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Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: the Red Deer River, Alberta, Canada

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Abstract. Flooding patterns and variations in the composition and successional trends of riparian vegetation in the upper and lower Red Deer River in southern Alberta, Canada, were studied in order to establish which flood regimes were most important in the regeneration and maintenance of riparian vegetation communities, with a particular focus on riparian poplars. The dominant riparian tree in the upper river is *Populus balsamifera* with some *Picea glauca* and in the lower river *Populus deltoides* (the plains cottonwood). Dendrochronological studies of the poplars along the river show that major periods of regeneration correspond with major flood events during the record period. Extensive cottonwood regeneration occurred in the period 1900–20, corresponding with a series of floods, some as high as the 1 in 100-year event. In addition, just prior to and during this period there was a significant reduction in use of the floodplain by bison, clearance of forests and a higher incidence of fires in upper reaches of the river and a series of high rainfall years. A series of floods greater than the 1 in 10-year flood occurred in the 1950s and stimulated the most extensive regeneration of poplars experienced since the 1920s. Parts of the lower Red Deer floodplain are now at elevations well above the 1 in 100-year flood event. It is suggested that fringe replenishment of riparian poplars is currently the dominant form of regeneration and that the large stands of mature poplars found on the floodplain, initiated during the end of the last century and first decades of this century, are unlikely to be replaced unless large floods (>1 in 50-year events) occur again. Construction of the Dickson Dam above the city of Red Deer in 1983 has led to attenuation of floods and a reduced likelihood that extensive flooding and poplar regeneration will occur again. A number of recommendations are made regarding flow management to both retain the fringe regeneration of poplars currently occurring and to stimulate more widespread regeneration of poplars on the floodplain.

Key words. Riparian vegetation, flooding, poplar (*Populus* spp.), bison, fire, Red Deer River, Alberta, Canada.

INTRODUCTION

Riparian vegetation occupies a unique location within river basins, lying at the interface between terrestrial and aquatic ecosystems. Functionally, it performs a number of important roles including nutrient buffering of groundwater from adjacent terrestrial areas (Lowrance, Leonard & Asmussen, 1984; Haycock, Pinay & Walker, 1993), stabilizing river bank sediments and providing cover and habitat for wildlife (Harper *et al.*, 1994; Large & Petts, 1994). The distribution of vegetation within riparian zones has been linked to numerous abiotic factors such as hydroperiod, floodplain landforms and sediment types as well as to competition and life-history factors (Hupp & Osterkamp, 1985; Bradley & Smith, 1986; Dunn & Stearns, 1987; Nilsson *et al.*, 1989; Hughes, 1990). While many studies now exist to demonstrate these relationships for particular stretches of river on a lateral transriparian scale, fewer studies address the longitudinal variations in riparian vegetation patterns along the intrariparian scale as defined by Johnson & Lowe (1985) and the ways in which these have changed during the historical period and in response to more recent flow manipulation.

Longitudinal variations in riparian vegetation can be explained in terms of both Holocene and historical changes in climate, sea-level and the length of time surfaces have been available for colonization (Baker, 1989; Nilsson *et al.*, 1991). Variations in elevation, stream gradient, geomorphological processes, sediment load and substrate diversity also largely explain longitudinal vegetation patterns (Nilsson *et al.*, 1991; Bendix, 1994). Spatially, the nature of many of these factors covary along the length of a river and are reflected in their influence on the distribution of species along the intrariparian continuum. The composition of contemporary vegetation communities found along a river also reflects the different lag-times involved in the response of abiotic and biotic elements of

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the riparian ecosystem to change through time and is therefore in a state of constant adjustment. This adjustment is effected through the changing availability of regeneration niches (Hughes, 1994).

Most riparian species in the prairie rivers of western North America have strong seasonal needs for particular amounts of water and habitat availability. In the case of riparian tree species, with life-cycles of at least 100 years, while minimum annual flows are necessary for their maintenance (e.g. Stromberg & Patten, 1990), a varied intra-annual, inter-annual and inter-decadal pattern of flows is also necessary to meet particular life-cycle needs, including regeneration and establishment, and the needs of community succession (Bradley & Smith, 1986; Baker, 1989; Hughes, 1994; Marken, 1994). It is also well established that deposition of sediment and creation of sites suitable for regeneration are necessary in order to satisfy these needs (Bradley & Smith, 1986; Virginillo *et al.*, Mahoney & Rood, 1991; Hughes, 1994).

Construction of dams has been shown to adversely affect the regeneration potential of riparian woodlands in many semi-arid and prairie rivers with consequent depletion of the extent of riparian woodland (Bradley & Smith, 1986; Rood & Heinz-Milne, 1989; Hughes, 1990; Rood & Mahoney, 1990; Cordes, 1991). In the Platte River (Nebraska), however, *Populus–Salix* communities have expanded despite dam construction, due to complex interactions between historical factors, environmental and plant life-history factors (Carter-Johnson, 1994). As well as dam construction in the upper reaches of prairie rivers, there is increasing competition for water resources along their whole length, particularly for drinking-water supplies for settlements and for irrigation.

In order to maintain existing and restored riparian woodland and to ensure their long-term regeneration, it has become important to understand in some detail both the contemporary and historical relationships between riparian vegetation and hydrological and geomorphological factors. Stromberg & Patten (1990) have developed simple and effective models which link annual growth rates to flows for *Populus trichocarpa* and *Pinus jeffreys* in a small river in semi-arid California. This has enabled them to determine minimum and optimal flows for the growth of these species. In a later study, species richness was shown to be highest in streams experiencing intermediate flow regimes while various biomass indices increased with growing season flow volume, in the Verde River Basin, Arizona (Stromberg, 1993). These findings have allowed development of simple instream flow models for riparian vegetation relating flows to riparian community characteristics. There remains a contemporary need to develop simple ways of defining the flow needs for the regeneration and succession of riparian vegetation in prairie rivers that take account of their longitudinal diversity and their response to changes in both biotic and abiotic factors.

The purposes of this paper are to:

1. Describe the riparian vegetation of the Red Deer River, Alberta, downstream of the Dickson Dam, its longitudinal variation and successional trends.
2. Link the present-day vegetation patterns to contemporary processes and historical change in order to present some preliminary flow needs of the riparian vegetation of the Red Deer River.

THE RED DEER RIVER

In most prairie regions of North America, the only naturally occurring woodlands are those found in riparian zones. Although the floodplains in which these riparian woodlands occur only occupy about 1% of the land area, they provide critical wildlife habitats and are refuges for plant species not found elsewhere in the prairie landscape (Johnson, Burges & Keammerer, 1976; Thomas, Maser & Rodiek, 1979; Saunders & Cordes, 1989). These riparian woodlands are also important for both recreational activities and cattle ranching. In southern Alberta they occupy less than 500 km^2 in total area and therefore represent a very restricted and valuable habitat (Bradley, Reintjes & Mahoney, 1991).

The Red Deer River rises in the Sawridge Range of the Rocky Mountains on the western border of Alberta and flows through south central Alberta, draining an area approximately 40,000 km^2 before crossing into Saskatchewan where it joins the South Saskatchewan River before flowing into Hudson Bay (Fig. 1). The Red Deer is the last river in southern Alberta that has not been highly regulated and which has not been excessively used for irrigation water abstraction. It has a low capacity dam, the Dickson Dam, above the city of Red Deer. Ecologically, it is one of the least disturbed and most interesting floodplains in western North America and is one of the most northern extensions of the plains cottonwood. The study area discussed in this paper lies between the Dickson Dam and the Alberta/Saskatchewan border. Within the study area, the Red Deer River flows through three distinct ecoregions or biophysical zones, as defined by Strong (1992), Aspen Parkland, Mixed Prairie and Short-Grass Prairie. These ecoregions reflect the considerable climatic differences across the river basin including a precipitation variation from nearly 500 mm/year at the city of Red Deer to around 330 mm/year near Empress. The three ecoregions included in this study account for more than 90% of the area of the Red Deer River Basin (Figliuzzi & Richmond, 1989). However, the mountains–foothills zones upstream of the study area contribute nearly 50% of the gauged flow at Bindloss. Of the mean discharge at the Saskatchewan border (approx. 67.4 m^3/s), 76% is contributed by the 26% of the river basin area located above the city of Red Deer.

In this study, two distinct yet connected floodplain biophysical regions were identified. The upper river from the Dickson Dam to Drumheller and the lower river from Drumheller, downstream to Empress. The upper river is characterized by a gravel riverbed with narrow, partially incised channels and limited floodplain development. The lower river is characterized by a meandering to unconfined meandering channel with numerous alluvial islands and large point-bars which support large stands of riparian woodland. In this lower reach, the river flows through extensive badlands including those of Dinosaur Provincial Park, which contribute a disproportionately high percentage

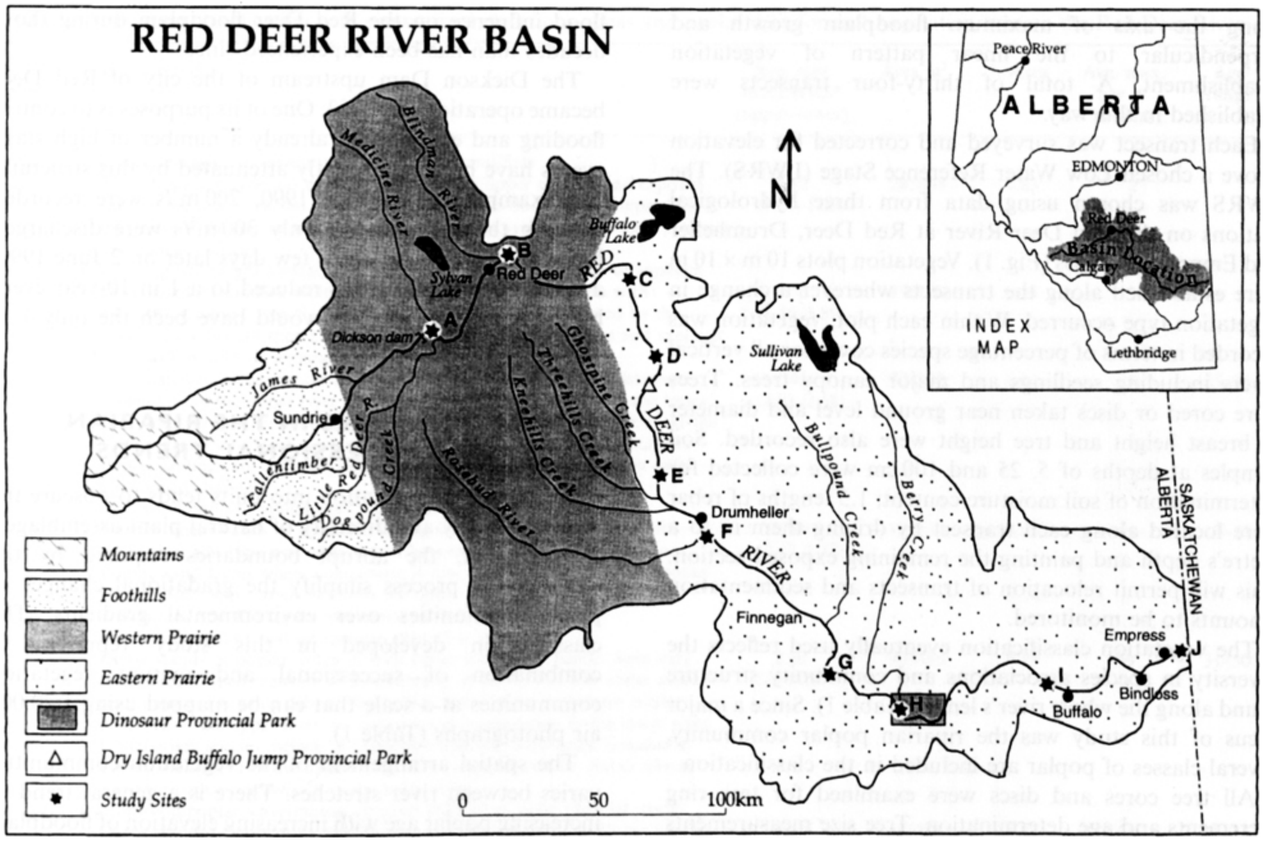

FIG. 1. Red Deer River Study Area Map. Adapted from Figliuzzi & Richmond (1989).

of the river's sediment load. The riparian poplar communities are represented primarily by balsam poplar (*Populus balsamifera*) in the upper part of the study area and by cottonwood (*Populus deltoides*) in the lower river. Around Drumheller the two species hybridize.

FIELD METHODS

In order to represent the diversity of riparian vegetation within the study area, ten sites (A–J) were chosen along the length of the Red Deer River, based on examination of aerial photographs and preliminary field surveys. The following list of criteria were used for their selection, aimed at achieving maximum representation:

1. All ecoregions within the study area were to be represented. Moving in a downstream direction, sites A, B, C and D are located in Aspan Parkland, sites E, F and G in Mixed Prairie and H, I and J in Short-Grass Prairie (Fig. 1).
2. All major riparian trees were to be represented in two or more study sites. Moving in a downstream direction, these included white spruce (*Picea glauca*), aspen poplar (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), balsam/cottonwood hybrid (*Populus × jackii*), peach-leaved willow (*Salix amygdaloides*) and Manitoba maple (*Acer negundo*).
3. Based on previous classification of riparian poplar communities in southern Alberta (Bradley *et al*., 1991) all density classes in the cottonwood-dominated section of the river were to be represented. Densities include Sparse (sites E and J), Moderate (site J) and Dense (sites, G, H and I). Dense stands have been further classified by age-structure.
4. All channel and floodplain types were to be represented from the upstream areas with gravel bars and well-defined terraces on the floodplain, to the narrow floodplain and incised channel upstream of the badlands and the well-developed meandering floodplain of the lower river to the Saskatchewan border.
5. All geomorphic–vegetation units and successional series were to be represented.

At each site a 2- to 3-kilometre stretch of river was mapped using 1:20,000 blueline mosaics; 1:40,000 and 1:30,000 black and white aerial photographs and preliminary site visits. This provided the basis for the iterative process of classifying vegetation in a preliminary way in order to choose representative transects and then adding both new sites and new transects and re-classifying vegetation on the basis of more detailed field work in order to achieve a representative coverage of all floodplain vegetation communities. Since alluvial plant communities are typically organized along an elevational gradient of decreasing flood duration and frequency (Gill, 1971; Nanson & Beach, 1977; Noble, 1979; Cordes, McLennan & Pearce, 1985; Pautou & Decamps, 1985; Hughes, 1990), two, three or four transects were established in each study site following elevational gradients along the axis of maximum floodplain growth and perpendicular to the linear pattern of vegetation establishment. A total of thirty-four transects were established in this way.

Each transect was surveyed and corrected for elevation above a chosen Low Water Reference Stage (LWRS). The LWRS was chosen using data from three hydrological stations on the Red Deer River at Red Deer, Drumheller and Empress/Bindloss (Fig. 1). Vegetation plots 10 m × 10 m were established along the transects wherever a change in vegetation type occurred. Within each plot, vegetation was recorded in terms of percentage species cover for all vertical layers including seedlings and major canopy trees. Trees were cored or discs taken near ground level and diameter at breast height and tree height were also recorded. Soil samples at depths of 5, 25 and 100 cm were collected for determination of soil moisture content; 1.5 lengths of rebar were located along each transect by driving them in to a metre's depth and painting the remaining exposed section. This will permit relocation of transects and sedimentation amounts to be monitored.

The vegetation classification eventually used reflects the diversity in species associations and community structure found along the whole river's length (Table 1). Since a major focus of this study was the riparian poplar community, several classes of poplar are included in the classification.

All tree cores and discs were examined for tree ring increments and age determination. Tree size measurements (d.b.h. and height) have been found ineffective in determining poplar age because growth rates vary considerably (Mahoney, Koegler & Rood, 1991). There is also a systematic 7–10% underestimation of ages using tree increment cores for poplars (Mahoney *et al.*, 1991). In this study, therefore, all results are given as 'decades of establishment'.

RED DEER RIVER FLOWS

Two types of floods occur on the Red Deer River. Ice-jam floods occur in early spring (late March–April), while snow meltwater and rainfall floods occur from late spring to late summer (May–August). The three hydrological monitoring stations used in this study (Red Deer, Drumheller and at Bindloss/Empress, Fig. 1) represent a record of hydrological inputs from the mountains and foothills, the foothills and western prairies and eastern prairies, respectively. Natural flows of the Red Deer River are extremely variable both along different stretches of the river within years and between years (Fig. 2). In the past 80 years of records, there have been runs of wet and dry years demonstrated by the mean flows during ice-free months between 1951 and 1955 (Fig. 3(a)) and between 1975 and 1979 (Fig. 3(b)). High stage events can experience considerable transformation longitudinally, such as a flood in June 1952 which was a 20-year event at Red Deer, but only a 10-year event by the time it reached Bindloss. Ice-jam floods are frequently not recorded on the hydrograph. Severe ice-jam floods were experienced in 1948 and 1952. These and the high spring floods experienced during the 1950s led to a wider zone of flood influence on the Red Deer floodplain during those decades than has been experienced since.

The Dickson Dam upstream of the city of Red Deer became operational in 1983. One of its purposes is to control flooding and erosion and already a number of high stage events have been significantly attenuated by this structure. For example, on 26 May 1990, 700 m^3/s were recorded entering the reservoir but only 300 m^3/s were discharged below the dam. Similarly, a few days later on 2 June 1990, a >1 in 30-year event was reduced to a 1 in 10-year event by the dam (Fig. 4). This would have been the only 1 in 30-year event since 1954.

VEGETATION TYPES IN THE RIPARIAN ZONE AND SUCCESSIONAL TRENDS

Classification of vegetation into units tends to obscure the true complexity and diversity of natural plant assemblages. In particular, the abrupt boundaries required by the classification process simplify the gradational changes of plant communities over environmental gradients. The classification developed in this study represents a combination of successional and mature vegetation communities at a scale that can be mapped using 1:20,000 air photographs (Table 1).

The spatial arrangement of the vegetation communities varies between river stretches. There is a general trend of increasing poplar age with increasing elevation of floodplain sites (Table 1). In stretches of the river which are incised, the distances between vegetation types are greatly reduced compared to freely meandering stretches at the downstream part of the study area. Successional cycles in riparian zones have been described for many rivers in the prairies of North America (Johnson *et al.*, 1976; Shaw, 1976; Noble, 1979; Bradley & Smith, 1986). Typically, they are directly associated with the hydrological cycles and dynamic fluvial geomorphology of their adjacent rivers. Successional cycles in the Red Deer River vary in different stretches, determined by variations in floodplain morphology, dominant sediments, species mixes and hydrological events. The surveyed transects studied along the Red Deer allow comparisons to be made in the relative heights and locations of different vegetation types.

The variations in vegetation communities found along the length of the Red Deer eventually led to the development of two successional models, one typical of the balsam poplar–spruce communities of the upper river (sites A–C) and the second model more typical of the hybrid and true cottonwood-dominated sites downstream (sites D–J) (Figs 5 and 6). These models were based on experience and observation and on qualitative analysis of the plot data which are summarized in Table 2. Both begin at the edge of the active channel and represent the most frequently observed changes in association following the axis of maximum channel migration into the distal parts of the floodplain. Both are necessarily generalized and inevitably do not reflect all the variability in vegetation change found along the Red Deer River. The two models are distinguished not only by having many different species as well as many common species but also by the different elevations with

TABLE 1. Vegetation classification with summarized elevations, areas and poplar ages for each vegetation type on the Red Deer River.

Map symbol	Vegetation type	Avg. elev. m.a.LWRS* (upper–lower)	Area m²	% Area	Avg. max. age of poplars	Age range
SV	Sparsely vegetated to unvegetated gravel/mud/sand/flats This vegetation type has exposed gravel in the upper reaches and exposed sand in the lower reaches. It experiences frequent flooding and typically may have some poplar seedlings with *Beckmania syzigachne*, *Scirpus pungens* and *Juncus balticus*	1.12 (1.27–1.07)	285808	1.83	2	
CW	Colonizing willow/grass/sedges, with or without poplar seedlings or saplings Dominated by sandbar willow (*Salix exigua*) in dense thickets with 40–100% ground cover. Sediments are coarse and easily trapped by the willow. Low overall species diversity but some poplar seedlings and saplings	1.76 (1.46–1.89)	978168	6.25	7	
W	Mature willow with or without poplar seedlings or saplings Dominated by large mature *Salix* spp. with *Cornus stolnifera*, *Elaeagnus commutata* in the upper river and *Symphoricarpus occidentalis* in the lower river, and various herbs in undergrowth. Soils consist of silt and clay at the surface grading to sand at depth. Usually found near the active channel. Poplar saplings are common and occasional poplar regeneration in older abandoned channels	2.41 (2.03–2.58)	724132	4.63	24	15–35
Cy	Cottonwood/poplar—young (less than 10 m in height) Narrow linear bands of poplar in young areas of the floodplain. In the lower river this type was often found between the CW and W types on sloping sand levées where competiton is low Common understorey species include *Salix* spp., *Alnus viridis* in the upper river, *Salix* pp., *Betula occidentalis* and *Elaeagnus commutata* in the lower river	2.34 (2.42–2.32)	129130	0.83	14	7–27
Cm	Cottonwood/poplar—mature (greater than 10 m in height) Dense stands of poplar, often in wide linear concentric bands. Soils vary from undeveloped regosols to development of an Ah horizon under several centimetres of organic debris Vegetative regeneration by balsam poplar observed in the upper river, no cottonwood regeneration in the lower river. Understorey species include *Amelanchier alnifolia*, *Shepherdia canadensis*, *Cornus stolonifera* in the upper river, *Ribes oxyacanthoides*, *Rubus ideaus*, *Symphoricarpos occidentalis* in the lower river	2.59 (1.99–2.79)	905488	5.79	49	31–50
Co	Cottonwood/poplar—overmature (greater than 10 m, older than 60 years) Dense stands of poplar In the lower river these are found in linear bands on the margins of concentric sandy scroll ridges. Soils typically have a loam texture with several centimetres of LFH accumulation over a well-developed Ah horizon and occasionally a narrow B horizon. Usually >100 m away from the active channel. Insignificant poplar regeneration and similar understorey species to Cm	3.61 (2.83–4.07)	401888	2.57	102	75–153
C/G	Cottonwood, open to scattered with grassland Typically found in the lower river with generally mature and overmature cottonwoods. Some younger poplars on sandy bars and dune ridges experiencing blow-outs Soils are coarse with little organic accumulation or soil development Common understorey species include *Heterotheca villosa*, *Calmovilfa longifolia* and *Artemesia frigida*	3.54 (N/A–3.54)	1646728	10.53	117	45–134
C/S	Cottonwood/poplar, open to scattered with shrub Mature poplar forests with shrub understorey in both the upper and lower river. It covers a much greater area (85% of all C/S areas) in the lower river, where it occupies large areas between scroll ridges on older parts of the floodplain. Soils are well developed with good LFH deposition. No poplar regeneration occurs here but white spruce seedlings are common in the upper river	3.14 (2.12–3.58)	3463860	22.15	79	
S	Mature shrub association This community is biotically heterogeneous but has structural and physiological homogenity. Typical species include *Shepherdia argentea*, *Salix bebbiana* var. *bebbiana* and *Betula occidentalis* in the upper river, *Alnus viridis*, *Cornus stolonifera* and *Prunus virginiana* in the lower river. Large dead willows in this association indicate a successional change from a willow to a shrub community It is often found at higher elevations in the floodplain adjacent to the W vegetation type	4.04 (N/A–4.04)	734520	4.70	39	
S/G	Shrub clumps intermixed with grassland Limited to the lower river on the oldest and most stable parts of the floodplain, it is characterized by a shrub/grassland mosaic Soils also vary from fully developed Chernozem under dense grass to undeveloped regosols. Typical species include *Shepherdia argentea*, *Artemsia cana*, *Prunus virginiana*, *Amelanchier alnifolia*, *Stipa comata*, *Koeleria macrantha* and *Bouteloua gracilis*	4.68 (N/A–4.68)	2621888	16.76	81	
G	Grassland This community is associated with the drier prairie of the lower Red Deer from site G downstream It is found in stabilized high sites on the floodplain and has species more typical of the upland prairie including *Opuntia fragilis*, *Artemsia fridgida* and *Malva rotundifolia*	4.10 (N/A 4.10)	2566612	16.41	N/A	

continued

TABLE 1 —*continued.*

Map symbol	Vegetation type	Avg. elev. m.a LWRS* (upper–lower)	Area m²	% Area	Avg. max. age of poplars	Age range
Ws	White spruce Restricted to sites A, B and C in the upper river with the occasional spruce tree as far downstream as site E. Typically, spruce has >50% ground cover and is associated with balsam poplar and trembling aspen (*Populus tremuloides* var *tremuloides*). These sites show signs of spruce domination as the poplar communities senesce. Typically, soils consist of sand and silt overlaying gravel. The diverse understorey includes *Linnea borealis, Galium boreale, Viburnum edule, Prunus virginiana* and *Cornus stolonifera*	2.62 (2.62–N/A)	708504	4.53	96	
A	Trembling aspen A rare community on the upland edge of the floodplain in the upper river downstream to site D. It frequently has some white spruce and balsam poplar associated with it and a diverse understorey. Well-developed soils on alluvial sand and silt with a thick humus layer	N/A	235040	1.50	66	
H	Herbaceous wetlands Found throughout the study area and usually associated with infilled channels at low elevations. Typical species include various grasses, sedges and horsetails with some willows	1.37 (1.02–1.91)	41991	0.27	N/A	
BC	Riverbank complex (combination of above units individually too small to map)	3.17 (1.89–4.45)	196200	1.25	N/A	

* Metres above low water reference stage

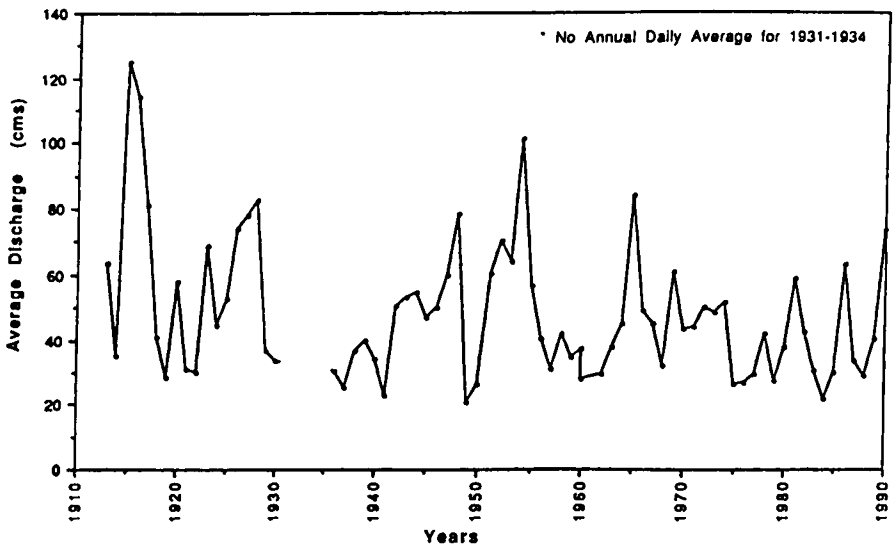

FIG. 2. Annual average daily discharge for the Red Deer River at Red Deer.

respect to the LWRS at which similar communities in the succession are found (Table 1). This reflects the great variations in channel processes and floodplain morphology between the upstream and downstream sites. In the absence of historical data the models assume a space for time substitution which may not be warranted but a comparison of aerial photographs taken in 1950 and in 1989 (discussed below) show changes in vegetation communities over a 39-year period which fit well with the proposed models.

In both models early successional stages are similar and begin with sparsely vegetated alluvium (SV), typically gravel in the upper river model and sand in the lower. Although poplar seedlings are occasionally found in these areas, sandbar willow is the usual colonizer, establishing in rapidly aggrading sediment and aiding stabilization of the site. Eventually, colonizing willow communities (CW) dominate, playing a significant role in trapping sediment during high stage events and providing seedbeds suitable for poplar regeneration. As aggradation continues, larger willow species (W) replace sandbar willow and poplars recruited in the previous stage grow and mature. Young poplars continue to be recruited in these areas but usually during floods greater than 1 in 10-year events because of the high elevations (around 2.4 m above LWRS). In the upper river, balsam poplar also spreads by suckering in these zones. The transition zone between CW and W vegetation types was observed to be particularly significant for poplar regeneration, especially where *Salix* densities are lower on steeper sandy levées. Here, arcuate bands of young poplars (Cy) tend to occur at elevations around 2.6 m above LWRS. At this point the models take different locations depending on the success of poplar colonization in the preceding stages:

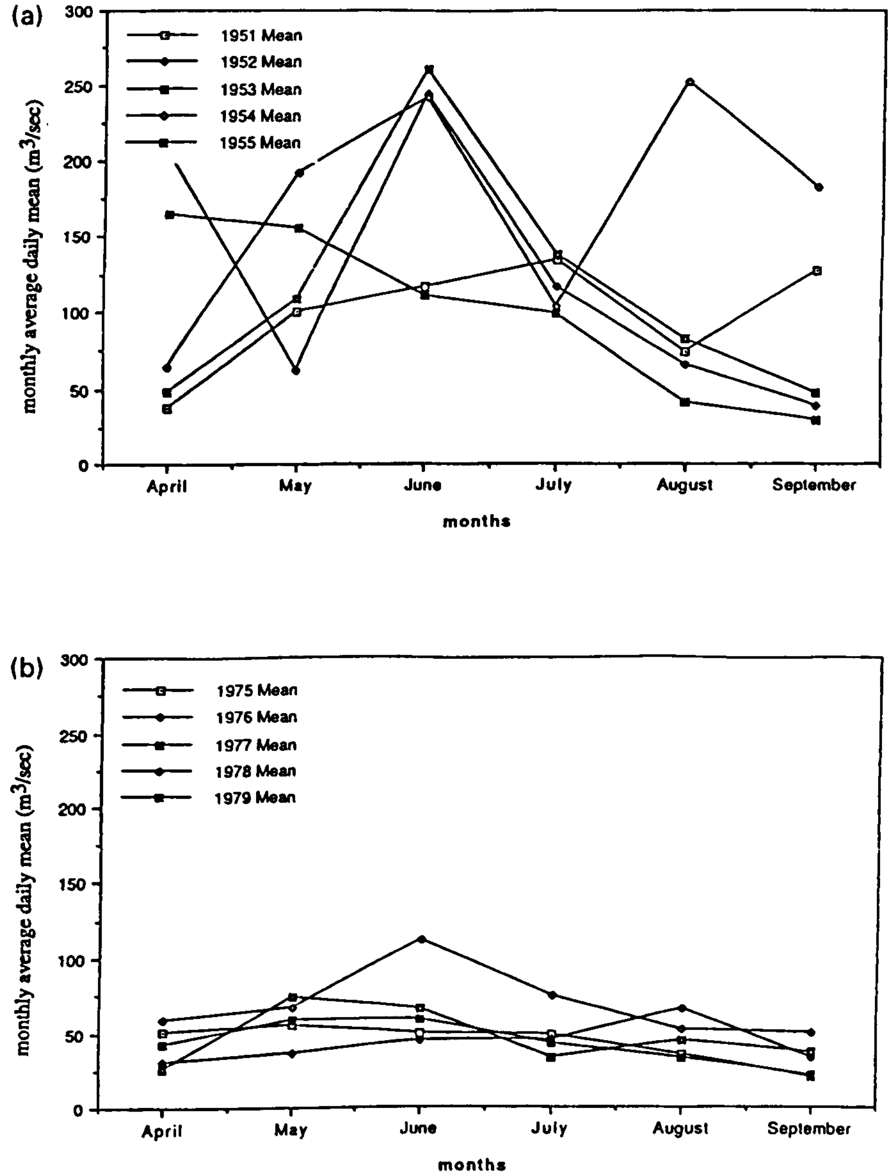

FIG. 3. Monthly average daily discharge at Red Deer. (a) 1951–55; (b) 1975–79.

1. Where poplars have established in high densities, then succession proceeds through the dense cottonwood/poplar classes.
2. Where poplars colonized, but sparsely (<50% canopy cover), balsam poplar/shrub associations usually follow in the upper river; cottonwood/shrub or cottonwood/grass in the lower river.
3. Unsuccessful colonization by poplars will typically result in transformation into a mature shrub community and rarely to a grass-dominated association.

As the riparian vegetation communities age and experience less frequent flooding and sedimentation, poplars decrease in density due to disease, old age and beaver activities. Plots in the S, S/G and G communities have few or no poplar trees in them (Table 2). Regeneration of poplars cannot occur in these areas and in the upper river, white spruce becomes dominant while in the lower river grass or shrub/grass communities become dominant. It is therefore possible that, in the case of the plains cottonwood, each successfully recruited cohort will survive for only one generation and although some seedlings may survive in abandoned channels and areas of secondary disturbance such as blow-outs, significant replacement of the cottonwoods only appears to occur through the continued stimulation of successional cycles by channel movement.

Hydrology and riparian vegetation

Age-structure of the riparian woodland

The age frequency of poplars in the upper and lower river was determined by decade. At sites A–E, in the upper river, many poplars established during the last 40 years with the

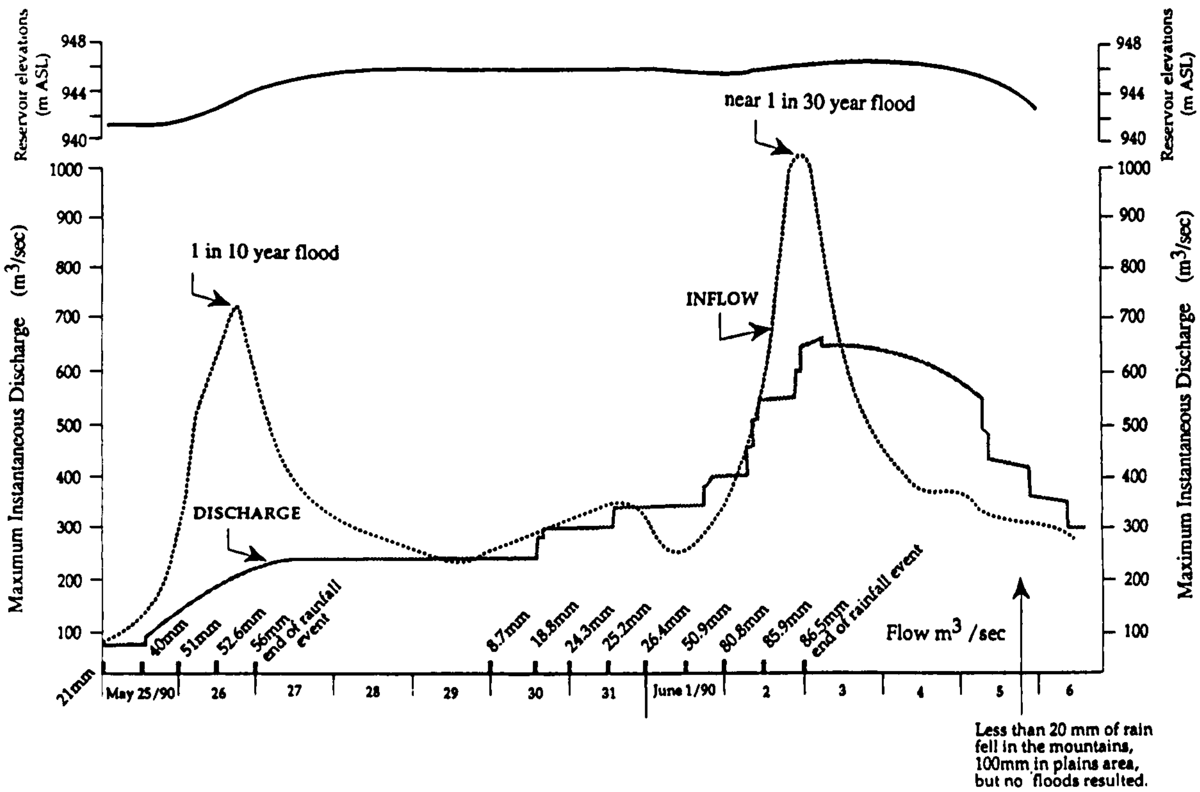

FIG 4. Alterations in Red Deer River flows resulting from flood attenuations at the Dickson Dam in 1990.

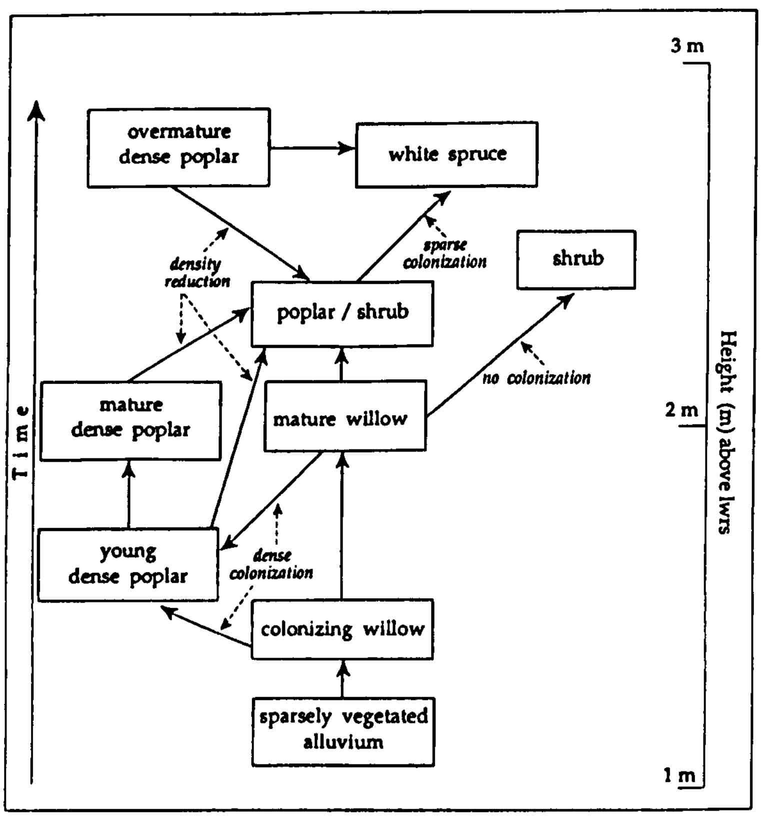

FIG. 5. Successional model for sites in the upper Red Deer River (A C).

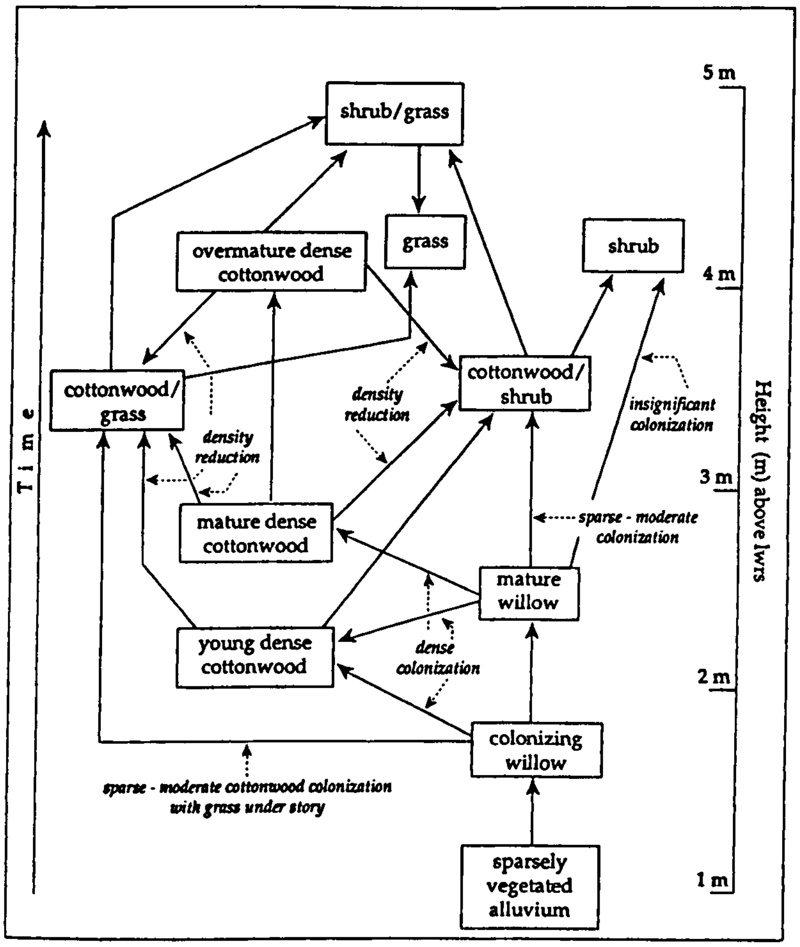

FIG. 6. Successional model for sites in the lower Red Deer River (D–J).

greatest number during the 1980s. Smaller peaks occur in the 1920s and 1880s. At sites F–J there are large peaks in the 1950s and 1960s and a lower peak in the 1920s and 1930s. As *Populus balsamifera* has a high ability to reproduce asexually and dominates in the upper river, the increased recruitment levels in recent decades probably reflect gradual regeneration by suckering in young and mature stands. In the lower river, *Populus deltoides* depends on recruitment by seeds. These data, however, tend to over-represent the number of younger trees because of the higher mortality in older trees. Approximately the same number of trees were sampled from each plot in a particular vegetation type but as different vegetation types occupy very different size areas, vegetation communities restricted in extent such as colonizing willow (CW) are over-represented. This is particularly a problem in the lower river. By comparing areas occupied by each vegetation type with the maximum age of each plot in it for the upper and lower rivers (Fig. 7), the area established in recent decades is shown to be much smaller than in the 1950s and 1960s or the earlier parts of this century. As expected, the area occupied by *Populus balsamifera* in the upper river is much smaller than that occupied by *Populus deltoides* in the lower river.

When this dendrochronological information is compared with the hydrological data for the Red Deer (Fig. 8), some similarities in trends can be observed between establishment of poplars and flooding events. Between 1920 and 1932 there were four floods with a greater than 1 in 10-year return frequency, all with four or more consecutive days with flows >500 cm. From 1948 to 1954 there was one 10-year event and two 20-year events, all with four or more consecutive days with flows >500 cm. From 1965 to 1971 there were four 5-year flood events with between 1 and 5 consecutive days with flows >500 cm. The 1920s floods correspond with a pronounced peak in poplars in the upper river (sites A–E) and with a less well pronounced peak in the lower river at sites F–J. The 1950s floods correspond most closely with peaks in poplar recruitment in the lower river (sites F–J) as do the lesser floods of the late 1960s (Fig. 8(c)). This is probably related to the dependence on recruitment by seed exhibited by *P. deltoides*. It is possible that flood magnitudes greater than or equal to 5-year events with several consecutive days of high stages are important for poplar recruitment but it is difficult to tie recruitment events to specific floods since both the timing of these events with respect to seed production by poplar and the antecedent moisture conditions on the floodplain can be critical in any year. These high flood years also tend to correspond with higher precipitation years on the prairies which will benefit seedlings trying to establish during their first growth season.

TABLE 2 Summarized plot data organized by vegetation type and vertical vegetation layer. Only poplar species are recorded in more than one vertical layer. The table gives data on the percentage cover of different species and on the percentage of plots in which species were found in each vegetation type (A = mature trees >7 m, B1 = tall shrub, including poplar saplings 2–7 m, B2 = low shrubs including poplar seedlings <2 m; C – herbaceous layer. In each vegetation type column: %pr. = the number of plots in which each species occurred, %co = the mean % cover of each species in those plots where it occurs, the value at the top of each column beside the vegetation type symbol is the number of plots on which the calculations are based.)

Veg horizon			Sv	13	CW	19	W	17	Cv	9	Cm	9	Co	6	C/G	12	C/S	7	S	17	S/G	9	G	7	WS	10	A	5	H	4	BC	11
			%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co
A	White spruce	*Picea glauca*					6	1			22	1	17	2			14	1							100	37	20	1				
	Balsam poplar	*Populus balsamifera*					6	2	22	1	67	44	50	41			71	12	6	1	22	1			20	20	20	3			22	6
	Cottonwood	*Populus deltoides*					12	2	11	1	33	27	50	33	100	18	43	32			11	2										
	Aspen poplar	*Populus tremuloides*																							30	4	100	24			11	5
B1	River alder	*Alnus tenuifolia*					12	14	33	4															20	2					11	6
	Saskatoon	*Amelanchier alnifolia*									44	3	17	12			43	37	35	9	56	7			80	6	60	40			44	10
	Dragonwort	*Artemisia biennis*			32	1	6	1																								
	Water birch	*Betula occidentalis*			5	1	29	8	44	1							29	6	59	22	33	5			40	5					33	2
	Silverberry	*Elaeagnus commutata*	8	1	11	6	47	4	33	6	33	24	50	8			29	2	59	6			14	2	60	8						
	White spruce	*Picea glauca*			5	1	6	1																								
	Balsam poplar	*Populus balsamifera*			5	1	35	4	33	10	22	5	17	1			29	2	18	2												
	Cottonwood	*Populus deltoides*			11	2	12	9	67	37	11	1					14	3														
	Choke cherry	*Prunus virginiana*			5	1			33	1	22	30	33	2	24	1	14	2							40	2	60	3			59	6
	Peachleaf willow	*Salix amygdaloides*					6	60	22	2	11	7																				
	Beaked willow	*Salix bebbiana*	23	1	42	14	59	38	33	18	33	22																				
	Sandbar willow	*Salix exigua*	92	8	84	46	53	17	33	5	44	4			24	10			35	16												
	Willow	*Salix* spp. (other)			21	20	24	22	44	20									59	22	44	5			40	1			75	9	22	13
	Thorny buffaloberry	*Shepherdia argentea*					24	22	33	1	33	22	17	15	24	15			47	14	56	7										
B2	Common bearberry	*Arctostaphylos uva-ursi*					6	1					17	10											60	20						
	Silver sagebrush	*Artemesia cana*																			44	2	29	1								
	Pasture sagewort	*Artemisia frigida*	15	1	5	1	6	1	11	1					43	2					56	1	100	1								
	Prairie sagewort	*Artemisia ludoviciana*									11	1	17	1	25	1	14	1			33	1										
	Bunchberry	*Cornus canadensis*							33	2	33	1															20	1				
	Red-osier dogwood	*Cornus stolonifera*	15	1	21	1	59	34	11	2	56	3	83	18			86	31	47	26					50	24	40	4				
	Balsam poplar	*Populus balsamifera*	15	13	47	4	12	1									14	1														
	Cottonwood	*Populus deltoides*	8	8	21	2	6	1	11	1																						
	Northern gooseberry	*Ribes oxyancanthoides*					12	2			33	3							24	2	11	7			30	2						
	Common wild rose	*Rosa woodsii*			5	7	71	13	33	4	67	15	67	6			86	2	71	17	67	2	14	1	80	11	80	8	25	10		
	Wild red raspberry	*Rubus ideaus*									33	16																				
	Canada buffaloberry	*Shepherdia canadensis*					6	1	11	1															30	2	20	3				
	Buckbrush	*Symphoricarpos occidentalis*	8	1	26	9	59	24	33	1	67	12	83	27	50	12	100	18	71	19	44	20			50	9	60	30			22	25
	Low bush cranberry	*Viburnum edule*	8	1							22	2	17	1			14	1			11	2					20	4				
C	Common yarow	*Achillea millefolium*			5	1	6	1															43	2			20	3				
	Northern wheat grass	*Agropyron dasystackyum*													29	6			35	4			29	4								
	Quack grass	*Agropyron repens*	46	3	21	13	35	12	22	10							14	3														
	Slender wheat grass	*Agropyron smithii*			5	1	12	2			22	6																				
	Rough hair grass	*Agrostis scabra*			5	30											14	1														
	Canada anemone	*Anemone canadensis*					6	1	22	1							29	1	47	4					10	1			25	1		
	Broad-leafed everlasting	*Antennaria* spp.													29	4					22	1	43	14								
	Aster	*Aster* spp.	8	1	48	5	29	5			11	1															40	2	50	4	11	1
	Slough grass	*Beckmannia syzigachne*	46	8									17	35																		
	Blue grass	*Bouleloua gracilis*																			22	7	29	14								
	Awnless brome	*Bromus inermis*			32	8	29	12	33	5	56	18	50	2	25	20	29	12	18	15			14	2					25	6		
	Bluejoint	*Calamagrostis canadensis*					6	5																							22	7
	Northern reed grass	*Calamagrostis inexpansa*			15	7																										
	Sand grass	*Calamovilfa longifolia*													43	32					22	4	14	12								
	Sedge	*Carex* spp.																					14	1			20	4	50	3		
	Canada thistle	*Cirsium* spp.			42	3	35	2																	10	1	20	1	25	1		
	White clematis	*Clematis ligusticifolia*									22	1	33	2	18	1	14	1	24	2												
	Creeping spike-rush	*Eleocharis palustris*	54	26																												
	Canada wild rye	*Elymus canadensis*	8	1	11	2	6	5							29	6	14	4	24	1	33	5			20	1	20	1				
	Common horsetail	*Equisetum arvense*	54	44	58	16	24	2	67	1									12	1												
	Marsh horsetail	*Equisetum palustre*	15	1	21	5	6	1	33	1					24	1	14	1							30	1			50	5		

continued

TABLE 2. *continued.*

Veg horizon		Sv 13		CW 19		W 17		Cy 9		Cm 9		Co 6		C/G 12		C/S 7		S 13		S/G 9		G 7		WS 10		A 5		H 4		BC 11	
		%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr	%co	%pr.	%co.
Philadelphia fleabane	*Erigeron* spp	8	1	26	1	24	1	33	1			17	1			29	1									20	1	50	1		
Wild strawberry	*Fragaria glauca*					12	12	33	8															60	12	20	2				
Northern bedstraw	*Galium boreale*					24	5			44	2	50	1			29	1	24	3					70	2	40	1				
Wild licorice	*Glycyrrhiza lepidota*	1	10	32	24	47	13	33	8	44	9	33	2			29	2	12	10	11	3					20	5			22	5
Northern hedysarum	*Hedysarum boreale*																							20	4						
Common tall sunflower	*Helianthus annuus*			16	5											14	1					14	1							11	11
Foxtail barley	*Hordeum jubatum*	15	9	16	2	6	1																					25	6		
Wire rush	*Juncus balticus*	38	12	11	5																										
June grass	*Koeleria macrantha*																			22	12	29	6								
Common pepper-grass	*Lepidium densiflorum*													29	2																
Twinflower	*Linnaea borealis*			5	1							17	75											50	7						
Wild lily-of-the-valley	*Maianthemum canadense*									11	4									33	1			20	1	20	1				
Pineappleweed	*Matricaria matricarioides*			5	1																							25	1		
Scentless chamomile	*Matricaria perforata*																														
White sweet-clover	*Melilotus alba*	23	1	37	14	18	1	67	2					25	8	14	1														
Yellow sweet-clover	*Melilotus officinalis*					12	2	33	8	33	5	17	1	25	2	14	1	24	1	11	1	114	8	10	8						
Wild mint	*Mentha arvensis*	15	2	32	2	12	1			11	5					14	1	12	1							20	1				
Wild bergamot	*Monarda fistulosa*																	35	4	56	6			10	2						
Prickly pear	*Opuntia polyacantha*																			11	1	29	1								
Reed canary grass	*Phalaris arundinacea*	23	8	5	20																							50	2		
Saline plantain	*Plantago eriopoda*	15	1																												
Common plantain	*Plantago major*	38	1	47	6	6	2									14	1											50	1	11	10
Bluegrass	*Poa* spp.	38	12	68	18	29	7	33	10	33	6					29	19	18	1	22	3					40	13	25	4	22	1
Knotweed	*Polygonum* spp.	8	1																							20	1	25	1		
Silverweed	*Potentilla anserina*	38	4	11	2																							25	3		
Common pink wintergreen	*Pyrola asarifolia*																							50	3	20	2				
Seaside buttercup	*Ranunculus cymbalaria*	15	3	11	1																							50	2		
Dock	*Rumex* spp.	54	2	5	1									25	2																
Three-square rush	*Scirpus pungens*	23	2	21	5																										
Common blue-eyed grass	*Syrinchium montanum*													25	3																
Star-flowered Solomon's-seal	*Smilacina stellata*			5	1	41	3			33	1	50	1	25	1	43	1	53	1	22	2			60	8			25	1		
Low goldenrod	*Solidago missouriensis*					12	2			56	1	50	3													20	1				
Goldenrod	*Solidago* spp	15	4	37	5	71	4	56	4					25	20			18	1							20	1			33	1
Long-leafed chickweed	*Stellaria longifolia*					6	1			11	1	17	1	25	1																
Needle-and-thread	*Stipa comata*														29	29				56	14	100	12								
Green needle grass	*Stipa viridula*														14	6						57	1								
Veiny meadow rue	*Thalictrum venulosum*					6	1			22	2					14	1							10	1	20	5				
Golden bean	*Thermopsis rhombifolia*									33	2			14	3	43	1	6	2												
Stinkweed	*Thlaspi arvense*	15	1																												
Alsike clover	*Trifolium hybridum*	8	1	16	3	6	1																								
Wild vetch	*Vicia americana*					41	2	33	1	44	1	33	1	25	1	57	1	18	1	33	1			20	1						
Tufted vetch	*Vicia cracca*	8	1	21	3	6	1									29	1														
Violet	*Viola* spp									11	1					14	1									20	2				

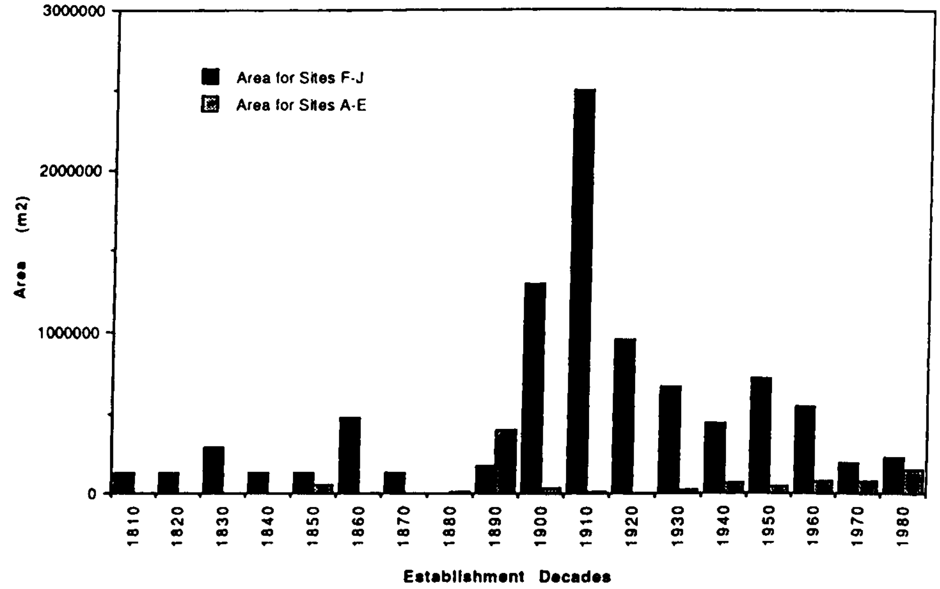

FIG. 7. Establishment decades and corresponding areas for *Populus* sp. sampled on the Red Deer River. Corresponding areas were calculated by assigning an equal proportion of the area of each vegetation type to each of the ages found within that type.

A relationship also exists between peak flooding years and the areal extent of cottonwoods established in the lower river (Fig. 8(c)). A 1 in 100-year flooding event occurred in 1915 followed by two 1 in 5-year events in 1915 and 1916. This period corresponds with the decade of largest areas of cottonwood establishment in the lower river. There are also historical records which indicate that catastrophic floods at least equal to the 100-year event occurred in June 1905 (Howe, 1971; Environment Canada, 1991). Again, major recruitment occurred in the first decade of this century (Fig. 7). The record shows that most extensive establishment occurred in decades which had floods in excess of the 1 in 50-year event or a series of consecutive years with stages greater than the 1 in 10-year stage (1910s, 1920s and 1950s). It is to be expected that high flows will correspond with the greatest extent of flooding in any year and therefore with the greatest potential for extensive recruitment in any year.

Mapped vegetation changes

In order to record more recent changes in the riparian zone, we compared photographs of the Red Deer River from 1950 and 1989. In the lower foothills zone represented by site A, substantial changes can be seen between the two time periods (Fig. 9(a) and (b)). The shape of the geomorphologically active area is very different at the two time periods. Areas of sparsely vegetated alluvium (SV) decreased by 60% between 1950 and 1989, while mature willow (W) communities expanded by 150%, shrub communities (S) by 116% and colonizing willows (CW) by 70%. These changes are all indicative of reduced geomorphological activity and availability of colonization sites in the study area. In the western prairie sections of the river, the geomorphological activity is limited by channel incision and relatively few changes in vegetation occurred between 1950 and 1989 (Fig. 9(c) and (d)). The downstream eastern prairie reaches have changed substantially during the same time interval (sites G and I). Here, point-bar accretion and incorporation and formation of new alluvial islands has continued but there is an overall decrease in the area of active alluvium (Fig. 9(e), (f), (g) and (h)). A similar pattern to site A can be seen with >90% decrease in sparsely vegetated alluvium (V) now colonized by willow and scattered cottonwood stands. In particular, the vegetation types CW and W have expanded from occupying approximately 0.5% to 4.5% of the floodplain. Overmature cottonwood stands (Co) also increased at both sites.

The sparsely vegetated areas of alluvium that are still being created are mostly unsuitable for successful poplar colonization due in part to physical abrasion stress experienced at the low elevations at which they are found. Instead, poplar regeneration occurs at slightly higher elevations in areas of colonizing willow (CW) and in the Cy community where they also experience higher levels of competition (Table 2). It is possible that, in the past, newly deposited areas of alluvium were at relatively higher elevations with respect to the LWRS, permitting extensive cottonwood establishment in the 1950s in areas now classified as mature cottonwood (Cm). This situation is similar to that described by Bradley & Smith (1986) in the Milk River floodplain further south in Alberta. The indications are that geomorphological activity has decreased since 1950. Hydrological data show overall lower flood levels post-1950 than pre-1950. Operation of the Dickson Dam has contributed to flood attenuation but there has also been increased withdrawal of river water for urban and agricultural use since the 1950s.

Patterns of sedimentation

Rates of sediment deposition are determined by the sediment load carried by the river and by geomorphological activity in the floodplain zone, both of which are closely linked to the hydrological cycle. In the lower Red Deer River, channel

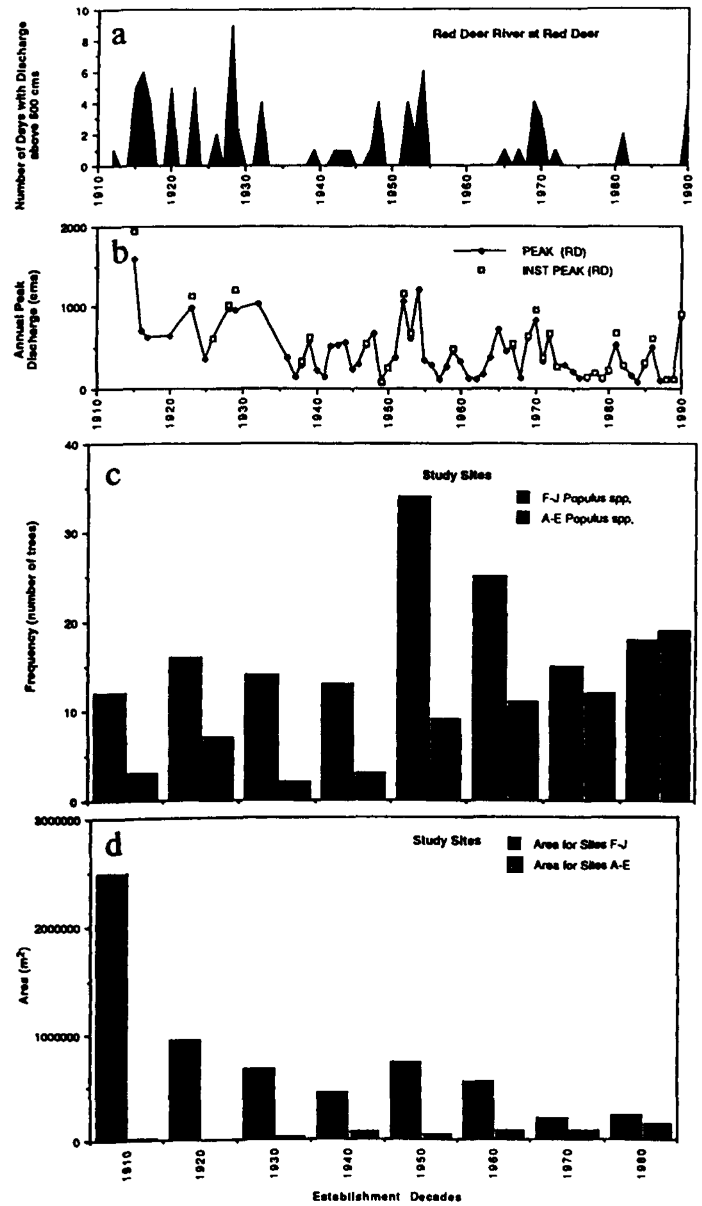

FIG. 8. Age frequency of Red Deer River poplars by decades (c) and poplar establishment areas by decades (d) compared to the duration of flood events (a) and annual peak discharge (b) at the city of Red Deer.

migration occurs in a non-systematic way and incorporation of sandbars and alluvial islands are an important component of floodplain construction (MacPherson, 1969). There are very few data on sedimentation rates in the Red Deer River although it is clear from observation that, spatially, they vary widely. By comparing the maximum ages of individual study plots and their elevations a broad pattern of sedimentation rates can be produced although this method assumes a space for time substitution (Fig. 10(a) and (b)). The graphs show that variance in the upper river is much greater than in the lower river. During the first 20 years in the lower river (Fig. 10(b)), sedimentation rates are high with low elevations experiencing high flooding frequencies. At this stage in point-bar development over 2 m of sediment are deposited. Over the next 50–60 years, less than 1 m of sediment is deposited. After 80 years deposition is minimal and most sites have reached an elevation of between 3 m and 4 m. Historically, the aggrading portions of point-bars have been the prime sites for poplar regeneration on the Red Deer floodplain but this study shows that currently, most poplar regeneration occurs in areas already colonized by willows, where sediment has recently been either deposited or removed. Relatively little aggradation of point-bars is now occurring, indicating a reduction in geomorphological activity in recent decades. The last period of extensive aggradation and vegetation establishment corresponds with the period of higher flows in the 1950s, preceded by the ice-jam flood in 1948.

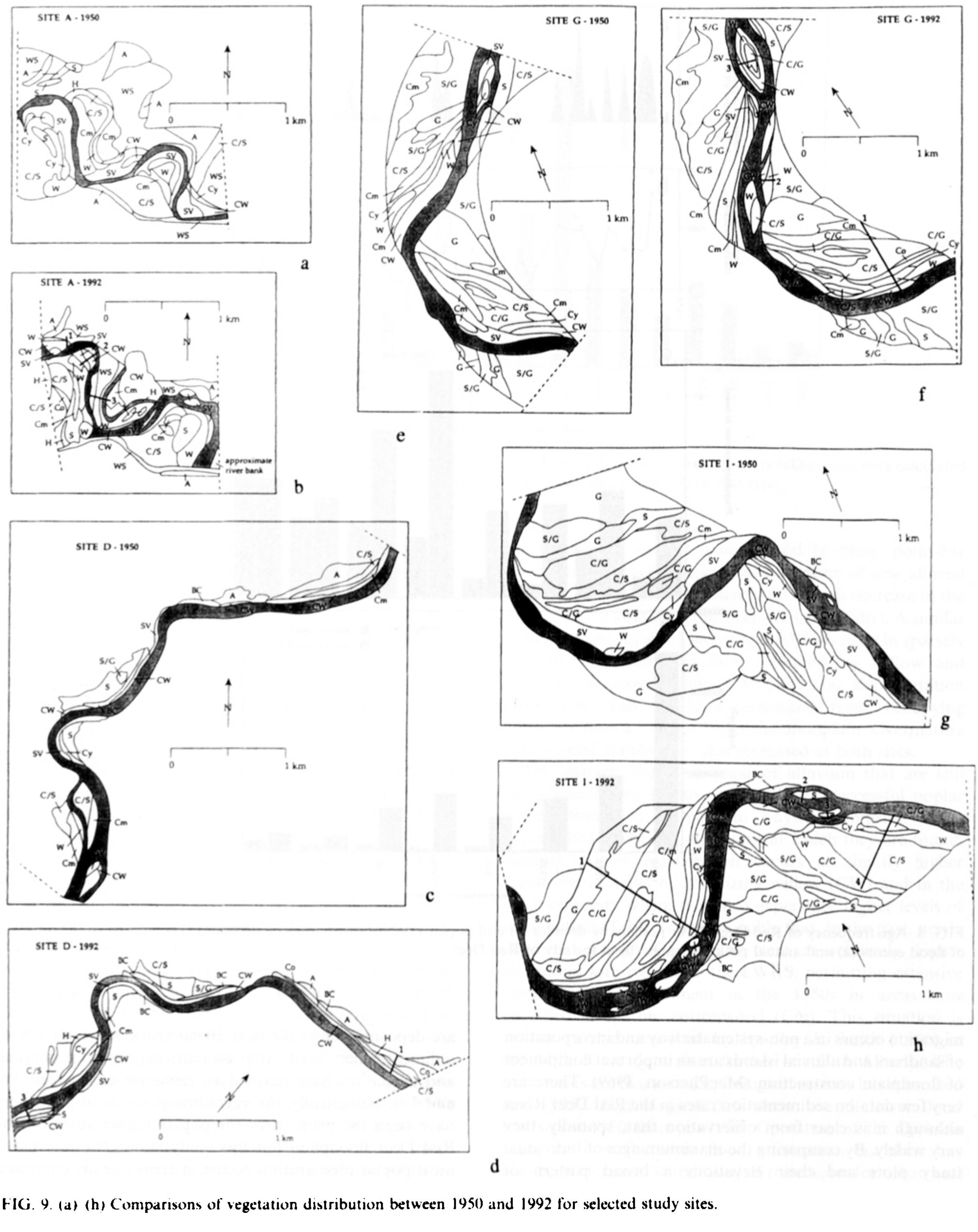

FIG. 9. (a)–(h) Comparisons of vegetation distribution between 1950 and 1992 for selected study sites.

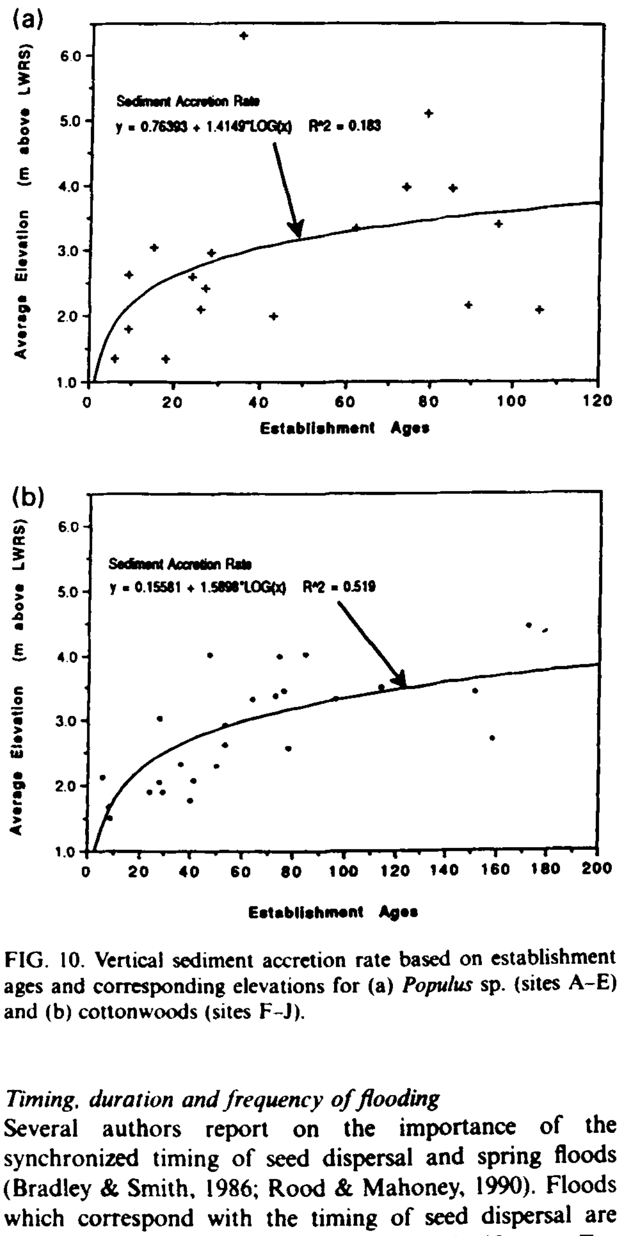

FIG. 10. Vertical sediment accretion rate based on establishment ages and corresponding elevations for (a) *Populus* sp. (sites A–E) and (b) cottonwoods (sites F–J).

Timing, duration and frequency of flooding

Several authors report on the importance of the synchronized timing of seed dispersal and spring floods (Bradley & Smith, 1986; Rood & Mahoney, 1990). Floods which correspond with the timing of seed dispersal are not the only ones which have ecological significance. For example, a late August 1 in 20-year flood, such as was experienced in 1954, may have played no direct role in seedling establishment that year, but may have deposited sufficient sediment to ensure the provision of seed beds in the following spring. No flood events of this size have occurred since 1954 although high summer precipitation in any year can contribute to successful establishment in the absence of significant flooding events. In this context the shape of the hydrograph following a flood is critical in successful poplar establishment. Rapid recession of stage levels and floodplain watertables following a flood are detrimental to seedling survival (Bradley *et al.*, 1991; Mahoney *et al.*, 1991). Drought stress was observed throughout southern Alberta during the dry summers of the 1980s when summer flows were particularly low (Bradley *et al.*, 1991).

A study of the number of times each vegetation type was flooded during the period of the hydrological record was made, using the records from Red Deer (since 1915) and Bindloss (since 1920) (Table 3). These data show that SV and H vegetation types are flooded more frequently than every 5 years (although the table only shows 5 years because this was the smallest flood return frequency considered in this analyis). The CW, Cy and Cm types have been flooded approximately every 10 years. The mature willow is less often inundated, with a 19-year return period in the upper river, but only a 35-year return period in the lower river. Most other vegetation types have not received flooding during the record period, using the criteria that at least 75% of the area has to be covered by flood waters. These flooding frequencies have played an important role in the regeneration and maintenance of a considerble portion of the riparian vegetation which currently survives on the Red Deer River floodplain.

DISCUSSION

A number of interesting features emerge from this analysis of the relationhips between the vegetation and hydrology in the Red Deer River floodplain. It appears that fringe replacement of cottonwoods is currently the principal mechanism for regeneration along the lower river, mostly in CW, Cy and W vegetation types. In the CW and W vegetation types, however, the higher density of willows has probably had a negative effect on cottonwood establishment since the 1950s. Fig. 11 shows that for the whole study area floods, up to and including the 10-year flood, have the potential to inundate most areas currently suitable for balsam poplar or cottonwood regeneration. Floods larger than the 10-year event cover increasingly extensive areas of floodplain and have the potential to initiate 'general replenishment' over larger areas. However, these sites will only benefit from the effect of these larger floods if geomorphic activity is also maintained to create new areas of new sediment suitable for regeneration. A study by Marken (1993) in a section of the lower river shows that in reaches which are meandering or confined–meandering, suitable sites are created by 1 in 10-year floods but in braided reaches significant floodplain development only occurs under much higher flows.

In the lower river, analysis of the area of the floodplain covered by different size flood events makes it clear that even during the 1 in 100-year flood, less than 50% of the floodplain area is inundated (Table 4). Thus, a 1 in 5-year event with a discharge of 673 cm (at Red Deer hydrological station) will have a stage of approximately 2.5 m above LWRS and will flood the sparsely vegetated and colonizing willow vegetation types. Such an event has occurred seven times during the 80 years of hydrological records. It has great ecological significance in maintaining the sandbar willow communities and, therefore, indirectly in aiding cottonwood establishment. A 1 in 10-year event (918 cm at Red Deer) will flood all of the colonizing willow, mature willow and most stands of young cottonwoods and some areas of mature cottonwoods. Six of these events have occurred during the record period. This is the minimum level of flooding required to cover a significant portion of all sites where fringe replenishment of cottonwoods occurs.

TABLE 3. Flooding frequencies of vegetation types (minimum 75% of area flooded) based on number of occurrences of floods in years for which records exist at the Red Deer and Bindloss hydrological stations.

Vegetation type	Red Deer		Bindloss	
	No. occurrences in 75 years	Return freq. (years)	No. occurrences in 70 years	Return freq. (years)
CV	15	5	14	5
CW	8	9.38	6	11.67
W	4	18.75	2	35
Cy	8	9.38	6	11.67
Cm	8	9.38	6	11.67
Co	0	0	0	0
C/G	0	0	0	0
C/S	1	75	0	0
S	0	0	0	0
S/G	0	0	0	0
G	0	0	0	0
WS	0	0	0	0
H	15	5	14	5

These higher floods lead to higher sedimentation in Cw and W vegetation types which in turn promotes lower densities of willow colonization and improved opportunities for cottonwood establishment. A 1 in 20-year flood (1160 cm at Red Deer) will flood all of the communities already mentioned and a small portion of the old floodplain forests and has only occurred once in the record in 1952. A 1 in 50-year event (1480 cm at Red Deer) covers around 30% of the floodplain and has occurred once, in 1954 during the record period. The 1 in 100-year event will cover nearly 50% of the floodplain and occurred in 1915 during the record period.

In the lower river, the oldest parts of the floodplain are characterized by sand ridges which are often >4 m above LWRS. Although the alignment of these ridges suggests that their formation was at least in part influenced by Chinook winds blowing from the south-west, their presence suggests a period of higher sediment availability and greater floods than have been experienced in the last 75 years. Many of the poplars on these ridges date from 75 to 105 years ago, suggesting initiation sometime between 1890 and 1920. Bradley (1982) notes some very large floods in other rivers of southern Alberta during the mid- to late 1800s. During the 1880s large floods were noted on the Bow River in Calgary and similar sand ridges can be found in the lower Bow River (Cordes, 1991). On the Red Deer River the flood which occurred in 1905 is thought to have been higher than the highest recorded flood in 1915 (Howe, 1971). The 1 in 100-year event which occurred in 1915 was the only recorded event capable of reaching the height of these ridges but floods with a discharge capable of depositing the volumes of sediment required for construction of these features have not been recorded on the Red Deer.

The riparian zone of the lower river as it exists now might perhaps be more accurately characterized as having an active and an inactive floodplain. The inactive portion occupies just over 50% of the floodplain zone (Table 4), and around 70% has not been flooded since 1915 and will only be flooded by events greater than the 1 in 20-year event. Downcutting by the river might contribute to an explanation of this phenomenon but it is not a dominant geomorphological process in Alberta's prairie rivers at the present time. A recent dendroclimatic reconstruction of annual precipitation in the foothills and western prairies of southern Alberta since AD 1505 shows low rainfall with several drought years from around 1840 to 1870 with higher rainfall around 1860, but many years of high rainfall between 1875 and 1915 (Case & MacDonald, 1995). These data correspond with the dendrochronological data from the Red Deer River poplars (Fig. 7) although it is also true that the relatively short life-span of the poplars probably results in their under-representation in the mid-1800s. It seems likely that meteorological and hydrological changes in the Red Deer catchment could have had a major influence on poplar regeneration. However, it is also important to consider human impacts on the catchment over the same time period.

Early explorers' records show that during the 1700s, the lower Red Deer River was heavily utilized by large bison herds and that riparian poplars were sparse (Cordes & Bond, 1992). The Palliser expedition in the late 1850s and Dawson (1885) both noted the low numbers of cottonwoods in the lower Red Deer River (Cordes & Bond, 1992). Buffalo would have grazed or trampled in the riparian zone which may well have increased erosion rates and decreased survival of young poplars. In addition, local Indian tribes of the Blackfoot Nation frequently set fire to the prairie and in the process destroyed parts of the floodplain woodland (Nelson, 1973; Cordes & Bond, 1992). In the notes and diaries of the Palliser expedition written in 1858 and 1859 there are many references to the great herds of bison in the lower river area but by the time of the travels of John Macoun in the late 1870s the herds were already depleted (Roe, 1939; Spry, 1968; England & DeVos, 1969; Nelson, 1973; Cordes & Bond, 1992; Marken, 1993). Ranchers did not begin settling the lower Red Deer valley until 1896 but by 1910 a large number of ranchers with Mexican longhorn cattle had settled in the lower valley (Howe, 1971). There

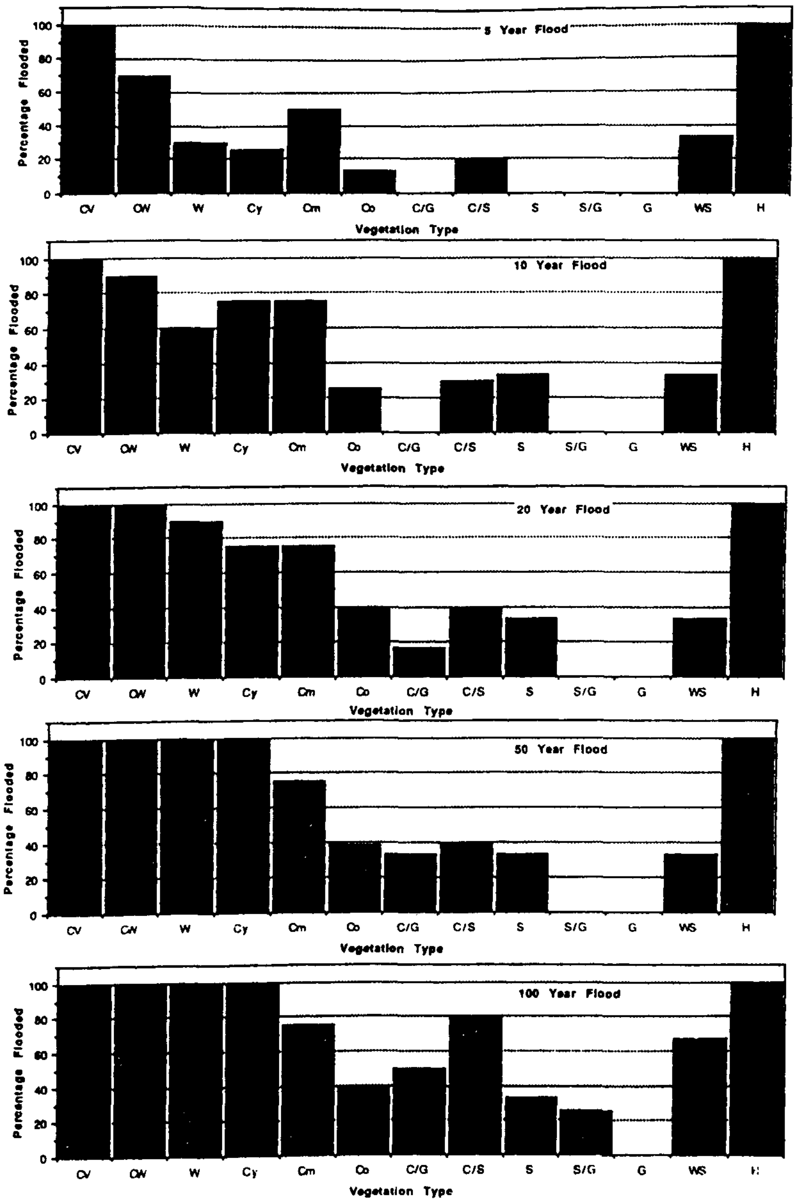

FIG. 11. Percentage of each vegetation type flooded with floods of increasing magnitude (based on elevations of different vegetation types along all surveyed transects).

was therefore a period of about 20 years with little trampling or grazing by either bison or cattle.

In the upper river, the first lands settled were those around the city of Red Deer, for farming rather than ranching. Here in 1884, a sawmill was established on the river flats near Red Deer and many poplars and spruce from the floodplain and further upstream were felled in anticipation of the needs of settlers (Dawe, 1954), probably increasing flooding and sediment loads. The incidence of fire in the foothills of the upper Red Deer catchment (and the adjacent Bow River catchment) also increased towards the end of the nineteenth century as a result of the greater number of Europeans in the area (Day, 1965). A study of the percentage of the area of the foothills with fire-origin stands of trees between the Bow and Brazeau Rivers (which includes the upper Red Deer catchment) shows an increase from 12.8% in the period 1830–70 to 36.1% by 1910 (Day, 1965). An increase in the incidence of fires is also noted by geologists and surveyors working in the foothills and front range of the Rockies during the 1880s (Nelson & Byrne, 1966). It is likely that these activities increased erosion and runoff in the upper catchment, providing high sediment loads and discharges to the lower river during the same decades (1880–1920) as higher rainfall was experienced.

Relationships between vegetation and regeneration in the upper river are less clear. The narrower and more gravelly floodplain has different morphological characteristics from the lower river. Vegetation bands are narrower and generally

TABLE 4. Areas of different vegetation types flooded by progressively greater flood magnitudes in the lower Red Deer River (sites F–J).

	Area m²	% Area	5 years	10 years	20 years	50 years	100 years
SV	141664	1.09	1.09	1.09	1.09	1.09	1.09
CW	626952	4.82	3.374	4.338	4.82	4.82	4.82
W	491120	3.79	1.137	2.274	3.411	3.79	3.79
Cy	109556	0.85	0.2125	0.6375	0.6375	0.85	0.85
Cm	784944	6.06	3.03	4.545	4.545	4.545	4.545
Co	254448	1.96	0.2548	0.49	0.7448	0.7448	0.7448
C/G	1615912	12.48	0	0	2.1216	4.1184	6.24
C/S	3100856	23.94	4.788	7.182	9.576	9.576	19.152
S	556420	4.3	0	1.419	1.419	1.419	1.419
S/G	2601448	20.08	0	0	0	0	5.02
G	2566612	19.82	0	0.03	0	0	0
H	3683	0.03	0.03	0	0.03	0.03	0.03
BC	98784	0.76	0	0	0	0.38	0.38
Total area flooded			13.916	22.0055	28.3949	31.3632	48.0808

occur at lower elevations with respect to the LWRS, giving them more frequent inundation during particular sized floods than experienced in the lower river. Balsam poplar has the ability to reproduce by suckering as well as by seed and therefore the upper river floodplain vegetation communities are less vulnerable to reduced flooding than the cottonwood-dominated communities of the lower river. Even here, however, there are few new areas of floodplain on which colonization can occur. In contrast, the plains cottonwood regenerates almost exclusively by seed and is therefore highly dependent on suitable flooding conditions for its successful regeneration.

In the lower river more frequent and less incremental replenishment as described by Bradley & Smith (1986) and Bradley *et al.* (1991) would appear to have replaced 'general replenishment' as a model of cottonwood regeneration. This latter model, described by Virginillo *et al.* (1991) and Rood & Mahoney (1990) for gravelly foothills floodplains in southern Alberta, associates major flooding events with widespread poplar regeneration. In both the upper and lower Red Deer River, reduced disturbance of the ecosystem has led to reduced regeneration opportunities. Similar trends are reported by Baker (1990) in the Animas River of Colorado and by Cordes (1991) for the Bow River of southern Alberta. There are cases, however, where reduced disturbance as a result of dam construction allows, at least in the short term, an increase in regeneration opportunities due to previously unsuitable parts of the channel becoming available for colonization (Carter-Johnson, 1994).

Historical analysis of events affecting the river highlight a number of factors that have combined to produce a different range of hydrological and geomorphological conditions on the floodplain since early in the twentieth century from those experienced in the latter half of the nineteenth century and around the turn of the century. These include the following:

1. A change in wildlife use of the floodplain. This included heavy utilization by large herds of bison prior to the 1870s and decimation of the bison herds by 1880. Bison trampled the floodplain area and would have had a particularly high impact in dry years when rivers were the only source of water on the prairies. Their impact was primarily during the summer months when young seedlings might be establishing, following overwintering in the foothills. Over the same time period European settlers greatly reduced beaver numbers. Ranching did not become important until after 1896.
2. Clearance of forests in the upper reaches of the river by European settlers and more fires in the foothills, leading to increased runoff and sediment reaching the river over the latter half of the nineteenth century and early twentieth century.
3. A series of very high-stage events recorded in travellers' records and by the physical features left on the floodplain in the form of high sand ridges in the lower river. It seems likely that no recorded stage events have been as high. A series of high rainfall years during the period 1875 to 1915 undoubtedly contributed to high runoff and floods.

These factors seem to have combined to give conditions in the late 1800s and early 1900s that favoured establishment of poplars in the Red Deer River across large parts of the floodplain which have subsequently become 'inactive'. It has been shown that ⩾1 in 100-year flood events could activate part of this 'inactive' floodplain but since the 1920s, fringe replenishment of the floodplain has been the usual form of poplar recruitment, occurring over approximately 30% or less of the floodplain area. It could be inferred that as a general model, the floodplain ecosytem of the Red Deer River would experience decades of fringe regeneration associated with low flows and decades of extensive regeneration associated with high flows. Although operation of the Dickson Dam since 1983 has greatly reduced the impact of higher flood events on the regeneration potential of the floodplain, at the present time it is having its effect on a hydrological regime that is significantly different from that which operated around the turn of the century. Current flow patterns do not allow replacement or recreation of the extensive mature poplar stands that we see in the Red Deer River today so that, in a sense, they are historical features.

It is possible that more extensive regeneration could occur again if a 1 in 100-year or greater flood event occurred and was not attenuated by the Dickson Dam. However, the combination of flood attenuation by the dam and the fact that the large poplar stands on the Red Deer River are reaching their lifespan have greatly reduced the chances of their being replaced.

FLOW NEEDS OF RIPARIAN VEGETATION OF THE RED DEER RIVER

In this section we have focused on defining simple flow needs for maintaining ecological processes in the currently active riparian zone but do not exclude the possibility of reactivating the wider, inactive floodplain zone. Even maintaining present levels of regeneration may prove difficult in the context of increasing demands on water supply for urban and agricultural use. The problem of defining the flow needs for riparian vegetation along a river is a complex one because needs vary between species and between parts of their life-cycles and because geomorphological and hydrological conditions vary in different river reaches. The data presented in this paper show that relationships between hydrology, floodplain geomorphological processes and vegetation patterns within river basins are constantly adjusting in relation to historical climatic and land-use changes. It is clear that contemporary ecological studies need to be located within a time-frame of change stretching beyond the recent historical period through the Holocene because post-glacial relaxation phenomena and changes in the ranges occupied by individual species through time will affect present-day patterns. Historical and Holocene records are not sufficiently good in Alberta's floodplains to know when and under what conditions poplars have lived on these floodplains. Their presence may be a relatively recent phenomenon taken over this time scale. The evidence presented in this paper suggests that climate and land-use around the turn of the century encouraged greater poplar establishment than was occurring previously or than has occurred since.

In the Red Deer River identification of the needs of species in different reaches has made it clear that the lower river is more vulnerable to change than the upper river and that within its vegetation communities, the plains cottonwood is the species least able to regenerate at the present time. It is logical, therefore, to direct suggested flow needs for maintaining the ecological integrity of the Red Deer River riparian ecosystem at maintaining the cottonwoods of the lower river. By ensuring the survival of the most vulnerable species, survival of all others should follow, a principle also discussed by Bovee (1982) and Gore, Layzer & Russell (1992) in their application of the Instream Flow Incremental Methodology to target instream fish and mammal species. Based on this principle and the data presented above, it is possible to identify the following broad instream flow needs for the floodplain vegetation of the Red Deer River.

1. Floods occurring during the ice-free season and having a magnitude ⩾1 in 5-year flood (673 cm at Red Deer) should be maintained as natural flows below the Dickson Dam. In the case that leaving the largest floods unmitigated is unacceptable, they should not be attenuated to a magnitude less than the 1 in 20-year discharge (1160 cm at Red Deer) since this is the minimum size flood for maintaining recent historical regeneration levels. Floods up to the 1 in 20-year flood will not reach heights that threaten property or lives in the Red Deer River valley.

2. The timing of all floods having a magnitude ⩾1 in 5-year flood should not be modified. It has been established that high magnitude flood events are important in maintaining geomorphological activity in the floodplain, particularly through their provision of new regeneration sites for vegetation. The timing of flood events with regard to the phenology of poplar seeding can be crucial to ensure success in any year.

3. The duration of floods having a magnitude ⩾1 in 5-year flood should not be modified. A flood event is considered to have ended when discharge at Red Deer falls below 240 cm. If flood recession is too rapid, poplar seedlings experience drought stress (Mahoney *et al.*, 1991); it is therefore necessary for late spring and summer flows to be held at a minimum height during the critical establishment phase for seedlings. It is also important that water levels are not held unnaturally high since most riparian species have a definable tolerance range to waterlogging.

4. Following floods with a magnitude ⩾1 in 10-year flood (918 cm at Red Deer) flows should be maintained unaltered through the flood year and the following year. Since floods of this magnitude and greater appear to be particularly significant for cottonwood regeneration it is important to maintain moisture levels in the floodplain through the first two summers of a newly regenerating cottonwood cohort.

5. Very high magnitude floods ⩾1 in 50-year event should not be modified. It is clear that long-term, very large flood events are the only ones capable of initiating widespread cottonwood regeneration and that construction of dams reduces or removes their occurrence.

6. Minimum flows should be maintained during the ice-free season in all years. Summer and autumn water needs of riparian vegetation are as yet not fully understood but it is thought that overwinter survival of trees is higher when trees enter the winter with a healthy moisture balance (Bradley *et al.*, 1991). In southern Alberta, winters are characterized by extreme cold and the drying effects of Chinook winds, both of which create drought stress in trees.

It should be possible in a long-term management programme to conceive of periodically meeting these needs as part of a water-budgeting approach to river management rather than simply setting minimum flows. Unless major floods are maintained then meander movement and the development of new point-bars will not occur. Without the availability of new regeneration sites even careful water-budgeting will not meet the regeneration needs of poplars. It is clear, therefore, that geomorphological as well as hydrological integrity of the floodplain must be maintained to ensure long-term current regeneration levels of poplars along the Red Deer River and that flows ⩾1 in 10-year floods have a key role to play in this. Higher regeneration levels clearly require larger floods.

CONCLUSION

Because of short- and long-term changes in river basin hydrological cycles, riparian ecosystems are in a constant state of adjustment, with different abiotic and biotic components adjusting with different lag-times, producing a complex-response situation. The long life-cycles of trees complicates our understanding of these ecosystems and our ability to produce numerical models suitable to help in their management. We have presented a case-study from the Red Deer River in southern Alberta which demonstrates the complex inter-relationships between components of riparian ecosystems and their variability along the river's length. An understanding of the functioning of these ecosystems does at least allow broad definition of their regeneration needs and some insight into suitable river management practices for their maintenance.

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