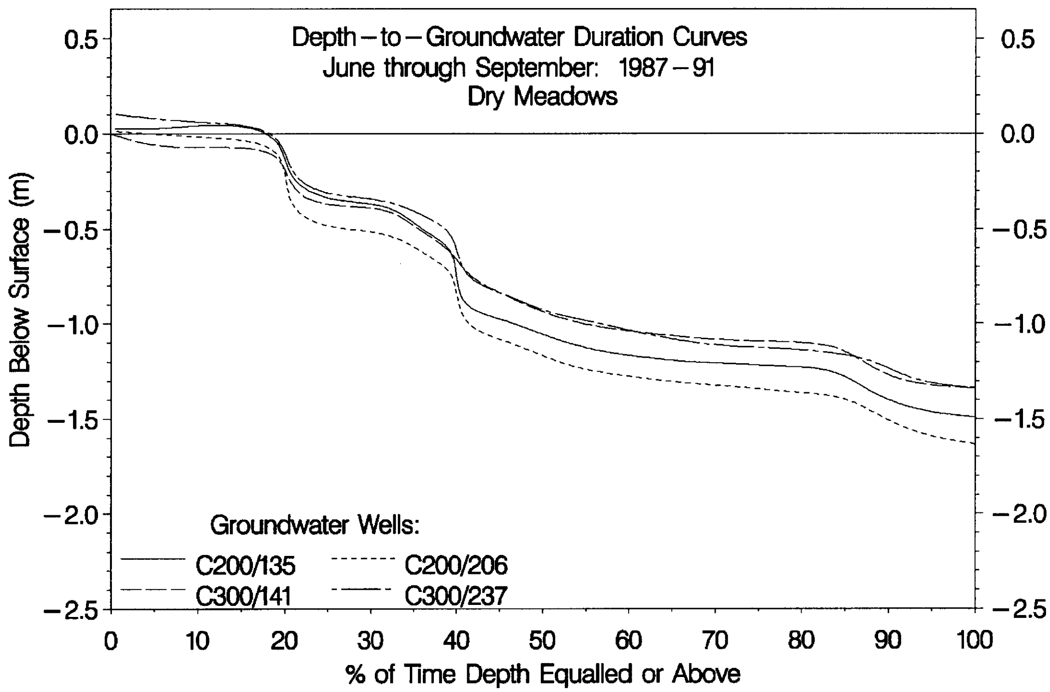

Figure 20. Depth-to-groundwater duration curves for the dry meadows without flow augmentation. Curves are for the June through September growing season for the years 1987 through 1991.

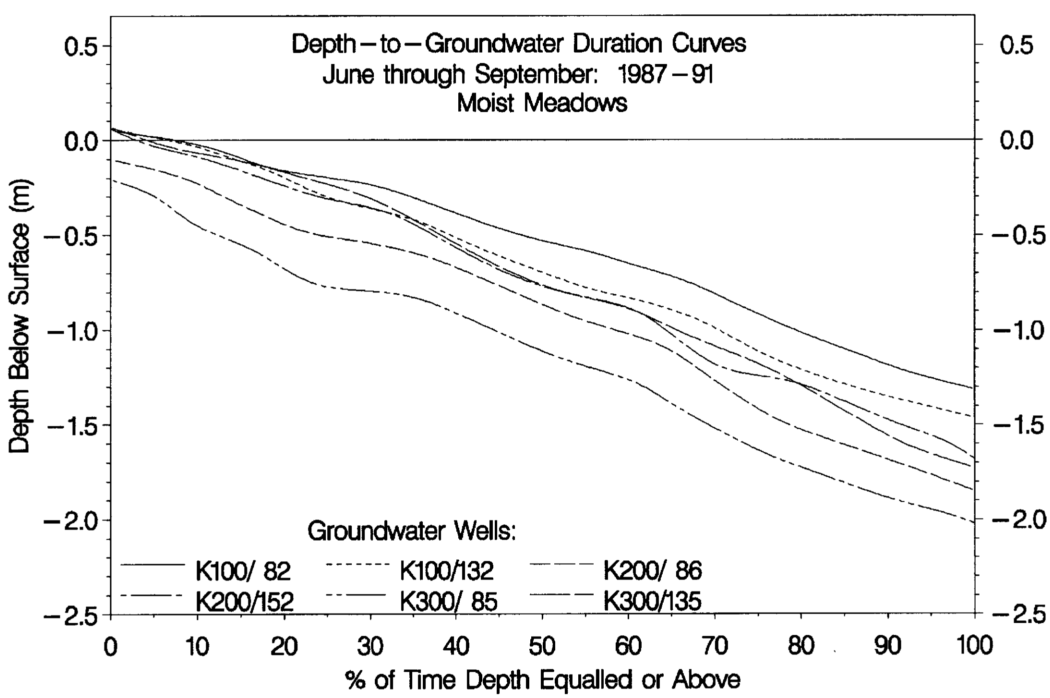

Figure 21. Depth-to-groundwater duration curves for the moist meadows without flow augmentation. Curves are for the June through September growing season for the years 1987 through 1991.

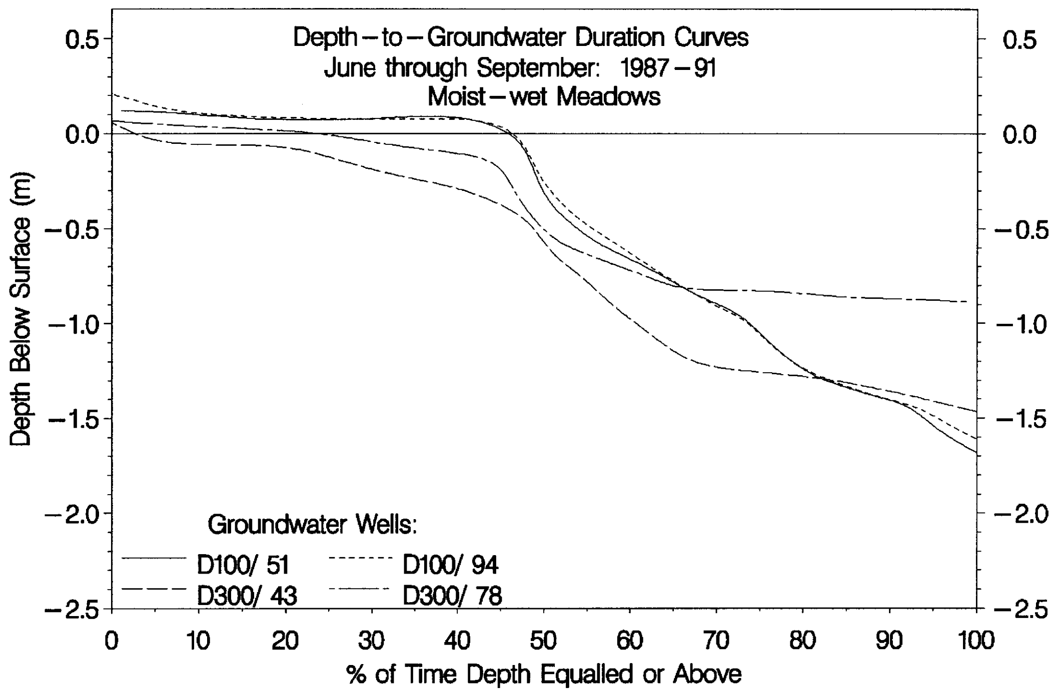

Figure 22. Depth-to-groundwater duration curves for the moist-wet meadows without flow augmentation. Curves are for the June through September growing season for the years 1987 through 1991.

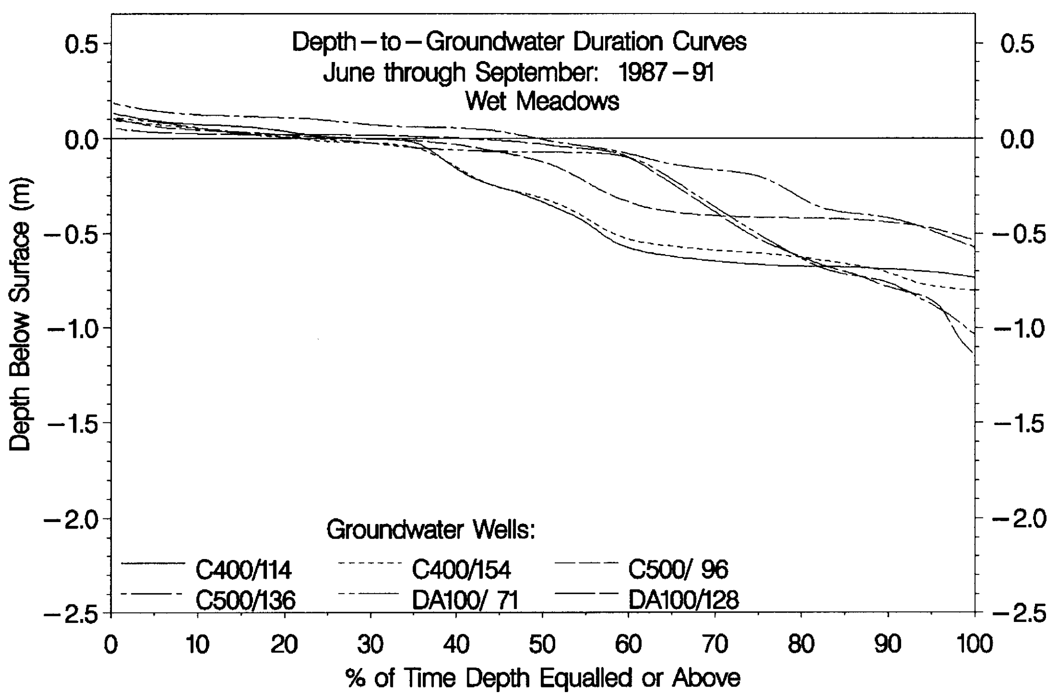

Figure 23. Depth-to-groundwater duration curves for the wet meadows without flow augmentation. Curves are for the June through September growing season for the years 1987 through 1991.

specific depth was equaled or above that level for the June though September growing season. Individual wells are labeled by reach (letter), cross section (number before "/"), and distance across the valley bottom (number after "/").

The highest mean daily water level for the dry meadows (Figure 20) was 0.10 m above the surface, and the deepest mean daily groundwater depth was 1.62 m below the surface. All 4 wells had the water level above the surface for at least 0.3% of the time, and 2 wells had water levels at or above the surface for at least 18% of the time. Mean daily groundwater depths were within 0.5 m of the surface from 27-39% of the time, and were deeper than 1.0 m below the surface from 43-59% of the time (e.g., for well C200/206: 100% - 41% = 59%).

Moist meadow water levels (Figure 21) varied between a high of 0.07 m above the surface and a low of 2.03 m below the surface. Three of the 5 wells had the water level above the surface for at least 2% of the time. Mean daily groundwater depths were within 0.5 m of the surface from 12-47% of the time, and were deeper than 1.0 m below the surface from 21-56% of the time. Groundwater levels in the moist meadows never remained at any depth for more than 10% of the time, unlike the other 3 meadow types (Figures 20, 22, and 23) where the water level tended to occur at 1 or more general elevations for 10-40% of the time. This dynamic nature of groundwater regime in the moist meadows can also be seen in the hydrograph (Figure 17a), and shows that the water level seldom remained at the same level for more than a few days throughout the growing season.

Moist-wet meadow water levels (Figure 22) varied between a high of 0.20 m above the surface and a low of 1.67 m below the surface. All 4 wells had water above the surface at least 2.5% of the time, and 2 wells had water above the surface for at least 46% of the time. Mean daily groundwater depths were within 0.5 m of the surface from 49-56% of the time, and 3 wells were deeper than 1.0 m below the surface from 26-39% of the time. The 2 wells at cross-section D100 had groundwater levels that never remained at any depth for more than 10% of the time once the water level was below the surface, while the 2 wells at cross-section D300 had groundwater levels that remained nearly constant for about 35% of the time at the deeper depths. Cross-section D300 was located on a minor tributary to the channel that D100 was located on, and was apparently fed by a relatively constant underground water supply during the drier months.

Wet meadow water levels (Figure 23) were above the surface for 21-49% of the time, and ranged from a high of 0.19 m above the surface to a low of 1.12 m below the surface. Mean daily groundwater depths were within 0.5 m of the surface from 57-97% of the time. Only 2 wells had water depths below 1.0 m, and that was for less than 3% of the time.

DEPTH-TO-GROUNDWATER SUITABILITY CURVES. The depth-to-groundwater at each site (Table 6) was combined with the plant response at each site (Table 7) to produce depth-to-groundwater suitability curves for sedge, tufted hairgrass, and slimstem reedgrass (Table 8 and Figures 24 through 26). Three duration values (D_{10}, D_{50}, and D_{90}) were selected to represent the range of groundwater levels observed at each site (Table 6). These duration values were calculated with the same procedures used to produce the depth-to-groundwater duration curves (Figures 20 through 23), except the period of record was limited to the years when the vegetation was sampled and the duration values represent the mean from the wells at each site. The vegetation response (biomass or density, Table 7) was normalized (Table 8) for the suitability curves to provide a consistent scale between species and response variables.

Standing water about 0.15 m above the surface produced the maximum sedge biomass (Figure 24a). Since all 3 duration series (D_{10}, D_{50}, and D_{90}) peaked at about the same depth, it appears that these sedges prefer a nearly constant level of standing water. It may also be possible that the optimum level of standing water was deeper than observed in the study area. This might force the 3 series to peak at nearly the

Table 6. Depth-to-groundwater (m) for 10, 50, and 90% of the time (D_{10}, D_{50}, and D_{90}) for June through September at each site. Values shown are the depths that were equaled or above for each duration series, and are the mean of 2-4 wells per site. Data are from 1987 through 1989 for the meadows without flow augmentation, and for 1989 for the meadows with flow augmentation.

			Depth-to-groundwater		
Meadow Type	Site	Wells	D_{10}	D_{50}	D_{90}
Meadows Without Flow Augmentation					
Dry	C200	2	-1.04	-1.26	-1.52
Dry	C300	2	-0.85	-1.10	-1.31
Moist	K100	2	-0.14	-0.90	-1.32
Moist	K200	2	-0.29	-1.23	-1.65
Moist	K300	2	-0.47	-1.30	-1.79
Moist-wet	D100	2	0.05	-0.91	-1.49
Moist-wet	D300	2	-0.25	-1.02	-1.14
Wet	C400	2	-0.16	-0.62	-0.74
Wet	C500	2	0.03	-0.29	-0.46
Wet	DA100	2	-0.02	-0.37	-0.85
Meadows With Flow Augmentation (pre-augmented flow classification)					
Dry	19721	4	-0.06	-0.13	-0.20
Dry	20219	2	-0.29	-0.43	-0.54
Dry	21009	2	-0.71	-0.79	-0.84
Dry	21231	3	-0.74	-0.81	-0.86
Moist	2100	4	-0.01	-0.11	-0.16
Moist	2228	2	0.08	-0.01	-0.10
Moist	2395	4	0.08	0.05	0.03
Moist	12080	2	0.12	0.11	0.09
Moist	12195	3	0.11	0.02	-0.05
Moist-wet	8460	2	0.09	0.07	0.06
Moist-wet	8708	2	0.03	0.01	-0.15
Moist-wet	10874	2	0.15	0.13	0.12
Moist-wet	11003	3	0.17	0.16	0.15
Moist-wet	12288	3	0.04	0.03	0.02
Wet	12725	3	0.03	0.02	0.01
Wet	14239	2	0.07	0.06	0.05
Wet	15370	3	0.07	0.06	0.06
Wet	15945	2	0.08	0.07	0.05
Wet	18906	2	0.05	0.05	0.04
Wet	19300	3	0.02	0.00	-0.02

Table 7. Mean biomass ($g \cdot m^{-2}$) and density ($number \cdot m^{-2}$) for the meadows without flow augmentation (n = 3 years) and for the meadows with flow augmentation (n = 1 year). Density for *Carex* spp. and *Calamagrostis neglecta* was for stems, and density for *Deschampsia cespitosa* was for bunches. Values less than 0.5 and greater than 0.0 are labeled as trace (T).

			Carex spp.		*Deschampsia cespitosa*		*Calamagrostis neglecta*	
Meadow Type	Site	Years	Biomass	Density	Biomass	Density	Biomass	Density
Meadows Without Flow Augmentation								
Dry	C200	3	4	49	3	3	3	24
Dry	C300	3	7	60	4	5	4	25
Moist	K100	3	21	91	10	9	4	19
Moist	K200	3	15	85	7	7	4	31
Moist	K300	3	20	70	6	7	3	21
Moist-wet	D100	3	24	118	8	7	3	17
Moist-wet	D300	3	26	139	8	7	2	10
Wet	C400	3	43	143	T	T	1	6
Wet	C500	3	37	191	1	2	2	9
Wet	DA100	3	25	171	3	4	3	9
Meadows With Flow Augmentation (pre-augmented flow classification)								
Dry	19721	1	30	122	2	5	1	7
Dry	20219	1	24	111	1	3	3	6
Dry	21009	1	3	44	T	T	1	11
Dry	21231	1	2	35	0	T	1	20
Moist	2100	1	29	90	5	7	2	5
Moist	2228	1	17	68	2	6	1	6
Moist	2395	1	22	56	T	2	5	9
Moist	12080	1	71	105	T	T	2	8
Moist	12195	1	32	143	0	1	3	24
Moist-wet	8460	1	50	103	1	2	1	3
Moist-wet	8708	1	62	99	T	T	4	10
Moist-wet	10874	1	48	142	0	0	1	1
Moist-wet	11003	1	55	139	0	T	2	4
Moist-wet	12288	1	43	125	0	1	1	7
Wet	12725	1	35	118	T	T	0	3
Wet	14239	1	46	111	0	0	3	14
Wet	15370	1	48	151	T	T	1	15
Wet	15945	1	34	144	0	0	1	4
Wet	18906	1	78	162	0	T	2	3
Wet	19300	1	52	176	0	0	4	15

Table 8. Equations and coefficients used to produce the depth-to-groundwater suitability curves. Curves were fit to the groundwater depths measured in English units (ft). Groundwater depths were converted to metric units (m), and the sign was reversed by subtracting the depth from zero to make the groundwater levels negative for Figures 24 through 26. Formulas and coefficient descriptions for the Poisson (1), logistic (2), and exponential (3) equations are presented in the methods. Values for the coefficients are followed by an asymptotic 95% confidence interval (SAS Institute Inc. 1985b).

Species	Response Variable	Duration	Equation	Equation Coefficients a	b	c	d	Normalizing Factor
Carex spp.	Biomass	D_{10}	Exponential	37.87 ± 6.85	-0.54 ± 0.51			49.25
		D_{50}	Exponential	44.14 ± 6.49	-0.22 ± 0.16			49.25
		D_{90}	Exponential	45.44 ± 6.81	-0.16 ± 0.11			49.25
	Density	D_{10}	Exponential	122 ± 15	-0.15 ± 0.28			133.41
		D_{50}	Poisson	1.40 ± 0.86	165 ± 9×10^6	304 ± 2×10^7	28 ± 1×10^6	191[1]
		D_{90}	Poisson	2.49 ± 1.46	12 ± 120	56 ± 8985	0.30 ± 40.96	191[1]
Deschampsia cespitosa	Biomass	D_{10}	Poisson	0.55 ± 0.38	291 ± 2930	156 ± 1580	1456 ± 15920	10[1]
		D_{50}	Logistic	6.69 ± 1.90	66[2]	2.21 ± 1.15		6.69
		D_{90}	Logistic	7.00 ± 2.04	69[2]	1.52 ± 0.61		7.00
	Density	D_{10}	Poisson	0.95 ± 0.63	4.25 ± 10.51	0.87 ± 5.46	10.82 ± 21.41	9[1]
		D_{50}	Logistic	6.53 ± 2.38	63[2]	2.16 ± 1.42		6.53
		D_{90}	Logistic	6.78 ± 2.33	77[2]	1.59 ± 0.77		6.78
Calamagrostis neglecta	Biomass	D_{10}	No well defined relationship with the data available					5[3]
		D_{50}	No well defined relationship with the data available					5[3]
		D_{90}	No well defined relationship with the data available					5[3]
	Density	D_{10}	Exponential	9.83 ± 2.72	0.28 ± 0.15			25.69
		D_{50}	Exponential	7.52 ± 2.48	0.28 ± 0.11			25.69
		D_{90}	Exponential	7.40 ± 2.46	0.21 ± 0.08			25.69

1. Poisson equation was developed using data normalized by the maximum observed value (biomass or density).
2. Logistic equation was developed by fixing "b" so that the normalized value for f(x) would be equal to approximately 0.1 when x = 0.0.
3. No equation was developed for *Calamagrostis neglecta* biomass, but the data were normalized with the maximum observed biomass.

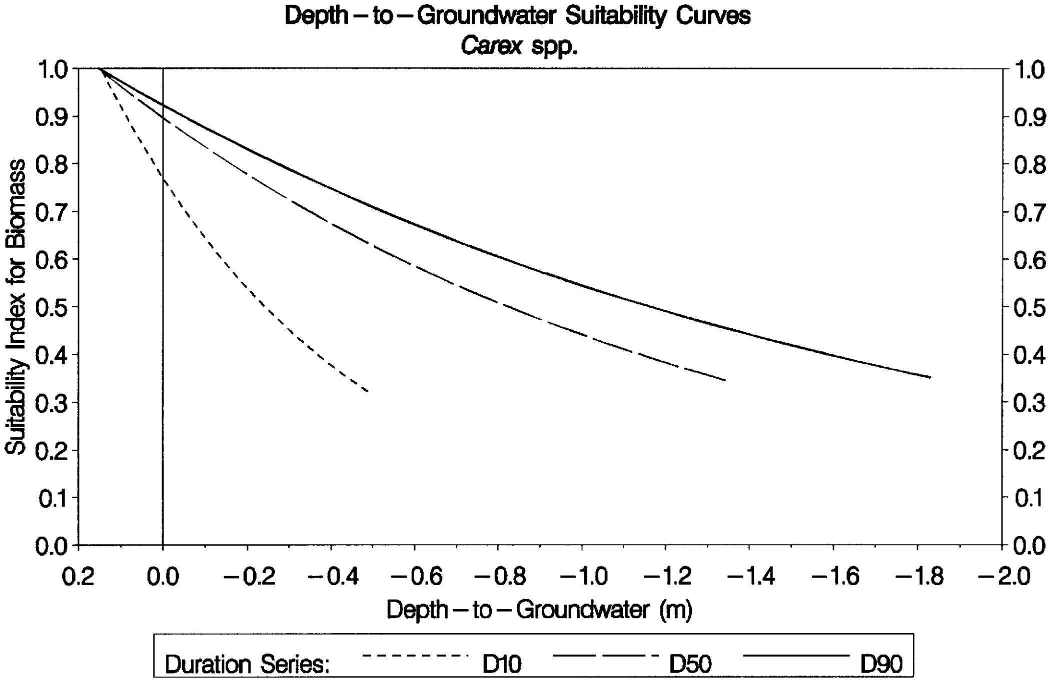

Figure 24a. Depth-to-groundwater suitability curves for sedge biomass. Three duration series are shown, representing the typical shallowest (D_{10}), median (D_{50}), and deepest (D_{90}) groundwater levels observed during the June through September growing season.

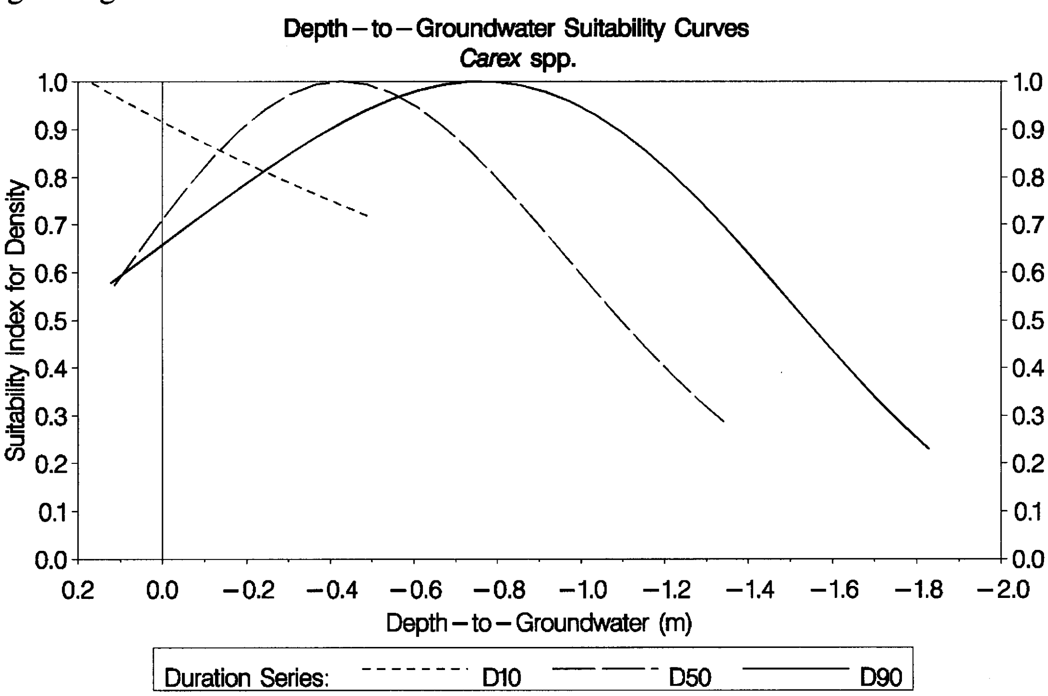

Figure 24b. Depth-to-groundwater suitability curves for sedge density. Three duration series are shown, representing the typical shallowest (D_{10}), median (D_{50}), and deepest (D_{90}) groundwater levels observed during the June through September growing season.

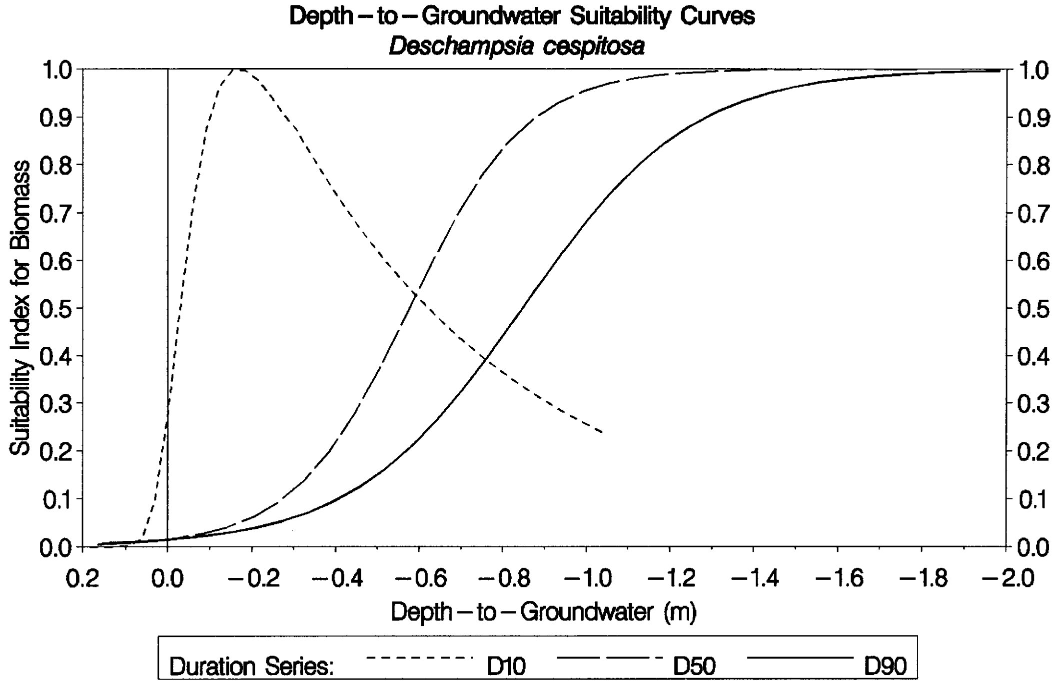

Figure 25a. Depth-to-groundwater suitability curves for tufted hairgrass biomass. Three duration series are shown, representing the typical shallowest (D_{10}), median (D_{50}), and deepest (D_{90}) groundwater levels observed during the June through September growing season.

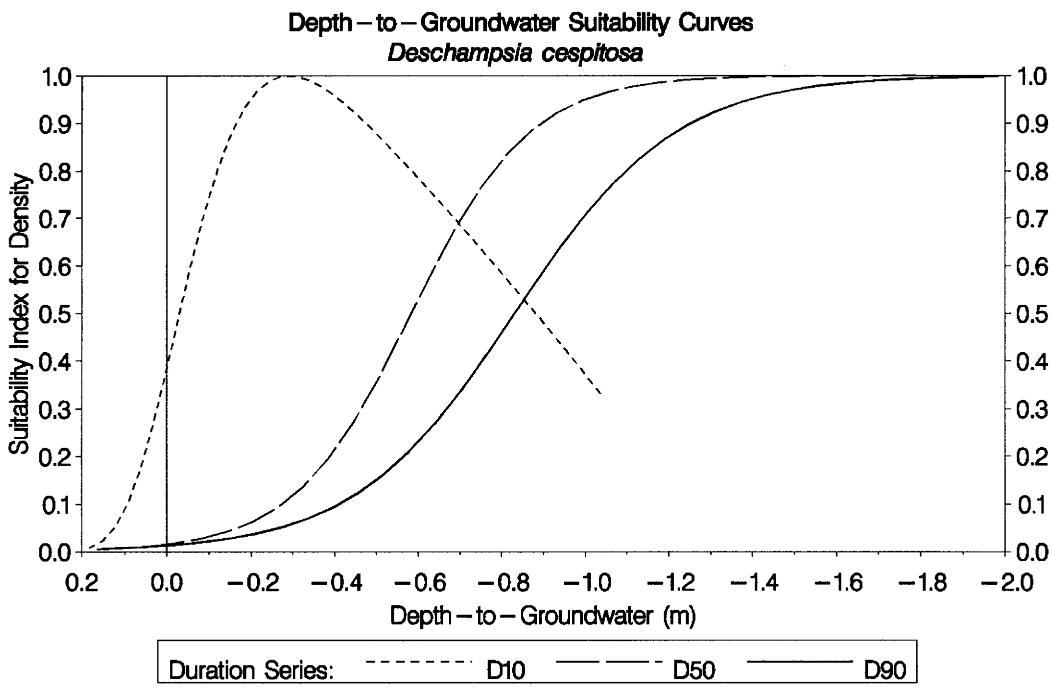

Figure 25b. Depth-to-groundwater suitability curves for tufted hairgrass density. Three duration series are shown, representing the typical shallowest (D_{10}), median (D_{50}), and deepest (D_{90}) groundwater levels observed during the June through September growing season.

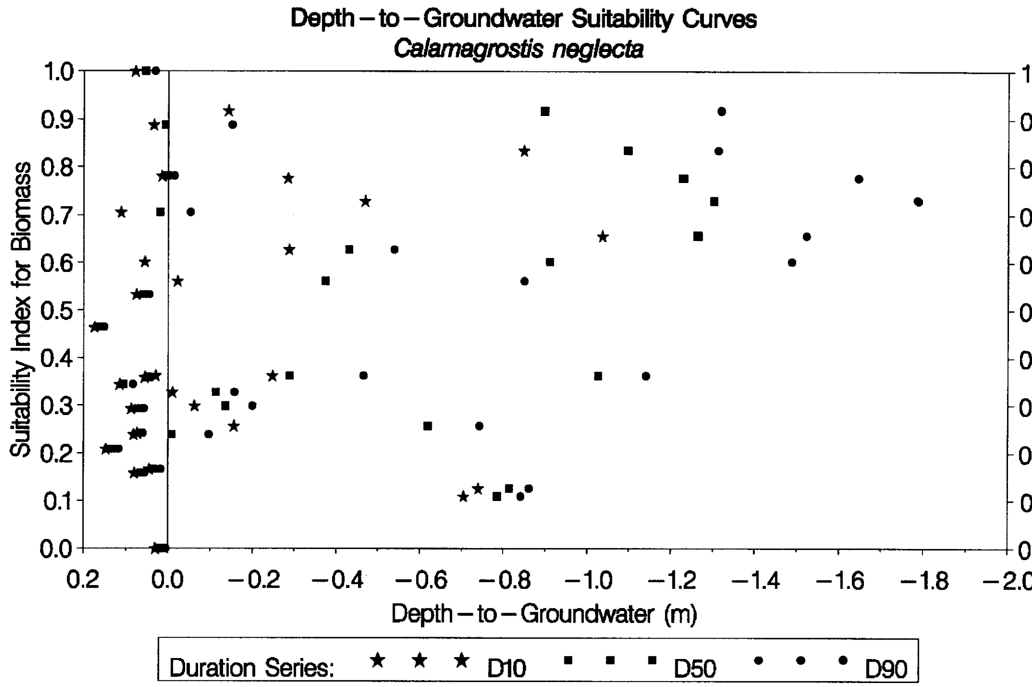

Figure 26a. The relationship between slimstem reedgrass biomass and the depth-to-groundwater. These relationships (D_{10}, D_{50}, and D_{90}) were too poor to fit depth-to-groundwater suitability curves.

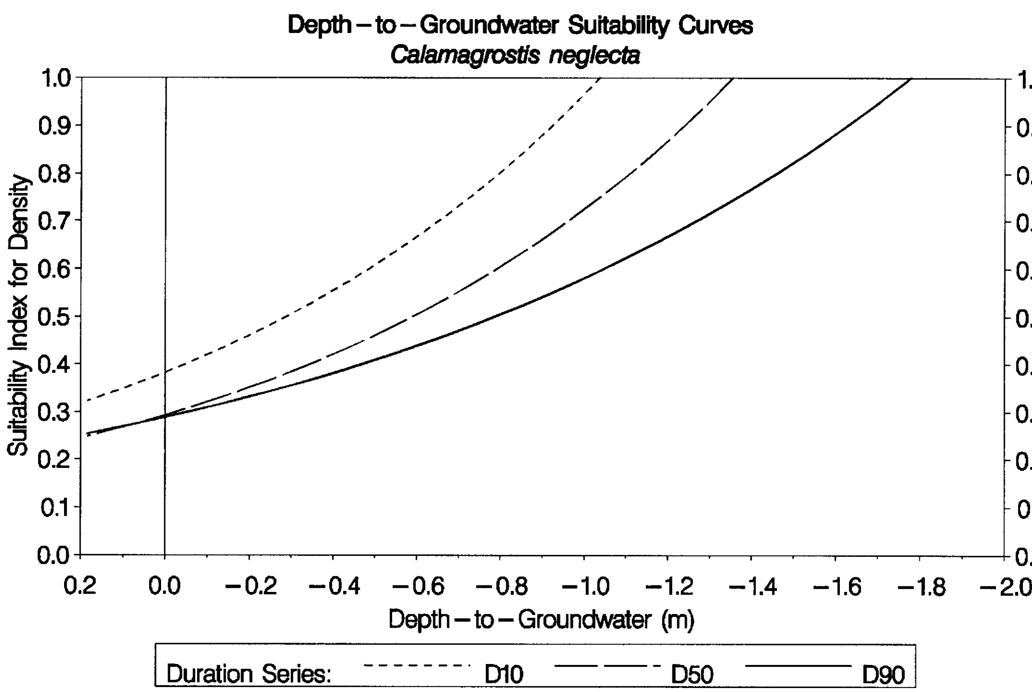

Figure 26b. Depth-to-groundwater suitability curves for slimstem reedgrass density. Three duration series are shown, representing the typical shallowest (D_{10}), median (D_{50}), and deepest (D_{90}) groundwater levels observed during the June through September growing season.

same depth because the optimum depth for each peak was not observed. When the groundwater level was at or below -1.17 m for 90% of the growing season, the suitability index for sedge biomass was less than 0.5. The dry meadows (Table 7) were not included in these suitability curves (Table 8 and Figure 24), because the dry meadows had mesic sedge species rather than the hydric species characteristic of the moist, moist-wet and wet meadows. Unlike sedge biomass, sedge density (Figure 24b) peaked at water levels that were above (0.18 m for D_{10}) or below the surface (-0.43±0.26 m for D_{50} and -0.76±0.45 for D_{90}). Sedge density had more variability than sedge biomass, and this was expressed in the confidence intervals for the coefficients affecting the curve shape (i.e., b, c, d). The confidence intervals for the coefficient (a) affecting the suitability index when the water level is at the surface (exponential equation) or the peak (Poisson equation) had less variation, however, and still should provide a useful guide for predicting sedge response.

Tufted hairgrass biomass (Figure 25a) was maximized when the depth-to-groundwater was at -0.17±0.12 m for D_{10}, deeper than -1.21 m for D_{50}, and deeper than -1.79 m for D_{90}. Optimum depth-to-groundwater for the two logistic curves (D_{50} and D_{90}) were chosen for a suitability index of 0.99, since the logistic curves are asymptotic to 1.0. When the groundwater level was at or above 0.41 m below the surface for 90% of the time, the suitability index for biomass was less than 0.1. Tufted hairgrass biomass tolerated standing water for short periods (D_{10} suitability index <0.3), but standing water deeper than 0.10 m for 10% of the time produced a suitability index of almost zero. The dry meadows with flow augmentation (Table 7) were not included in these suitability curves (Table 8 and Figure 25), because the tufted hairgrass in these meadows was apparently still adjusting to flow augmentation. One wet meadow site without flow augmentation (C400) was also not included in these suitability curves, because the depth-to-groundwater durations appeared to be too deep for this site. The depth-to-groundwater suitability curves for tufted hairgrass density

(Figure 25b) were similar to the suitability curves for biomass. Tufted hairgrass density was maximized when the depth-to-groundwater was at -0.29±0.19 m (D_{10}), deeper than -1.23 m for D_{50}, and deeper than -1.71 m for D_{90}. Density appeared to be slightly less susceptible to standing water for short periods compared to biomass (D_{10} suitability index <0.4), but standing water for 90% of the time still produced a suitability index of almost zero.

Slimstem reedgrass biomass did not show a strong relationship with the depth-to-groundwater durations, so no suitability curves were developed (Figure 26a). There appears to be a tendency for less low suitability values deeper than about -1.0 m, but a broader range of groundwater depths would be required to support this. In contrast to biomass, slimstem reedgrass density showed a relationship with the depth-to-groundwater durations (Figure 26b). Predicting the response of slimstem density to groundwater depths greater than those available would be difficult, but it appears that slimstem reedgrass density will decrease if the groundwater depths are shallower than -1.05 m for D_{10}, -1.34 m for D_{50}, and -1.81 m for D_{90}. Slimstem reedgrass density was more tolerant of standing water than tufted hairgrass density, but not as tolerant as the sedges.

DISCUSSION AND CONCLUSIONS

GROUNDWATER HYDROGRAPHS. Box-and-whisker plots simplified the interpretation of long-term data for the depth-to-groundwater hydrographs, because they show the timing and variation of groundwater levels for multiple periods (e.g., seasons, years) and wells without overlapping hydrographs on the same figure. The hydrographs might also be considered characteristic depth-to-groundwater hydrographs for each riparian community. For these characteristic depth-to-groundwater hydrographs to be valid, however, there must not be any long-term trend in the data. If there is a trend, such as a decline in groundwater level due to groundwater mining, then the traditional time-line hydrograph would be more appropriate. If these data were based on continuous observations, then each box would show the percent of time during the month (or other time unit specified) that a water level was maintained or above (similar to the duration curves). Periodic observations can also be used, as in our analysis, but then the data must be interpreted as the percent of *observations* instead of the percent of *time*.

Groundwater hydrographs for riparian wetlands are uncommon, and depth-to-groundwater hydrographs with box-and-whisker plots were not available. No continuous groundwater hydrographs for any wetland type with plant communities containing slimstem reedgrass or tufted hairgrass were available, but there were a few hydrographs for various species of hairgrass, reedgrass, and sedges based on at least bi-weekly measurements. These hydrographs tend to show less variation within months and between the highest and deepest values than was observed in the SFMCC meadows without flow augmentation. The water level in plant communities containing *Deschampsia flexuosa* ranged from about 0.01 m above the surface to about 0.87 m below the surface over a 7 year period in Sweden, with the highest levels occurring from mid December through April and the deepest levels occurring between August and September (Mörnsjö 1969). Mörnsjö (1969) also found that the water level ranged from between about 0.05-0.40 m above the surface to about 0.47-0.85 m below the surface in plant communities containing *Calamagrostis canescens*. *Calamagrostis inexpansa* and water sedge were most abundant around a well (well CM26CDA) in Nebraska where the water level ranged from 0.12 m above the surface to 0.84 m below the surface over a 2 year period, with the highest levels occurring in June and the deepest levels occurring in August (Henszey and Wesche 1993, Henszey et al. unpublished data, P. Currier pers. commun.). Beaked sedge in Sweden was observed where the water level was at or up to 0.70 m above the base of the plant shoots for most of the time, and the water level was never deeper than about 0.30 m below the base of the plant shoots (Mörnsjö 1969, Hultgren 1988). Godwin (1931) working in an English fen containing *Carex panicea* found that the water level declined from between 0.10-0.20 m below the surface in early June to a low of between 0.30-0.50 m below the surface before mid September. The highest water level he observed over a 2½ year period was about 0.03 m below the surface, and the deepest level was about 0.50 m below the surface. All these studies were located in large depressions or the wetlands were maintained by a perennial surface-water source. In contrast the SFMCC meadows were located in narrow valleys and fed by ephemeral streams. When surface flow stopped, the water supply from other sources (e.g., precipitation and subsurface flow) was apparently unable to prevent subsurface drainage and evapotranspiration from progressively lowering the groundwater level until recharge began after the growing season. The SFMCC moist meadows without flow augmentation illustrate this particularly well (Figure 17a). Other riparian wetlands in the semiarid western United States may also exhibit wide variation in groundwater levels, but additional data are needed to support this.

Continuous recorders provide the most accurate water-level data for developing hydrographs and depth-to-groundwater duration curves. Periodic observations risk missing short-term water-level changes caused by precipitation or short-duration streamflow fluctuations. These short-term changes (1 to a few days) might be beneficial to plants, and should be documented. In addition, continuous recorders provide data that may be useful for estimating evapotranspiration (Gerla 1992) and the effective rooting depth for the riparian plant community (Henszey and Wesche 1993). Although continuous recorders provide the most accurate data, it may still be possible to construct reasonably accurate hydrographs and duration curves. Continuous data for wells without recorders can be estimated by regression with nearby wells or stream gages equipped with recorders. This technique provides an estimate of the variation explained by the regression model (r^2), and may provide a good estimate for continuous data. Linear interpolation between observations can also be used to estimate continuous data, but the observations must be adequate to describe the hydrology. For the SFMCC we believe the number of observations to be sufficient to reasonably describe the hydrology based on our experience from other sites with groundwater recorders (Peacock 1992, Henszey and Wesche 1993). To verify this assumption, we now have continuous recorders installed in the study area and plan to investigate the difference between continuous and estimated-continuous data.

DEPTH-TO-GROUNDWATER DURATION CURVES. Depth-to-groundwater duration curves predict the availability and variability of sustained water levels, but they do not represent the actual sequence of observed events like a hydrograph (Viessman et al. 1977). This is an important point, since a duration curve might look superficially like a hydrograph. Duration curves show the cumulative frequency of observed water levels without indicating the actual time sequence. For example a depth-to-groundwater of 0.50 m might be observed on both June 10 and August 30, but the duration curve would show both days as having the same duration value (say 10%). Given that precaution, depth-to-groundwater duration curves show important hydrologic properties such as how often the water level is at or above the soil surface, how often the water level is at or below a critical depth (e.g., the rooting zone), and the median water level. Differences between the groundwater regime at different sites can also be tested. Grootjans and ten Klooster (1980) presented a method developed by Niemann (1973) to separate differences between duration curves from different plant communities. They found that this method lead to a detailed characterization of the groundwater regime, but it appeared unfit to predict changes in vegetation. This lack of sensitivity, they noted however, may have been because periodic groundwater level measurements were used instead of continuous measurements.

A few depth-to-groundwater duration curves for wetland species other than those on the SFMCC were available. Rheinhardt and Hershner (1992) used "inundation curves" to describe the relationship between groundwater fluctuations and tree canopy composition in Chesapeake Bay. Grootjans and ten Klooster (1980) showed that plant communities dominated by *Carex acuta* had higher water levels than plant communities dominated by either *Carex nigra* or *Carex panicea*, and that the water regime for the latter 2 species differed only when the water level was below the surface.

Depth-to-groundwater duration curves were available for water sedge, but the number of days used to develop the duration curves differed between studies. Water was at or above the surface most often in the Netherlands (up to 93% of the time), and the water level was never deeper than about 0.72 m below the surface (210 day study, Grootjans and van Tooren 1984). In the subalpine zone of Wyoming Peacock (1992) found that the water level was at or above 0.15 m below the surface about 30% of the time, and the water level was never deeper than 0.46 m below the surface (13 June to 19 September for 1 year). The deepest water level observed for other plant communities containing water sedge was 0.84 m below the surface in a meadow along the Platte River in Nebraska, although the water level was within 0.15 m below the surface about 58% of the time (3 year study, Henszey et al. unpublished data). Although the SFMCC wet meadows without flow augmentation (June through September for 5 years) had a mixture of sedges including water sedge, the duration curves were still similar to the above studies. Standing water was deeper (up to 0.19 m above the surface) and the maximum depth was deeper (1.12 m below the surface) than the other studies, however. The SFMCC sites with these extreme values may have been dominated by sedges other than water sedge, but we did not sample the sedges by species.

Tufted hairgrass in the subalpine zone of Wyoming (Peacock 1992) had depth-to-groundwater duration curves that were sigmoid shaped, while the duration curves for the SFMCC moist meadows were nearly linear (Figure 21). The inflection point for the sigmoid curves occurred at about D_{50}, indicating that 50% of the time the water level was close to the surface and 50% of the time the water level was relatively deep. The water level was higher in the subalpine sites with tufted hairgrass compared to the SFMCC sites. From 40-45% of the time the water level was at or above 0.15 m below the surface in the subalpine sites, while the water level was at or above 0.15 m below the surface from 0-18% of the time in the SFMCC moist meadows.

DEPTH-TO-GROUNDWATER SUITABILITY CURVES. Depth-to-groundwater suitability curves are an effective technique for quantifying the relationship between the water-level regime and the plant species response, but may not be applicable to all riparian plant species (e.g., slimstem reedgrass). This technique has been used extensively by fish habitat managers to develop instream flow relationships for maintaining fish populations (Bovee 1986). Designing instream flow relationships for riparian wetlands may not be as straightforward, however, since the relationship between groundwater and streamflow is not always obvious or direct. A relationship between streamflow and riparian hydrology may be established by simple linear regression between the groundwater well and a stream gage, or a more elaborate groundwater model may be required. Precipitation, evapotranspiration, and groundwater withdrawals for irrigation, industry and municipalities are some of the possible confounding factors influencing riparian hydrology (Henszey and Wesche 1993).

Besides establishing a relationship between riparian hydrology and streamflow, other factors may need to be considered before applying depth-to-groundwater suitability curves. By considering only groundwater depth, these curves may omit other potentially important physical (e.g., soil chemistry), biological (e.g., reproductive relationships, regional variation, competition), and management (e.g., grazing, previous seedings) factors. Many of the physical factors are directly modified by the hydrology, however, suggesting that their influence may be reasonably well represented by the water table alone (Walker and Wehrhahn 1971, Grootjans and ten Klooster 1980, Mitsch and Gosselink 1986, Hultgren 1988). If more than one physical factor is important, Bovee (1986) suggests using multiple axes to account for their interaction. An alternative to monitoring the groundwater level might be to monitor the soil water content in the root zone, since many riparian plants have most of their roots above the water table for a substantial period during the growing season (Chapter 2). Reeves and Smith (1992) used time domain reflectometry to monitor soil water content in rangeland soils. This technique is insensitive to several problems affecting other methods for measuring soil water content (Reeves and Elgezawi 1992), and may prove useful for developing future suitability curves. The long-term reproductive relationships for plants may not be adequately represented by depth-to-groundwater suitability curves, because the curves are usually developed for mature plants. If these relationships are different (e.g., Rood and Mahoney 1990), then additional suitability curves should be developed to address the life cycle of the species. Plant species response may vary by region, and as more depth-to-groundwater data become available it may be necessary to regionalize the data (Bovee 1986). Competition between species should also be considered. Rahman (1976) and Rahman and Rutter (1980) concluded that tufted hairgrass was restricted to wet soils because it was unable to compete in the drier soils. Many management practices influence the physical and/or the biological environment, and they should be considered when developing and applying depth-to-groundwater suitability curves.

The optimum depth-to-groundwater for water sedge frequency in the subalpine zone of Wyoming was at or above 0.15 m below the surface for 90% of the growing season (Peacock 1992), while the optimum water level for the SFMCC sedges (which included water sedge) was a nearly constant 0.15 m of standing water (D_{10} to D_{90}). These values are approximately similar, and might have been closer if standing water was available for the subalpine study. The true optimum groundwater depths (D_{10} to D_{90}) might not have been observed, however, since deeper standing water was unavailable for either study. Several investigators have noted optimum sedge response in standing water (0.06 to <0.60 m), but the response declined when the level of standing water increased beyond the optimum depth (Harris and Marshall 1963, Rumburg and Sawyer 1965, Millar 1973, van der Valk and Davis 1976, Sjöberg and Danell 1983, Hultgren 1988). Sedge density (Figure 24b) was optimized at deeper groundwater depths than biomass or frequency, and suggests that 2 optimum depth-to-groundwater duration curves are appropriate. Based on the available information the optimum depth-to-groundwater duration curve to maximize sedge biomass (beaked sedge, Nebraska sedge, water sedge, fieldclustered sedge) appears to be a nearly constant 0.15 m (D_{10} to D_{90}) of standing water. In contrast, the optimum depth-to-groundwater duration curves to maximize sedge density appears to be 0.18 m (D_{10}), 0.43±0.26 m (D_{50}), and 0.76±0.45 m (D_{90}) below the surface.

The optimum D_{90} depth-to-groundwater for tufted hairgrass was deeper than -1.79 m for biomass (Figure 25a), deeper than -1.71 m for density (Figure 25b), and -1.07 to -1.22 m for frequency (Peacock 1992). The relative insensitivity (suitability index ≥0.9) of tufted hairgrass biomass and density to D_{90} depths greater than about 1.20 m suggests that tufted hairgrass may not be very sensitive to deeper groundwater depths. Tufted hairgrass appears to be sensitive to short-duration, shallow groundwater depths, however, since the rising limbs for the D_{10} biomass and density suitability curves are very steep. This also suggests that the optimum depth-to-groundwater duration curve should tend to be on the deeper side, since raising the water level less than 0.20 m can change the suitability from 1.0 to less than 0.4 (e.g., D_{10} for biomass). Based on the available information, therefore, the optimum depth-to-groundwater duration curve for tufted hairgrass appears to be between -0.17 and -0.29 m for D_{10}, deeper than -1.23 m for D_{50}, and deeper than -1.79 m for D_{90}.

Slimstem reedgrass had the least well defined depth-to-groundwater relationship of the 3 species/assemblages investigated. Slimstem reedgrass biomass had a relationship too poor to develop suitability curves, and only the upper limit for water levels was suggested for slimstem reedgrass density. These poor relationships suggest that slimstem reedgrass might have a relatively broad ecological tolerance for groundwater levels, making it difficult to define suitability curves without additional data for deeper standing water and deeper groundwater depths. Based on the available data, however, it appears that slimstem reedgrass density will decrease if the groundwater depths are shallower than -1.05 m for D_{10}, -1.34 m for D_{50}, and -1.81 m for D_{90}.

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CHAPTER 5

SUMMARY AND CONCLUSIONS

Streamflow augmentation has been used since 1985 to supply the previously ephemeral South Fork of Middle Crow Creek (SFMCC) with a perennial water source. This water conveyance strategy was intended to partially mitigate the Cheyenne Stage II water diversions in the Sierra Madre and Snowy Range by enhancing the aquatic and riparian resources of the SFMCC with water that would normally be transported through pipelines or open channels. Water was piped from the Snowy Range 60 km west of the study site and released into 2 small watercourses at the headwaters of the SFMCC. These controlled releases represented nearly 100% of the SFMCC streamflow in the study area from mid summer until spring runoff. Flow augmentation was continuous, except for one month during peak spring runoff and for occasional maintenance on the supply system. If this type of mitigation proves to be successful on the SFMCC, then resource managers will have an additional option to consider when evaluating methods to mitigate the effects of interbasin water diversions.

Flow augmentation created a brook trout fishery (Wolff 1987, Wolff et al. 1989), increased the length of channel from 24% (2,017 m) of the study area before flow augmentation to 41% (3,446 m) by Year 6 (Chapter 3), and shifted the plant species composition to more water tolerant species (Chapter 2). All these changes are dependent upon an uninterrupted source of augmented streamflow, and some changes may be irreversible (e.g., channelization). Should management priorities shift and flow augmentation be discontinued, then this mitigation option may do more harm than good in the long run. Besides terminating an artificial fishery, discontinuing flow augmentation will decrease the streamflow available to fill the artificially channelized watercourse. This downcut channel will probably lower the "restored" natural surface and ground water regime, and cause the "restored" riparian plant communities to form a different plant species composition than before flow augmentation. Clearly once streamflow augmentation is initiated in an ephemeral watercourse, the natural aquatic and riparian resources may never be the same, even if flow augmentation is discontinued. Streamflow augmentation, therefore, should be considered an irreversible mitigation option and not a short-term option.

Biological diversity may be enhanced with streamflow augmentation, if the area chosen has few perennial streams. Ideally, streamflow augmentation could be used to create additional perennial stream habitat in areas where this habitat is uncommon. In contrast, streamflow augmentation can decrease biological diversity by diverting water from an area with few perennial streams to create a perennial stream in an area with an abundance of perennial streams and few ephemeral streams. The SFMCC may fall into this second category, since there are few ephemeral streams in the Laramie Range with the type of riparian plant communities that were along the SFMCC before flow augmentation. Additional information would be required, however, to examine this possibility.

The long-term changes caused by converting the SFMCC to a perennial stream remains to be seen. Given the relatively slow rate of channel development and plant community adjustments, however, there should not be any sudden, unexpected changes. The following conclusions can be made about the hypotheses proposed in Chapter 1 and the overall response of the SFMCC to streamflow augmentation based on 4-6 years of evaluation.

1. Streamflow augmentation elevated the groundwater level. In areas without a channel to convey the augmented flow, the water level was near ($\geq$-0.02 m) or above the surface ($\geq$0.06 m) for 10% of the growing season. Sites with a

channel (e.g., dry meadows) also had elevated groundwater levels, but this was less pronounced. Ninety percent of the time during the growing season the water levels in the flow augmented sites were from 0.47 m (wet meadows) to 1.68 m (aspen) above the water levels in similar sites without flow augmentation.

2. The amount (biomass, density, and cover) of sedge changed during 4 years of streamflow augmentation. The mean biomass for all meadows with flow augmentation increased from 240 $g \cdot m^{-2}$ in 1986 to 350 $g \cdot m^{-2}$ in 1988, and then decreased to an intermediate value (285 $g \cdot m^{-2}$) by the fourth year of flow augmentation (1989). Stem density also increased in the dry meadows (160 to 580 $stems \cdot m^{-2}$), while the mean basal cover for all meadows with flow augmentation decreased from 14% in 1986 to 4% in 1989.
3. The amount (biomass and density) of tufted hairgrass decreased during 4 years of streamflow augmentation (18 to 3 $g \cdot m^{-2}$, and 20 to 7 $bunches \cdot m^{-2}$), but the basal cover remained unchanged.
4. The amount (biomass, density, and cover) of slimstem reedgrass did not change during 4 years of streamflow augmentation, except for a temporary increase in biomass for the dry meadows between 1986 and 1987 (4 to 31 $g \cdot m^{-2}$).
5. The below-ground biomass decreased (4,900 to 3,400 $g \cdot m^{-2}$) during 4 years of streamflow augmentation, and the biomass under the developing channel was 53% of the biomass under the adjacent vegetation (3,900 $g \cdot m^{-2}$).
6. The above- and below-ground response to flow augmentation was dominated by elevated water levels. This may change when a channel develops, however. If the channel continues to downcut, then tufted hairgrass may increase while the sedges may decrease.
7. The length of channel increased from 24% (2017 m) before flow augmentation to 41% (3446 m) by Year 6 in the SFMCC study area. Low gradient sedge

meadows were highly resistant to channel formation. The previously unchannelized sedge meadow in Reach 4 was only 5% channelized by Year 6. Flow augmentation decreased the above-ground cover and the below-ground biomass, thus allowing most of this channel to form by downcutting rather than by the upstream migration of abrupt breaks in channel gradient (nick points).

8. The time-of-travel decreased during 6 years of streamflow augmentation, but the results were confounded because streamflow also tended to increase each year. Even still, there were examples when the time-of-travel decreased substantially among years while the change in discharge was minimal. The initial channel roughness values for Manning's *n* were high, ranging from 0.446 for the steeper reaches to 1.181 for the lower-gradient meadows. Channel roughness decreased with time but remained high, suggesting that the channel was still adjusting to flow augmentation 6 years after augmentation began.

9. There was a relationship between the depth-to-groundwater and the response (biomass and density) of the SFMCC sedges. This relationship was based on depth-to-groundwater duration values representing the groundwater depths that were at a specific level or above for 10, 50 and 90% (D_{10}, D_{50}, D_{90}) of the growing season. The optimum depth-to-groundwater for sedge biomass was a nearly constant 0.15 m (D_{10} to D_{90}) of standing water, while the optimum depth-to-groundwater for sedge density was 0.18 m (D_{10}), 0.43$\pm$0.26 m ($D_{50}\pm$95% CI), and 0.76$\pm$0.45 m ($D_{90}\pm$95% CI) below the surface.

10. There was a relationship between the depth-to-groundwater and the response (biomass and density) of the SFMCC tufted hairgrass. Tufted hairgrass response was optimized when the depth-to-groundwater was between 0.17 and 0.29 m for D_{10}, deeper than 1.23 m for D_{50}, and deeper than 1.79 m for D_{90}.

11. The relationship between slimstem reedgrass biomass and the depth-to-groundwater was too poor to develop suitability curves, but slimstem reedgrass

density appeared to decrease if the groundwater depths were shallower than 1.05 m for D_{10}, 1.34 m for D_{50}, and 1.81 m for D_{90}. Slimstem reedgrass may have a relatively broad ecological tolerance for groundwater levels, making it difficult to define optimum groundwater levels without additional data for deeper standing water and deeper groundwater depths.

12. The depth-to-groundwater suitability curves were useful for explaining the plant response to flow augmentation, and should also be useful for predicting the plant response to altered groundwater levels for future water development projects.

FUTURE RESEARCH NEEDS

Future research needs for the South Fork of Middle Crow Creek Study Area should concentrate on maintaining a continuous hydrologic data base, while expanding the research to address other important riparian wetland issues. The SFMCC and adjacent comparison watersheds have continuous or periodic data for precipitation, surface water, and groundwater collected since 1985 from 2 precipitation gages, 6 stream gages, and nearly 300 alluvial groundwater observation wells. These data have proven invaluable for evaluating the response of the SFMCC to streamflow augmentation and for developing depth-to-groundwater suitability curves. Although there may not be a research project conducted every year in the study area, it is essential to maintain the hydrologic data base to interpret properly the results of future projects. For example, when it comes time to re-evaluate the riparian vegetation response to streamflow augmentation after a perennial stream channel has fully formed, it will be necessary to describe how and when the surface and ground water regime has changed since the initial assessment. Similarly, it is important to continue to record channel development with the annual permanent photo points and cross-sections surveys, and the biannual channel length surveys. The cost of maintaining this continuous hydrologic and morphologic data base is minimal (2-3 work-months per year) when compared to the potential information gained.

One important question that remains to be answered about streamflow augmentation on the SFMCC is the water conveyance efficiency. The water lost to evapotranspiration and deepwater percolation will be the long-term cost of this mitigation to the City of Cheyenne, Wyoming. Without knowing the water conveyance losses, it will be difficult to judge the overall, long-term costs and benefits of using streamflow augmentation as a mitigation option. Much of this data has been collected, but it will take time to analyze the information. This could provide the research topic for a Master's Degree project.

The depth-to-groundwater suitability curves developed in Chapter 4 are one example of expanding the SFMCC research to address other important riparian wetland issues. These curves may provide the basis for a vegetation response model that can be linked to a hydrologic model such as HEC-6 (U.S. Army Corps of Engineers 1977) to analyze the possible effects of modified flow regimes for montane riparian areas throughout the intermountain west. The depth-to-groundwater suitability curves might also be further refined by developing the plant response to soil moisture in addition to groundwater level. Other important issues that could be addressed using the SFMCC study area include: the effect of root biomass on streambank strength, and the effect of different livestock grazing schemes on aquatic and riparian habitat using the 6 SFMCC livestock grazing exclosures. With the facilities established in the SFMCC study area and its proximity to the University of Wyoming, we have both the opportunity to study the effects of streamflow augmentation and the opportunity to address other important riparian wetland issues.

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APPENDIX

Table 9. Above-ground biomass ($g \cdot m^2$) for the 4 meadow types investigated on the South Fork of Middle Crow Creek (Flow) and adjacent watersheds (No flow), showing the back-transformed means. Flow augmentation began August 1985. Means within a column for a category followed by the same letter were not significantly different ($p > 0.05$, Bonferroni t test). Means not followed by a letter were not tested.

		Dry meadow		Moist meadow		Moist-wet meadow		Wet meadow		All meadows	
Category	Year	Flow (n=4)	No flow (n=2)	Flow (n=5)	No flow (n=3)	Flow (n=5)	No flow (n=3)	Flow (n=6)	No flow (n=3)	Flow (n=20)	No flow (n=11)
Calamagrostis neglecta	1986	4 ^{a}	34 ^{a}	47 ^{a}	69 ^{b}	12 ^{a}	9 ^{a}	24 ^{a}	8 ^{ab}	20 ^{a}	24 ^{b}
	1987	31 ^{b}	21 ^{a}	38 ^{a}	16 ^{a}	13 ^{a}	7 ^{a}	18 ^{a}	3 ^{a}	23 ^{b}	10 ^{a}
	1988	21 ^{ab}	39 ^{a}	23 ^{a}	52 ^{ab}	10 ^{a}	16 ^{a}	19 ^{a}	12 ^{ab}	17 ^{a}	26 ^{b}
	1989	10 ^{ab}	25 ^{a}	19 ^{a}	24 ^{a}	14 ^{a}	28 ^{a}	11 ^{a}	28 ^{b}	13 ^{a}	26 ^{b}
Carex spp.	1986	30	59	262	115	385	235	337	306	242 ^{a}	176 ^{ab}
	1987	71	62	382	172	489	231	456	317	343 ^{b}	196 ^{b}
	1988	99	38	372	186	464	258	486	256	354 ^{b}	185 ^{b}
	1989	92	26	257	82	412	156	382	253	285 ^{ab}	124 ^{a}
Deschampsia cespitosa	1986	3	2	69	66	19	12	5	1	18 ^{c}	14 ^{a}
	1987	5	23	19	64	4	30	2	3	6 ^{b}	25 ^{ab}
	1988	5	31	17	80	1	71	1	11	5 ^{b}	45 ^{b}
	1989	4	30	7	38	1	55	0	13	3 ^{a}	32 ^{ab}
Other Plant species	1986	299	126	51	48	20	40	40	40	68	54
	1987	222	123	65	52	28	38	49	42	71	55
	1988	322	148	49	110	56	76	50	97	87	103
	1989	233	99	24	43	35	43	41	41	59	51
Total Plant	1986	342	221	452	301	450	302	412	360	416	301
	1987	346	229	516	309	540	309	532	374	490	310
	1988	463	258	480	431	539	437	566	383	516	385
	1989	361	180	324	189	470	288	439	352	400	254

Table 10. Stem or bunch density[1] (number·m^2) for the 4 meadow types investigated on the South Fork of Middle Crow Creek (Flow) and adjacent watersheds (No flow), showing the back-transformed means. Baseline sites are shown within the group for the mean of all meadows. Flow augmentation began August 1985. Means within a column for a category followed by the same letter were not significantly different ($p > 0.05$, Bonferroni t test). Means not followed by a letter were not tested.

		Dry meadow		Moist meadow		Moist-wet meadow		Wet meadow		All meadows		
Category	Year	Flow (n=4)	No flow (n=2)	Flow (n=5)	No flow (n=3)	Flow (n=5)	No flow (n=3)	Flow (n=6)	No flow (n=3)	Baseline (n=5)	Flow (n=20)	No flow (n=11)
Calamagrostis neglecta	1986	17	141	124	194	41	81	83	61		63[a]	111[ab]
	1987	88	160	131	127	39	56	64	25		76[a]	77[a]
	1988	61	249	134	311	40	150	49	66		66[a]	175[c]
	1989	83	178	76	120	34	153	64	99		62[a]	133[bc]
Carex spp.	1985									688[a]		
	1986	160[a]	343[a]	822[ab]	599[ab]	1327[b]	1365[ab]	1101[a]	877[a]	854[a]	827[a]	795[a]
	1987	390[b]	434[a]	1112[b]	651[ab]	1269[ab]	1177[a]	1356[a]	1126[ab]	1067[a]	1039[b]	856[a]
	1988	508[b]	491[a]	980[ab]	836[b]	912[a]	1807[b]	1078[a]	1598[b]	936[a]	884[a]	1184[b]
	1989	584[b]	370[a]	719[a]	468[a]	968[ab]	966[a]	1142[a]	1291[ab]	853[a]	868[a]	766[a]
Deschampsia cespitosa	1985									31[a]		
	1986	4	5	65	104	18	34	10	4	25[a]	20[b]	28[a]
	1987	11	24	30	41	9	32	10	6	11[a]	14[b]	24[a]
	1988	9	27	24	78	4	46	2	16	11[a]	8[ab]	39[ab]
	1989	12	41	20	68	3	82	1	22	7[a]	7[a]	51[b]

1. Stems for *Calamagrostis* and *Carex*, and bunches for *Deschampsia*.

Table 11. Percent basal cover for the 4 meadow types investigated on the South Fork of Middle Crow Creek (Flow) and adjacent watersheds (No flow), showing the back-transformed means. Baseline sites are shown within the group for the mean of all meadows. Flow augmentation began August 1985. Means within a column for a category followed by the same letter were not significantly different ($p > 0.05$, Bonferroni t test). Means not followed by a letter were not tested. T = trace ($0 < T < 0.5\%$).

		Dry meadow		Moist meadow		Moist-wet meadow		Wet meadow		All meadows		
Category	Year	Flow (n=4)	No flow (n=2)	Flow (n=5)	No flow (n=3)	Flow (n=5)	No flow (n=3)	Flow (n=6)	No flow (n=3)	Baseline (n=5)	Flow (n=20)	No flow (n=11)
Calamagrostis neglecta	1986	0	T	2	2	T	0	T	T		T	T
	1987	T	1	T	0	0	0	0	0		T	0
	1988	0	0	0	T	0	0	T	T		0	0
	1989	0	T	0	T	0	T	0	0		0	T
Carex spp.	1985									8 [ab]		
	1986	2	2	14	6	22	10	20	8	17 [b]	14 [c]	6 [b]
	1987	2	8	11	7	15	10	12	13	14 [b]	10 [b]	9 [b]
	1988	1	2	2	2	4	4	6	4	6 [a]	3 [a]	3 [a]
	1989	2	1	4	T	5	5	4	4	4 [a]	4 [a]	2 [a]
Deschampsia cespitosa	1985									2		
	1986	0	T	2	4	0	T	0	0	1	T	1
	1987	T	T	T	2	0	T	T	0	T	T	T
	1988	0	1	T	2	0	0	0	0	T	0	T
	1989	T	1	0	1	0	1	0	T	0	0	1
Other Plant species	1986	10	3	2	1	1	2	1	T		2	1
	1987	9	5	1	2	T	T	1	0		1	1
	1988	6	T	1	1	0	T	1	1		1	1
	1989	5	2	1	T	1	1	1	1		2	1
Total Plant	1985									15 [b]		
	1986	12	6	22	13	23	12	22	8	23 [b]	20 [c]	10 [b]
	1987	14	14	13	12	15	12	14	13	17 [b]	14 [b]	13 [b]
	1988	7	3	4	5	4	4	8	6	8 [a]	6 [a]	5 [a]
	1989	7	5	5	3	7	8	6	6	6 [a]	6 [a]	5 [a]

Table 11, Concluded.

Category	Year	Dry meadow		Moist meadow		Moist-wet meadow		Wet meadow		All meadows		
		Flow (n=4)	No flow (n=2)	Flow (n=5)	No flow (n=3)	Flow (n=5)	No flow (n=3)	Flow (n=6)	No flow (n=3)	Baseline (n=5)	Flow (n=20)	No flow (n=11)
Moss	1986	1^{a}	1^{a}	21^{a}	46^{a}	25^{b}	32^{a}	3^{a}	10^{a}		10^{a}	21^{a}
	1987	6^{a}	16^{a}	23^{a}	58^{a}	4^{a}	54^{a}	8^{a}	31^{a}		10^{a}	41^{c}
	1988	5^{a}	5^{a}	31^{a}	50^{a}	6^{a}	53^{a}	2^{a}	37^{a}		8^{a}	37^{bc}
	1989	8^{a}	5^{a}	31^{a}	42^{a}	5^{a}	24^{a}	5^{a}	27^{a}		10^{a}	25^{ab}
Litter	1986	76	91	45	39	44	51	73	76		60^{b}	63^{c}
	1987	63	60	37	24	46	25	59	43		51^{ab}	35^{a}
	1988	70	80	32	40	31	32	34	38		40^{a}	45^{ab}
	1989	60	76	38	42	64	55	63	56		57^{b}	56^{bc}
Bare Ground	1986	9^{a}	1^{a}	4^{a}	1^{a}	1^{a}	2^{a}	T^{a}	2^{a}		2^{a}	1^{a}
	1987	9^{a}	9^{a}	16^{ab}	3^{a}	33^{b}	8^{a}	16^{b}	10^{a}		18^{b}	7^{b}
	1988	12^{a}	12^{a}	27^{b}	4^{a}	57^{c}	8^{a}	55^{c}	17^{a}		39^{c}	10^{b}
	1989	19^{a}	14^{a}	19^{b}	12^{a}	23^{b}	12^{a}	24^{b}	9^{a}		21^{b}	11^{b}

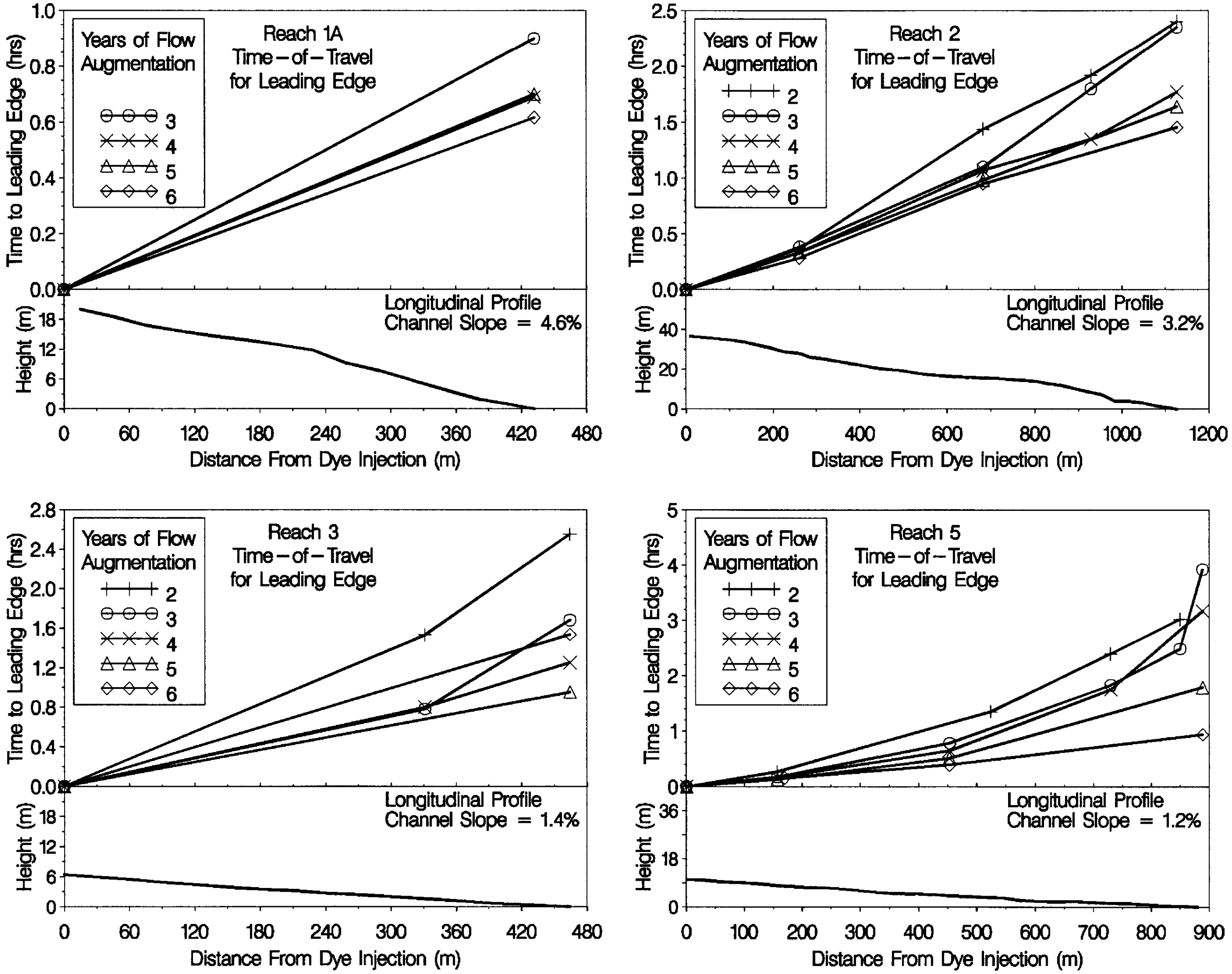


Figure 27. Time-of-travel for the leading edge, and the longitudinal profile for the second through sixth year of flow augmentation in Reaches 1A, 2, 3, and 5. Symbols indicate the time-of-travel sampling stations downstream from the injection point.

(a)
(b)
(c)

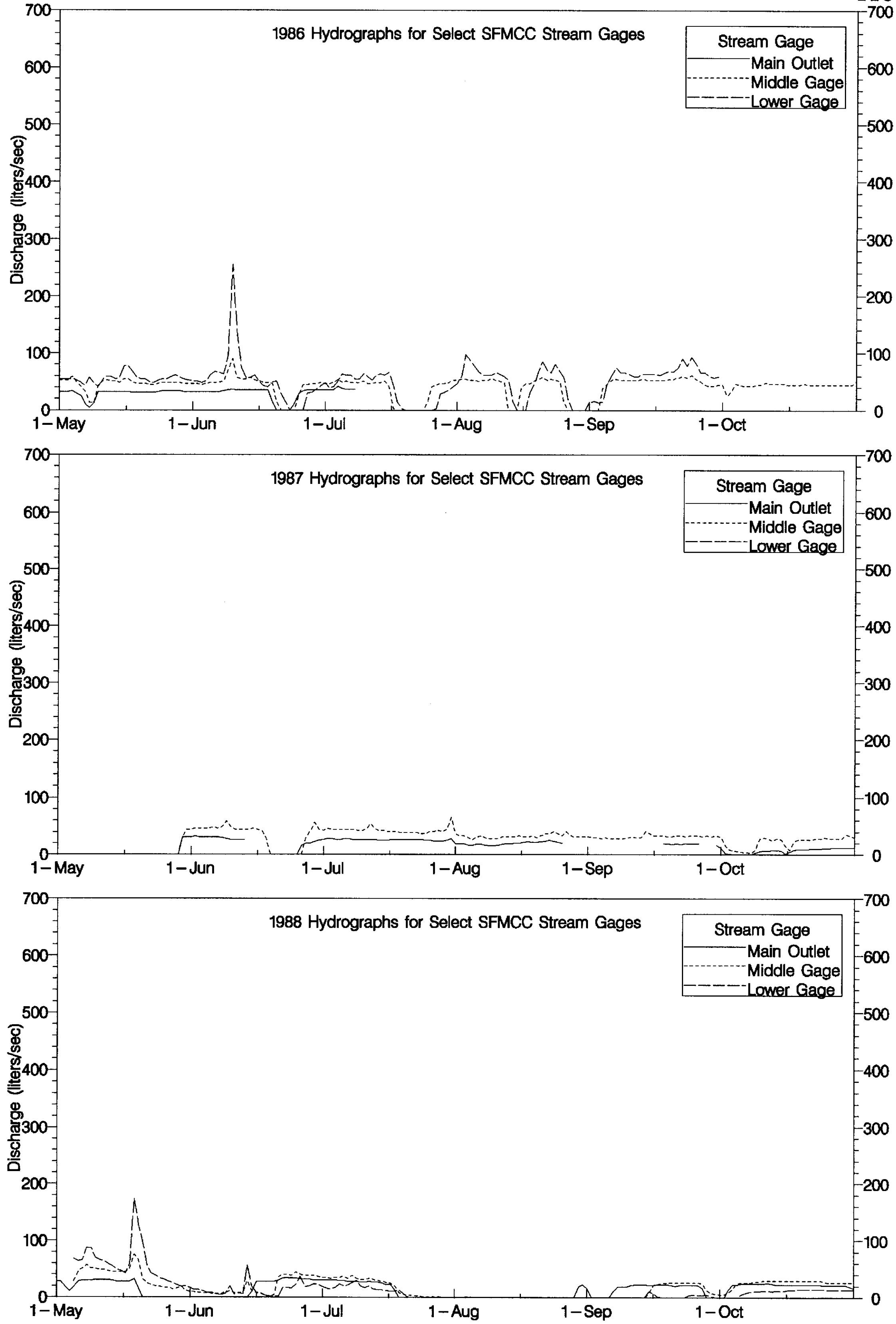
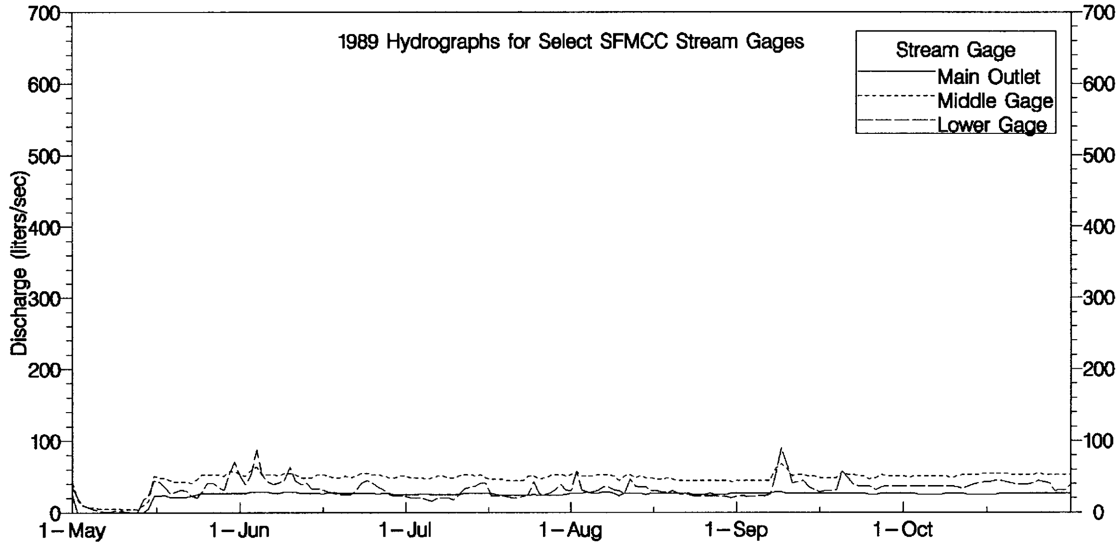
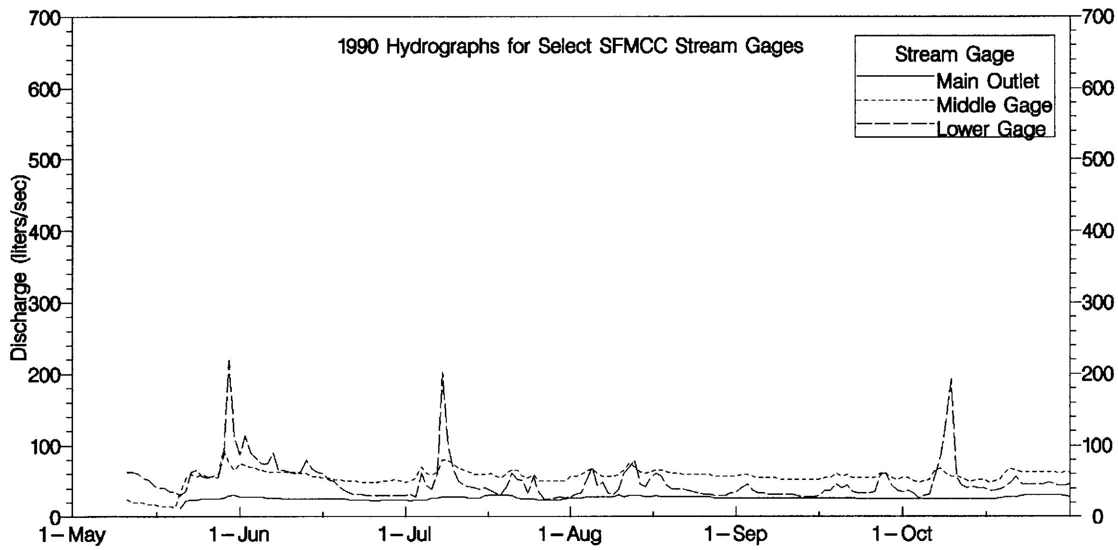


Figure 28. Hydrographs for select South Fork of Middle Crow Creek stream gages for May through October 1986-92. (Continued next page)

(d)



(e)



(f)

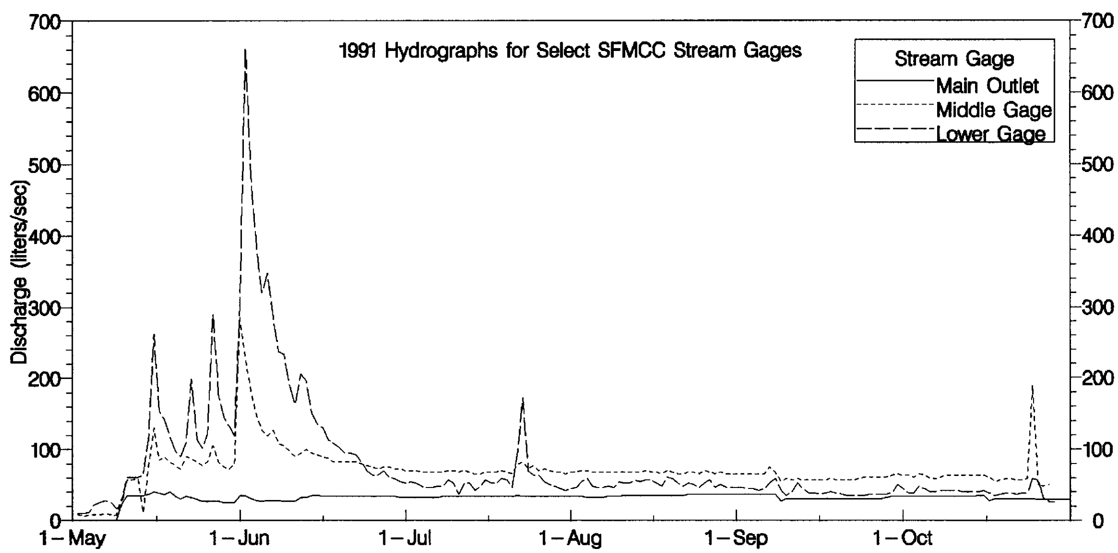


Figure 28, continued. The Tributary Outlet Gage had approximately the same discharge and timing as the Main Outlet Gage (Continued next page)

(g)

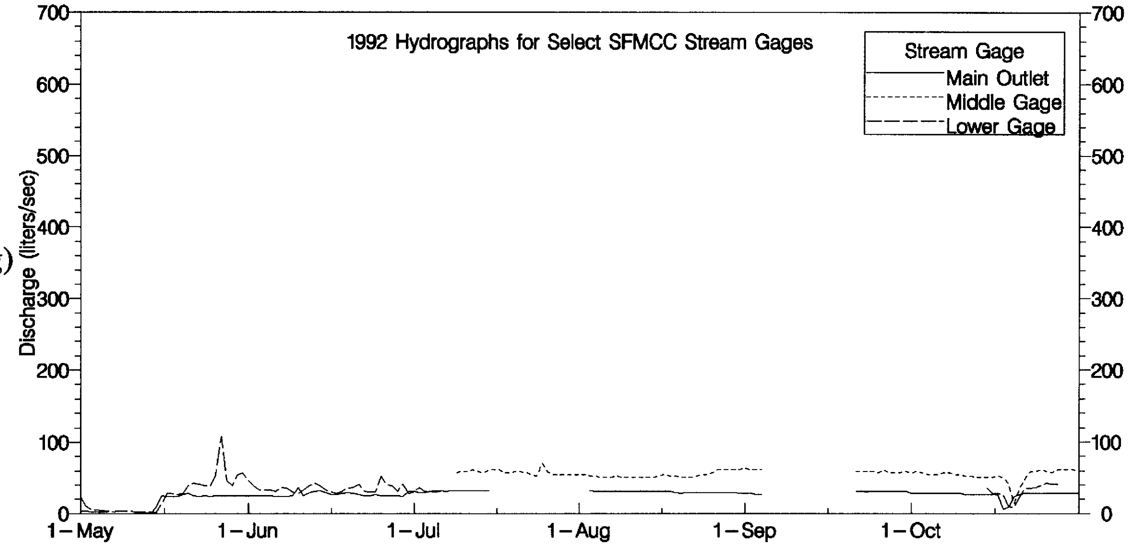


Figure 28, concluded. (i.e., discharge into the SFMCC was approximately 2 times the Main Outlet discharge).