7.0 RIPARIAN ECOSYSTEM INSTREAM FLOW NEEDS

The following section is largely a re-presentation of the work by Gom (2002) and Gom and Mahoney (2002) outlining a method for determining instream flow needs to sustain riparian poplars. These reports have benefited from external, independent review and encapsulate the latest developments in managing water resources for riparian ecosystems.

7.1 Introduction

Riparian zones in Alberta are highly diverse and include a number of habitat and vegetative community types (Thompson and Hansen 2002). Although riparian poplars (cottonwoods) are an important part of riparian forest ecosystems in the South Saskatchewan River Basin, they are only one component of the full array of community types.

In the semi-arid prairie regions of southern Alberta, cottonwoods are often the only native tree species present providing essential habitat and food sources for many wildlife species. Cottonwood forests also directly influence the associated aquatic ecosystem by contributing organic debris and shade to the aquatic ecosystem. Indirect effects on the aquatic ecosystem occur through stabilization of streambanks and trapping of floodplain sediments, thereby altering the channel forming process and the rate of channel movement.

Despite their overall importance, meeting the hydrological needs of riparian poplars does not necessarily mean the hydrological needs of all riparian species are met. Work in fisheries management has shown that management for a single species rarely gives positive results for all species present (Section 5). Further work on the links between river hydrology and other riparian species is needed before a comprehensive riparian Instream Flow Need (IFN) can be determined. However, maintaining the full range of hydrological variability when determining riparian cottonwood IFNs is expected to extend benefits to other riparian species.

Cottonwoods are well adapted to their riparian existence in this dry region known for its extremes in temperature. Despite being sensitive to drought stress, riparian cottonwoods are able to survive because they are phreatophytic; they are linked directly to a dependable water supply from the riparian water table through a deep root system. Cottonwood reproduction is also adapted to riparian conditions. Each mature female tree releases millions of seeds every year at a time that coincides with the spring peak in river flows (Bessey 1904). Seed germination occurs rapidly on moistened sediments that have been cleared of vegetation by spring flooding. Seedling root growth is rapid enough to maintain contact with the moist capillary fringe above the receding water table. Although they are vulnerable to flow-related scouring and burial in their first several years, saplings become increasingly resilient as they grow to maturity. After the roots are established, saplings are capable of re-sprouting vigorously when buried or decapitated.

Cottonwoods have adapted to natural river flow patterns over thousands of years and are sensitive to changes in streamflow. They are especially vulnerable to flow management that changes minimum, moderate and peak flows. Reduced minimum flows can result in a corresponding lowering of the riparian water table. If the water table is dropped below the depth that cottonwood root systems can access, the trees will become drought stressed. This stress can lead to branch dieback or tree death depending on the severity and duration of the drought condition (Tyree et al. 1994). Reductions to moderate flows impact cottonwoods because moderate flows elevate the floodplain water table and saturate floodplain substrates. The added moisture enhances overall forest health by providing moisture for young saplings and trees on higher floodplain terraces. In addition to minimum and moderate flows, higher flows are essential to cottonwoods because the magnitude, duration, and seasonal timing of peak flows are essential to the recruitment and long-term survival of seedlings. Changes to peak flows can reduce seedling recruitment and lead to the gradual deterioration of riparian forests (Bovee and Scott 2002).

The following section discusses the biological basis for determining the instream flows needed to sustain riparian cottonwoods in southern Alberta. The instream flow requirements are then applied to natural flow conditions to develop a set of operational flow targets based on naturalized historic flows. The 'Poplar Rule Curves' (PRC) are designed to provide practical flow-management guidelines for meeting the minimum, moderate and high flow requirements of cottonwoods and to help preserve and restore riparian forest ecosystems.

7.2 Links Between Cottonwood Biology and Hydrology

Riparian cottonwoods are intimately dependent on the riparian water table that is connected directly to the nearby stream. Water is either percolating towards or away from the streambed, depending on surrounding hydraulic conditions (Dunne and Leopold 1978, Linsley et al. 1986). The zone of saturation extends horizontally from the stream's surface into the floodplain and fluctuates with stream elevation.

Despite growing in the driest regions of southern Alberta, cottonwoods are extremely sensitive to drought stress (Tyree et al. 1994). They are able to survive in such dry environments only because their phreatophytic root systems tap into the riparian water table, connecting them to a reliable water supply even during natural seasonal changes in temperature and precipitation. Although the limit of cottonwood root growth is not fully known, it can be deduced that the roots of mature cottonwoods growing on raised floodplain terraces may penetrate to depths greater than 5 m to reach the saturated zone.

Although poplars can grow vigorously, they are relatively short-lived trees, usually living less than 100 years. Combined with the fact that riparian areas are prone to disturbances that can continually reset forest succession, riparian poplar forests require ongoing reproduction to drive forest colonization and replenishment. Every year, each mature female cottonwood can release millions of seeds during a 2-3 week period in early June (Bessey 1904). Each cottonwood seed is only about 3 mm long and has a cottony enclosure of fine hairs that aids dispersal by wind and water. The small energy reserve stored in the seed limits seed viability to a few weeks. Germination will occur on any moist substrate, but for a cottonwood seedling to successfully grow into a mature phreatophytic tree, it requires specific substrate and moisture conditions during its first few weeks and subsequent growing season.

Fresh sediments, those scoured by ice or flood flows, provide the moist, barren seedbeds that are suitable for cottonwood seedling establishment. Once moistened, a cottonwood seed will germinate within 24 hours and immediately begin root elongation at a rate of about 0.5 to 1 cm/day, reaching a length of about 60 cm after the first growing season (Mahoney and Rood 1998). As springtime streamflows recede, so does the riparian water table. Young cottonwood seedlings will only survive if their root growth is able to keep pace with the moist capillary fringe above the declining water table. If the substrate dries out too quickly, the young cottonwoods will be vulnerable to desiccation. If the site is repeatedly flooded, seedlings can be buried by sediments or scoured away.

The precarious establishment of cottonwood seedlings is therefore limited to a narrow elevational band above the river water level. This 'recruitment zone' is defined at the top by a combination of root growth potential plus the extent of capillary fringe above the water table during late summer streamflows. It is defined at the bottom by the potential for subsequent scouring and deposition (Figure 7.1). Consequently, the recruitment zone extends from about 60 cm to about 150-200 cm above base flow depending on substrate texture (Mahoney and Rood 1998). For seedlings to survive in this zone, stream stage decline must be gradual enough to allow root growth to keep pace. The maximum survivable rate of decline suggested by Mahoney and Rood (1998) is 5 cm/day, although more gradual declines are more effective at limiting seedling mortality.

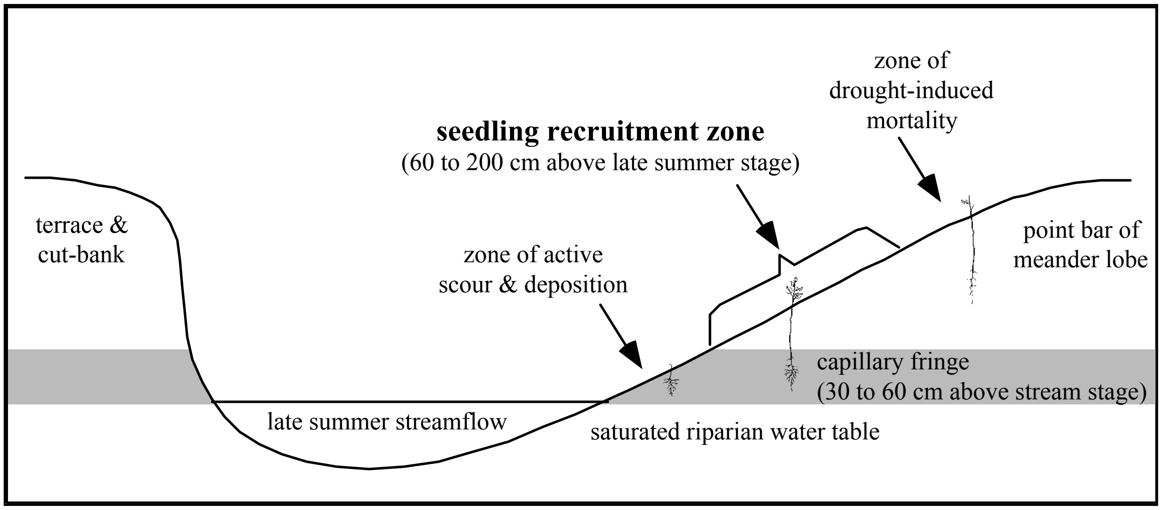

Figure 7.1. Cross-section of a streambank showing the extent of moistened substrates and the suitability of zones for cottonwood seedling establishment (adapted from Mahoney and Rood 1998).

Given the specific moisture requirements for successful cottonwood seedling establishment, it is not surprising that dendrochronological analyses have shown natural cottonwood recruitment is associated with 5 to 10 year-return flood events along the Southern Tributaries of the Oldman River (reviewed by Mahoney and Rood 1998). These moderate floods recharge the riparian water table and mobilize sediments to create new seedling nursery sites in the form of meander lobes and lateral bars. Due to the geomorphic changes they cause, larger scale floods can improve recruitment opportunities for the next several years or even decades. In early June of 1995, the highest flows on record occurred along many streams in the Oldman River watershed. Following the flood peak, releases from the tributary dams were coordinated to deliver a gradual flow recession of about 2.5 to 5 cm/day. Unprecedented numbers of cottonwood seedlings were observed to survive through 1996 and 1997 at elevations of 1.7 to 3 m above base flow (Rood et al. 1998).

7.3 Impacts of Damming and Diversions

Water management projects have been implicated in the decline of riparian cottonwood ecosystems across large areas of North America (Rood and Mahoney 1990). Subsequent research suggests it is not the presence of a dam or diversion, but rather the way it is operated that has the greatest impact on downstream vegetation. The purpose of a flow regulatory structure dictates the type of flow regime that is produced downstream and consequently, the impacts it has on downstream riparian forests.

Many factors, including agricultural clearing, domestic settlement, livestock grazing, direct harvesting, onstream reservoirs, gravel mining, channelization, herbicide spraying, and beavers, can have a negative impact on riparian cottonwood forests (Rood and Mahoney 1991b). Therefore, the contributing effects of each of these factors must be considered in any program to conserve or replenish declining riparian forests. The regulation of streamflow appears to affect the most basic functioning of the system. Riparian cottonwood forest decline is usually attributed to one or both of two problems: inadequate seedling replenishment to balance natural attrition in aging populations, and/or accelerated mortality due to chronic or cumulative water stresses (Table 7.1). Although both effects are related to modifications in natural streamflow variability and/or volume, they tend to involve different aspects of the natural annual flow pattern (annual hydrograph).

Table 7.1. Documented examples of riparian cottonwood declines associated with flow regulation along streams in North America.

Authors:	**River and region**	**Inadequate replenishment**	**Forest stress or mortality**
Auble et al. 1997	Boulder Cr., CO	X	X
Bradley and Smith 1986, Bradley 1982	Milk R., AB & MO	X	X
Cordes et al. 1997	Red Deer R., AB	X	
Fenner et al. 1985	Salt R., AZ	X	X
Howe and Knopf 1991	Rio Grande, NM	X	
Johnson 1992, Johnson et al. 1976	Missouri R., ND	X	X
Johnson 1998	Platte R., NB	X	X
McKay 1996	Nisqually R., WA	X	
McKay 1996	Cowlitz R., WA	X	
Miller et al. 1995	North Platte R., WY	X	X
Rood et al. 1998 and 1999, Rood and Bradley 1993	Bow R., AB	X	
Rood and Mahoney 2000, Rood et al. 1995	St. Mary R., AB	X	X
Reid et al. 1992, Rood and Heinze-Milne 1989	Waterton R., AB	X	X
Rood and Mahoney 1995	Marias R., MO	X	
Snyder and Miller 1992	Colorado R., CO	X	X
Snyder and Miller 1991	Arkansas R., CO	X	X
Stromberg and Tiller 1996	San Pedro R., AZ	X	X

As discussed previously, cottonwood seedling recruitment is adapted to capitalize on the barren, moist seedbeds revealed after high springtime streamflows recede. Failed seedling establishment has been consistently linked to reductions or delays of peak flows and abrupt or sustained low flows during the growing season. High flows drive erosion and deposition along the channel, scouring competing vegetation and laying down new seedbeds. Reduction of peak-flows below certain geomorphic thresholds can cause channel stabilization and meander stagnation that allows encroachment of upland vegetation. This can result in a paucity of nursery sites for cottonwood seedling establishment. Reduction of springtime peak-flows can also result in a lower, narrower elevational band available for recruitment, leaving seedlings susceptible to burial or removal by subsequent flooding and ice scour.

The timing of peak flow is also critical because mature cottonwoods release their short-lived seeds during only a few weeks in June. Provided peak flows position newly germinated cottonwood seedls appropriately, seedling survival depends on subsequent streamflow. The roots of the tiny, drought-sensitive seedlings must maintain contact with the moist, capillary fringe above the floodplain water table. If the rate of water table decline is more rapid than the seedling's root growth, the seedling will loose contact with its water supply and die. Alternatively, if streamflow rises enough to inundate the site again, new seedlings are likely to be washed away or buried by sediment.

Streamflow conditions conducive to cottonwood seedling replenishment do not need to occur every year. Consecutive years with high peak flows can repeatedly remove previously established seedlings. Successful seedling recruitment occurs on average only about once every 5 to 10 years in southern Alberta (reviewed by Mahoney and Rood 1998). Recruitment tends to occur most frequently (1-5 years) along meandering reaches with sandy beds (Bradley and Smith 1986, Hughes 1994). Widespread recruitment events, such as the one that occurred in 1995 along the Oldman River (Rood et al. 1998), are more rare, occurring, on average, less than once every 30 to 50 years (Rood and Mahoney 1991a, Stromberg et al. 1993, Hughes 1994). Thus, in the time scale of a cottonwood's lifespan (about 100 years), natural streamflows that support cottonwood recruitment occur relatively infrequently. When streamflow is regulated, these events may occur less frequently, if at all. Reduced frequency of forest replenishment may lead to unbalanced age distributions and eventually to population collapse if left uncorrected.

Cottonwoods remain sensitive to drought stress as they mature. Because their root systems are deeper and more established, mature trees are less likely to become drought stressed than seedlings and saplings. However, they are still dependent on the riparian water table for survival. If the water table drops below their rooting-zone, cottonwoods become water stressed and show symptoms such as premature leaf senescence, branch dieback, and complete trunk mortality (Albertson and Weaver 1945, Rood and Mahoney 1991a, Tyree et al. 1994). The effects of repeated drought stress can be cumulative, weakening the trees and leading to increased stress sensitivity.

7.4 Targeting Flows to Sustain Riparian Forests

The flows required to sustain riparian cottonwood forests may vary greatly from reach to reach because each stream has its own combination of environmental constraints and species present. Logically, the natural flow regimes that riparian forests have been established under, and continue to be maintained by, should be adequate to support those forests' long-term survival. A new equilibrium of vegetation composition may be expected to develop if the pattern of streamflow is altered significantly. For example, consistently lowered flows may produce a new equilibrium state favouring the encroachment of grasslands rather than establishment of pioneer tree species such as cottonwoods. A less extreme change in flow regime may only favour cottonwoods closer to the water source, resulting in a narrower band of forest that tightly parallels the river channel. Although such a regime may feature a reasonably viable riparian forest, a more extensive forest, supported by natural conditions, would be more diverse and robust, thereby providing more resiliency and greater value for associated wildlife. Thus, the approach taken here will target flows for maintaining and restoring the natural extent and character of riparian cottonwood forests, rather than simply trying to ensure the survival of remnant groves of trees.

Cottonwood streamflow requirements can be grouped into four general categories, flows for:

- tree survival (minimum flows),

- tree growth (moderate flows),
- seedbed preparation (peak flows), and
- seedling and sapling survival (flow ramping and extended moderate flows).

It is necessary to recognize the tolerance ranges for each of these categories when targeting flows to sustain riparian forests as a whole.

7.4.1 Base flows for forest survival and maintenance

Many documented instances of riparian cottonwood decline have been associated with minimum base flows that have lowered the riparian water table. Water table declines of 1 to 4 m or more have been shown to cause extensive mortality (approximately 50 to 100%) in adjacent cottonwood groves (Reid 1991, Stromberg and Tiller 1996, Scott et al. 1999, Scott et al. 2000). These extreme cases define a threshold of unacceptable water table decline. A flow regime for sustaining natural cottonwood groves must avoid crossing this threshold by providing adequate base flows. Base flows required for the survival and maintenance of riparian cottonwoods have been estimated at between 40 and 60% of average weekly flow (Stromberg and Patten 1991).

A single minimum flow determination will not suffice for every situation because each reach has unique characteristics that dictate tolerable water table levels for the cottonwoods residing there. For example, different reaches have different channel widths and substrate textures that affect the relative depth of the water table and the extent of the capillary fringe. The moisture requirements of individual trees also vary, due to differences in species, age and general health.

Naturally occurring riparian cottonwoods are adapted to tolerate natural extremes of streamflow, and can survive occasional acute drought conditions. However, natural minimum flows can be detrimental if the seasonal timing, frequency, and/or duration are altered. For example, cottonwoods are relatively unaffected by low flows during their winter dormancy, but are sensitive to moisture stress during the hottest, driest months of the growing season, typically in July and August. Cottonwoods can survive periods of drought during their growing season. However, the cumulative effects of prolonged or excessively frequent drought conditions may lead to reduced resiliency to subsequent stresses and gradual forest deterioration. Base flows should be selected with the goal of maintaining cottonwood survival under chronic implementation. Although isolated instances of more acute stress may be tolerated by cottonwoods, chronic exposure to that same level of stress would be detrimental.

7.4.2 Moderate flows for tree health and growth

Base flows alone are inadequate to sustain a healthy riparian forest. Moderate flows are required for optimal growth of cottonwoods. Tree growth, which can be measured using radial and branch growth increments, is strongly correlated with streamflow (Stromberg and Patten 1990, 1991, 1996, Willms et al. 1998). Thus, as with choosing minimum flows, it is recommended that moderate flows be modelled after trends in naturally occurring streamflows. For example, Stromberg and Patten (1990, 1991, 1996) have suggested that normal growth requires natural average streamflows, with 40 to 60% of natural streamflow being necessary for healthy tree canopies and 74 to 313% of long-term average annual flows being needed for maximum growth. These single streamflow values provide a general guide for selecting moderate flows for cottonwoods.

Cottonwoods are adapted to natural patterns of gradual flow recession following springtime flooding. This natural variability in moderate flows is important for maintaining the resilience of cottonwood populations. By exposing trees to a broader range of dynamic riverside conditions, as tends to occur naturally, the resiliency of the forest population can be improved to ensure its survival despite the inevitable disturbances and stress associated with high and low flow fluctuations. Thus, instead of implementing a single moderate streamflow, it is recommended the timing and variability of natural moderate flows be incorporated into the planning of flow regimes to meet riparian poplar needs.

7.4.3 Peak flows for seedling establishment

Although base and moderate flows will favour the survival of young and mature cottonwood trees, higher flows are also essential to the ongoing viability of riparian forests. Peak flows are important for driving channel dynamics that control erosion and deposition of sediment (sections 4 and 8). As discussed previously, reducing or eliminating peak flows can lead to channel stabilization, meander stagnation and the encroachment of upland vegetation. The resulting shortage of barren, moist nursery sites at required elevations will negatively impact cottonwood seedling establishment, and so reduce the long-term viability of the riparian forests.

A single, prescribed peak discharge is not suitable for every situation. Because each reach has its own unique combination of bed texture, stream gradient, and vegetation, each will require a slightly different rate of flow to mobilize sediments and create point or lateral bars. Thus, it is useful to refer to natural benchmarks, such as bankfull discharge, that incorporate this variability and relate to important flow levels.

Bankfull discharge is recognized as a threshold of flow magnitude conducive to cottonwood seedling replenishment (Bradley 1982, Howe and Knopf 1991, Johnson 1992, Auble et al. 1997). Flows beyond the bankfull threshold may be especially valuable to cottonwoods. A model developed by Richter and Richter (2000) suggests that 125% of bankfull discharge is instrumental in driving channel processes that support the long-term survival of cottonwood forests. Bovee and Scott (2002) recommend a flow slightly greater than bankfull, to balance flows that support riparian cottonwood seedling recruitment while meeting flood control objectives.

The flow magnitude required for channel maintenance increases with the coarseness of the bed material. For example, flows up to 130% and 160% bankfull have been reported as important for transporting bedload along coarser-substrate streams (Andrews and Nankervis 1995, Emmett and Wolman 2001). These larger floods can enhance recruitment for the next several years (Howe and Knopf 1991, Scott et al. 1993, McKay 1996, Scott et al. 1997). This is probably because larger floods, such as those with greater than 10 year return intervals (Stromberg et al. 1993), cross the geomorphic thresholds that cause channel and floodplain instability. Instability in the channel promotes the mobilization of sediments that are subsequently deposited as point and lateral bars and become nursery sites for cottonwood seedling establishment. Smaller peak flows may be able to maintain a dynamic channel until a new, stable channel alignment develops.

The seasonal timing of peak flows is important for ensuring successful seedling establishment. Cottonwoods naturally release seeds when peak flows are most likely to be receding. Consequently, a barren, moistened recruitment zone is immediately available to be colonized (Mahoney and Rood 1998). The window of seed release beginns in early June in southern Alberta, and can extend for several weeks depending on local weather conditions (Gom 2002).

7.4.4 Flow-ramping and moderate flows for seedling survival

The recruitment zone targeted for cottonwood seedling germination can be positioned up to 2 m above the late summer stream stage. In order for the drought sensitive seedlings to survive their first year, their root elongation must keep pace with the capillary fringe above the declining riparian water table. In general, the maximum survivable rate of stage decline suggested by Mahoney and Rood (1998) is 2.5 cm/day. The survivable rate of stage decline along reaches with very fine or very coarse substrates may need slight adjustment up or down respectively, because the extent of the capillary fringe is affected by substrate texture. The best way to ensure that the gradual rate of decline is delivered is to monitor the daily operations of the involved water control structures. This is a level of detail beyond the water balancing process completed for the present planning level study.

Following their first year, young cottonwood saplings continue to be more sensitive to drought stress than mature trees with more established root systems. Saplings are particularly vulnerable to abrupt reductions in flow because their roots are not yet fully established and root expansion may not be able to keep pace with rapid water table declines. Thus, in order to promote long-term survival of cottonwood saplings, variability in the flow regime should not exceed that which would occur naturally. By preserving the natural range of high and low flows that affect the riparian water table, cottonwood root systems will be encouraged to establish at depths that promote healthy tree growth and resiliency to future flow fluctuations.

7.5 Drafting the 'Poplar Rule Curve'

An important part of developing the necessary streamflow regime for supporting riparian cottonwoods is recognizing the seasonality of flow requirements for forest survival and maintenance, tree growth, seedbed preparation, and seedling or sapling survival. Using cottonwoods along the Oldman River at Lethbridge as a general index, Table 7.2 describes the annual calendar of events related to poplar growth and development (phenology). The cottonwood-growing season extends from mid-April until mid-September, and it is the pattern of flow during this period that is particularly important to the growth and development of riparian cottonwoods. Therefore, the growing season defines the Poplar Rule Curve's period of concern.

The events that occur during the cottonwood growing season have varied moisture requirements. These requirements are presented in Table 7.3 for cottonwoods along the Oldman River at Lethbridge. The flow requirements are based on minimum values and, as such, are not mutually exclusive. For example, although the streamflow requirements for seedling establishment exceed those for tree maintenance, mature trees will also benefit from the higher flows. These overlaps can be seen when displayed in the context of an annual hydrograph (Figure 7.2).

It would be impractical and could be environmentally damaging to generate a standard hydrograph, similar to the one shown in Figure 7.2, every year. To do so, operators would be required to predict wet versus dry year cycles, and so would face the uncertainty of being able to provide exact flows regardless of upstream supply. Even if it were possible to regulate flow in this manner, the lack of variability in streamflow would probably create artificial channel and forest characteristics, leading to overall reduced resiliency in the system. For example, it would be detrimental to have the same peak recruitment streamflows every year because the previous year's seedlings would be repeatedly removed by high flows the following spring. For these reasons it is necessary to incorporate a natural degree of variability in the design of flow regimes for sustaining riparian cottonwoods and the channel processes they depend on.

Table 7.2. Weekly calendar of riparian cottonwood phenology along the Oldman River at Lethbridge, AB. The growing season is shaded (after Gom, 2002).

Week	1st day of week	Growth & Development	Seedlings (< 1 year old)	Saplings (> 1 year old)
1-5	Jan.	dormant		dormant
6-9	Feb.	dormant		dormant
10-13	Mar.	dormant		dormant
14	Apr.2	dormant		dormant
15	Apr.9	dormant		dormant
16	Apr.16	flowering		dormant
17	Apr.23	flowering		bud flush shoot & root growth
18	Apr.30	bud flush flowering		bud flush shoot & root growth
19	May.7	bud flush flowering		bud flush shoot & root growth
20	May.14	shoot growth flowering		bud flush shoot & root growth
21	May.21	shoot growth		shoot & root growth
22	May.28	shoot growth seed release	germination root growth	shoot & root growth
23	Jun.4	shoot growth seed release	germination root growth	shoot & root growth
24	Jun.11	shoot growth seed release	germination root growth	shoot & root growth
25	Jun.18	shoot growth seed release	germination root growth	shoot & root growth
26	Jun.25	shoot growth	germination root growth	shoot & root growth
27	Jul.2	shoot growth	germination root growth	shoot & root growth
28	Jul.9	shoot growth	root growth	shoot & root growth
29	Jul.16	shoot growth	root growth	shoot & root growth
30	Jul.23	shoot growth	root growth	shoot & root growth
31	Jul.30	bud set / leaf maintenance	root growth	shoot & root growth
32	Aug.6	bud set / leaf maintenance	root growth	bud set shoot & root growth
33	Aug.13	bud set / leaf maintenance	root growth	bud set shoot & root growth
34	Aug.20	bud set / leaf maintenance	root growth	bud set / leaf maintenance
35	Aug.27	bud set / leaf maintenance	root growth	bud set / leaf maintenance
36	Sep.3	senescence	root growth	leaf maintenance
37	Sep.10	senescence	root growth	leaf maintenance
38	Sep.17	senescence	bud set root growth	senescence
39	Sep.24	senescence / abscission	bud set root growth	senescence
40	Oct.1	abscission	bud set root growth	senescence / abscission
41	Oct.8	abscission	bud set root growth	abscission
42	Oct.15	dormant	dormant	dormant
43	Oct.22	dormant	dormant	dormant
44	Oct.29	dormant	dormant	dormant
45-48	Nov.	dormant	dormant	dormant
49-52	Dec.	dormant	dormant	dormant

Table 7.3. Weekly flow requirements of riparian cottonwoods along the Oldman River at Lethbridge, AB. The growing season is shaded (after Gom, 2002).

Week	Date	Mature Trees: Survival & Maintenance	Mature Trees: Growth & Reproduction	Saplings (> 1 year old) Survival	Saplings (> 1 year old) Growth	Seedlings (< 1 year old) Fringe Establishment (1 : 5-10 yr)	Seedlings (< 1 year old) General Establishment (1 : 30-50 yr)
1-5	Jan.	nat ave min		nat ave min		nat ave min	
6-9	Feb.	nat ave min		nat ave min		nat ave min	
10-13	Mar.	nat ave min		nat ave min		nat ave min	
14	Apr.2	nat ave min		nat ave min		nat ave min	
15	Apr.9	nat ave min		nat ave min		nat ave min	
16	Apr.16	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
17	Apr.23	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
18	Apr.30	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
19	May.7	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
20	May.14	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
21	May.21	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
22	May.28	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
23	Jun.4	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
24	Jun.11	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
25	Jun.18	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
26	Jun.25	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
27	Jul.2	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
28	Jul.9	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
29	Jul.16	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
30	Jul.23	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
31	Jul.30	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
32	Aug.6	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
33	Aug.13	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
34	Aug.20	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
35	Aug.27	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
36	Sep.3	nat ave min		60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
37	Sep.10	nat ave min		60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
38	Sep.17	nat ave min		nat ave min		nat ave min	
39	Sep.24	nat ave min		nat ave min		nat ave min	
40	Oct.1	nat ave min		nat ave min		nat ave min	
41	Oct.8	nat ave min		nat ave min		nat ave min	
42	Oct.15	nat ave min		nat ave min		nat ave min	
43	Oct.22	nat ave min		nat ave min		nat ave min	
44	Oct.29	nat ave min		nat ave min		nat ave min	
45-48	Nov.	nat ave min		nat ave min		nat ave min	
49-52	Dec.	nat ave min		nat ave min		nat ave min	

Notes: nat wk ave = natural weekly average flow, nat ave min = natural weekly average minimum flow.

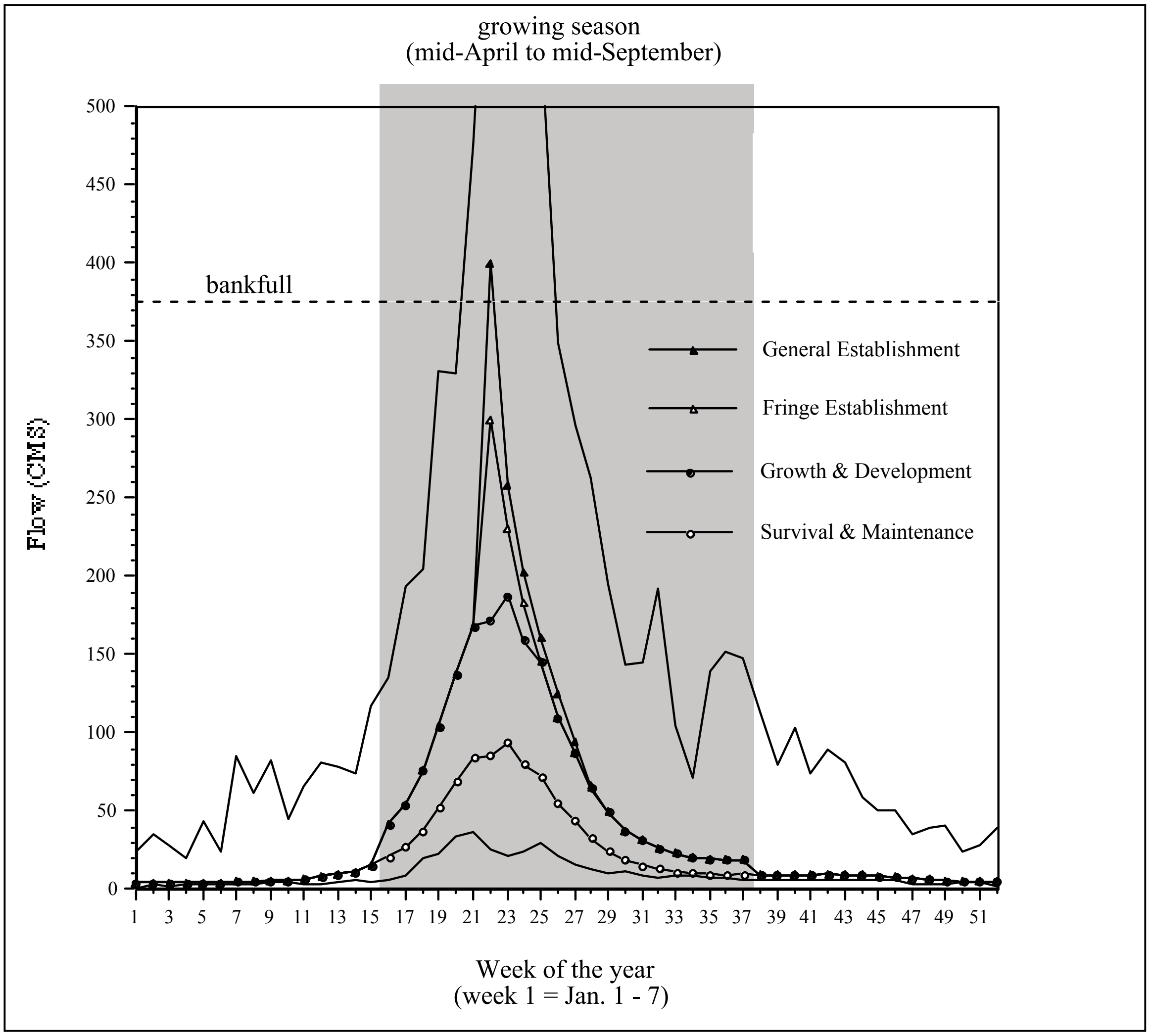

Figure 7.2. Generalized flows required by cottonwoods along the Oldman River near Fort Macleod. Flows required for growth and development consist of natural weekly average flows. Flows for survival and maintenance are 50% of the natural weekly average. Flows for fringe seedling establishment consist of a 1:10 year peak flow during the period of seed release, followed by a 2.5 cm/day rate of river stage decline. Flows for general seedling establishment include a 1:30 year peak flow followed by a 2.5 cm/day rate of river stage decline. The natural ranges of weekly minimum and maximum flows (from 1912 to 1995) are indicated as solid lines without symbols.

Where available, the annual record of natural flow can be used to estimate the degree of variability expected to occur naturally. The longer the historic record of flow, the more accurate this estimate will be. Using a weekly interval, flow variability can be described as the probability of occurrence of a particular flow and can be depicted on an exceedence curve (Figure 7.3). Each point on the exceedence curve corresponds with the flow observed during the same week (week 22 in Fig. 7.3) of each year during the period of record, in this case 1912 to 1995. Thus, a flow of 225 m^3/s corresponds with an exceedence of 20%, meaning that in 20% of years, flows of this magnitude or greater have been recorded along the Oldman River at Lethbridge during week 22 (Fig 7.3). The frequency probability of any given point can be calculated by inverting the exceedence value to produce the return interval (RI). Thus, the flow of 225 m^3/s, that has an exceedence of 20%, equates with a RI of 5. This means that on average, this magnitude of flow has been met or exceeded once every 5 years. Likewise, it may be expected that 100% exceedence flows will be exceeded every year, and 1% exceedence flows may be expected to recur less frequently than once in 100 years.

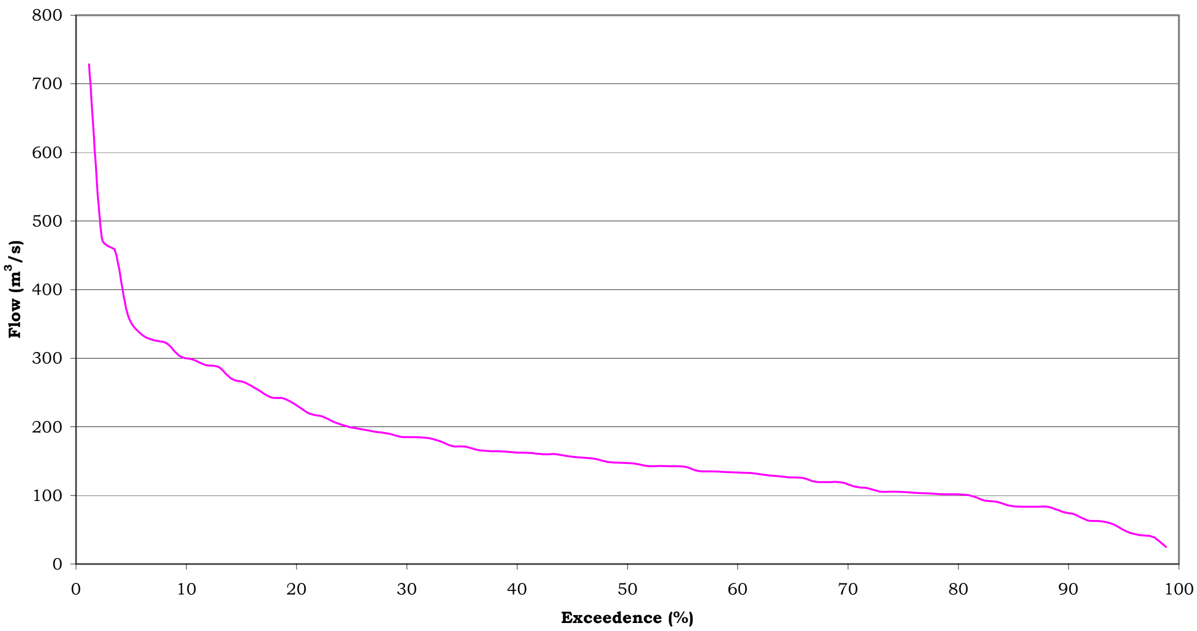

Figure 7.3. Exceedence curve for naturalized streamflows along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.

If streamflow was regulated each year to meet one of the four general flow requirements for cottonwoods described in Section 7.4 and shown in Figure 7.2, up to four distinct, artificial 'steps' would be created in each weekly exceedence curve (Figure 7.4). Although these steps may be based on meeting the basic flow requirements of cottonwoods they do not provide the continuum of flow variability that would be present in the natural system. (Where survival flows are met or exceeded every year, flows for growth are provided in 50% of years, and flows for seedling establishment are met in 10% of years.)

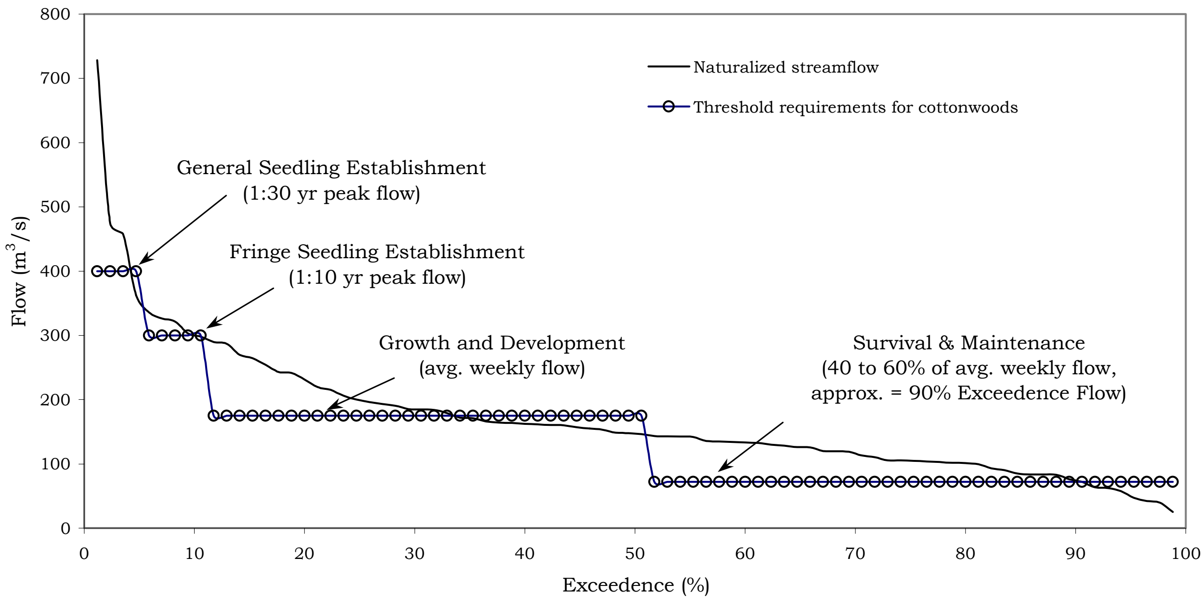

Figure 7.4. Threshold streamflow requirements for cottonwoods in relation to the exceedence curve for naturalized streamflow along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.

The goal of the PRC is to integrate the base, moderate, and high flow requirements of cottonwoods with a more natural pattern of flow variability. This will produce a more continuous exceedence curve that is somewhat flattened when compared with the exceedence curve for natural streamflow. Instead of depending solely on threshold flow values, the PRC is defined by a composite of three exceedence-based curves (Figure 7.5) and bankfull discharge. Each of these four components defines a portion of the overall PRC (Figure 7.6) for any given week of the year according to certain criteria (Table 7.4).

The first curve included in the PRC defines the base streamflow required for long-term cottonwood survival and maintenance as the 90% exceedence flow. Flows at this level of exceedence approximate the minimum requirement for 40% of natural average weekly flow that is outlined in Table 7.3. Lower flows will occur naturally, but cottonwoods should be able to tolerate these extreme events as long as the frequency and/or duration of these events is not increased. Thus, natural flows with exceedences greater than 90% are not reduced or increased (Figure 7.5).

Moderate to high PRC flows are defined by the higher of either the 75% of naturalized flow curve, or that flow corresponding with a 50% increase in the RI (e.g. a flow that has naturally occurred once every 10 years, now occurs once every 15 years). In general, the 75% curve defines a moderate range of PRC flows and the 50% RI shift defines a higher range of PRC flows. Thus, these two curves form a gradual bridge that connects the minimum flow requirements for cottonwood survival with those for healthy tree growth and seedling establishment as described in Figure 7.5.

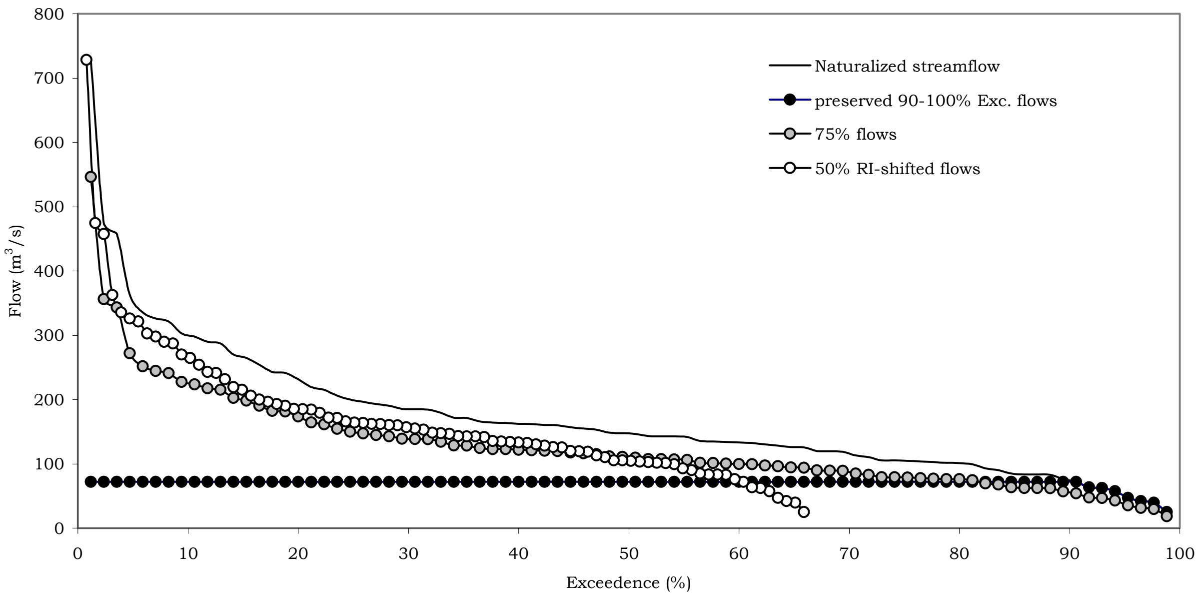

Figure 7.5. Three exceedence-based curves that each satisfy a portion of the streamflow requirements of cottonwoods along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.

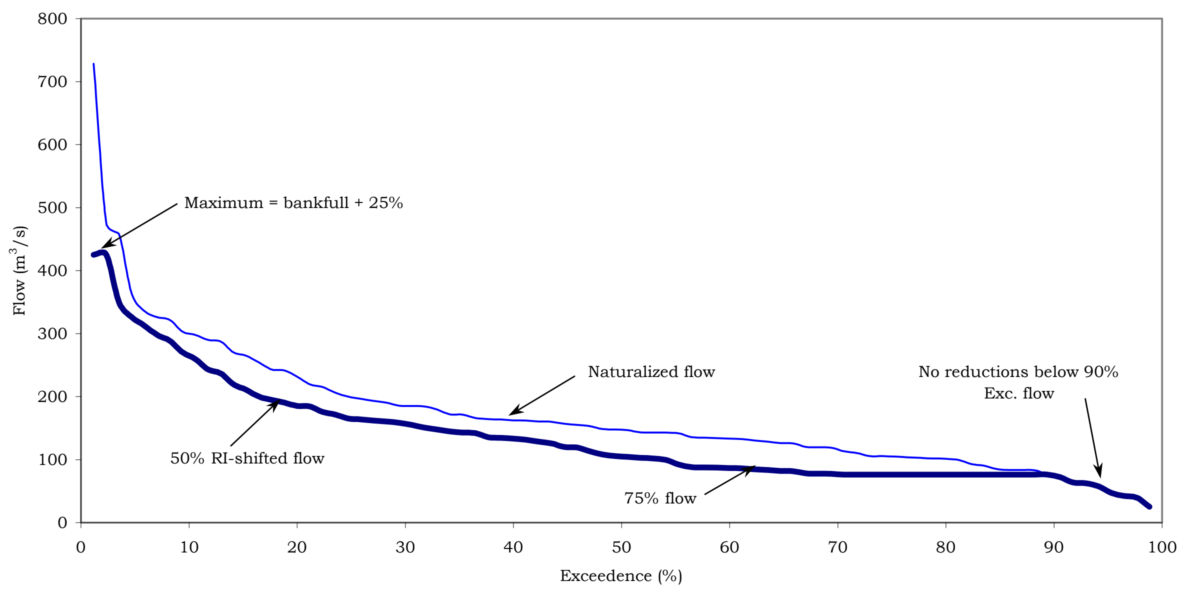

Figure 7.6. PRC for cottonwoods in relation to the exceedence curve for naturalized streamflow along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.

Table 7.4. Criteria for calculating PRC flows during a given week of the year.

Criteria:	**Condition:**	**PRC Flow:**
1. If natural flow exceedence	1a) >/= 90%	1a) **natural flow**
	1b) < 90%	*1b) (refer to criterion 2)*
2. If 75% of natural flow	2a) </= natural 90% exc. flow	2a) **natural 90% exc. flow**
	2b) > natural 90% exc. flow	*2b) (refer to criterion 3)*
3. If reduction to 75% of natural flow causes an RI increase of	3a) </= 50% of the natural RI	3a) **75% natural flow**
	3b) > 50% of the natural RI	*3b) (refer to criterion 4)*
4. If 75% of natural flow	4a) < 125% bankfull	4a) **flow corresponding to 50% increase of natural RI**
	4b) >/= 125% bankfull	*4b) 125% bankfull*

Finally, the maximum flow required by the PRC has been set at 125% of bankfull discharge. This threshold is slightly above bankfull to include flows that may be critical for maintaining the channel dynamics necessary to create nursery sites for poplar seedling establishment. Richter and Richter (2000) support the importance of flows at or above the 125% bankfull threshold for maintaining lateral channel migration. However, these flows may not be adequate, on their own, to provide all the functions required to maintain channel structure. More detailed analyses, including sediment transport, are carried out in Section 8.0. Figure 7.6 depicts the combined profile of the three curves and the maximum flows that have been integrated to form the final PRC curve for a given week along a particular reach.

The calculation of the PRC can be simplified into four rules (Table 7.4). These rules dictate that:

1. There be no reductions to flows with natural exceedences of 90% or greater;
2. Flows may not be reduced below the 90% exceedence level;
3. Reduction of up to 25% of naturalized flow is acceptable provided that the resulting RI shift is not greater than 50%; and
4. The maximum flow required is 125% of bankfull.

The PRC approach is designed to meet the flow requirements for cottonwood survival, growth and reproduction, within the context of a continuum of natural flow variability. To ensure both intra- and inter-annual variation are accommodated within a PRC recommendation, the PRC decision criteria are applied to weekly exceedence curves throughout the cottonwood growing season. A complete PRC recommendation is therefore comprised of a series of natural weekly exceedence curves adjusted according to the decision criteria described above.

7.6 Applying the PRC within the South Saskatchewan River Basin

The proposed PRC approach is based on information drawn from a variety of studies on many different stream systems. The weekly PRC is calibrated based on general flow requirements of riparian cottonwoods. These hydrological requirements need to be adjusted for application within the SSRB.

Streamflow regulation within the SSRB provides many examples of the effect a range of flow alterations has had on streamside forests. Of particular interest are the impacts of the different flow regimes of the St. Mary, Waterton, and Belly rivers in southern Alberta (Figure 7.7). Inventories of forest abundance upstream and downstream of major water management structures collected both pre- and post-regulation have been conducted along these rivers (Rood and Heinze-Milne 1989, Reid et al. 1992, Rood et al. 1995). Their analyses indicate that flow modification along the St. Mary River has contributed to severe declines in downstream cottonwood forests. In comparison, the flow regime imposed on the Waterton River is associated with more moderate declines of downstream cottonwoods, whereas regulation of the Belly River appears to have had little impact and may even have had a slightly favourable effect on its riparian forests. These three rivers provide an excellent opportunity to compare PRC flows with actual test cases.

Subsequent to adjustment of the proposed PRC to meet conditions on the Southern Tributaries of the Oldman River, it is expected that the details of the PRC rules will need to be revised slightly to address variability present along other reaches and sub-basins within the South Saskatchewan River Basin. This variability may relate to channel profiles and sediment characteristics, species present, or historic suitability of sites for forest establishment. Regardless of these final refinements, the PRC approach should preserve a natural range of variability to protect the dynamics and diversity present in these riparian ecosystems.

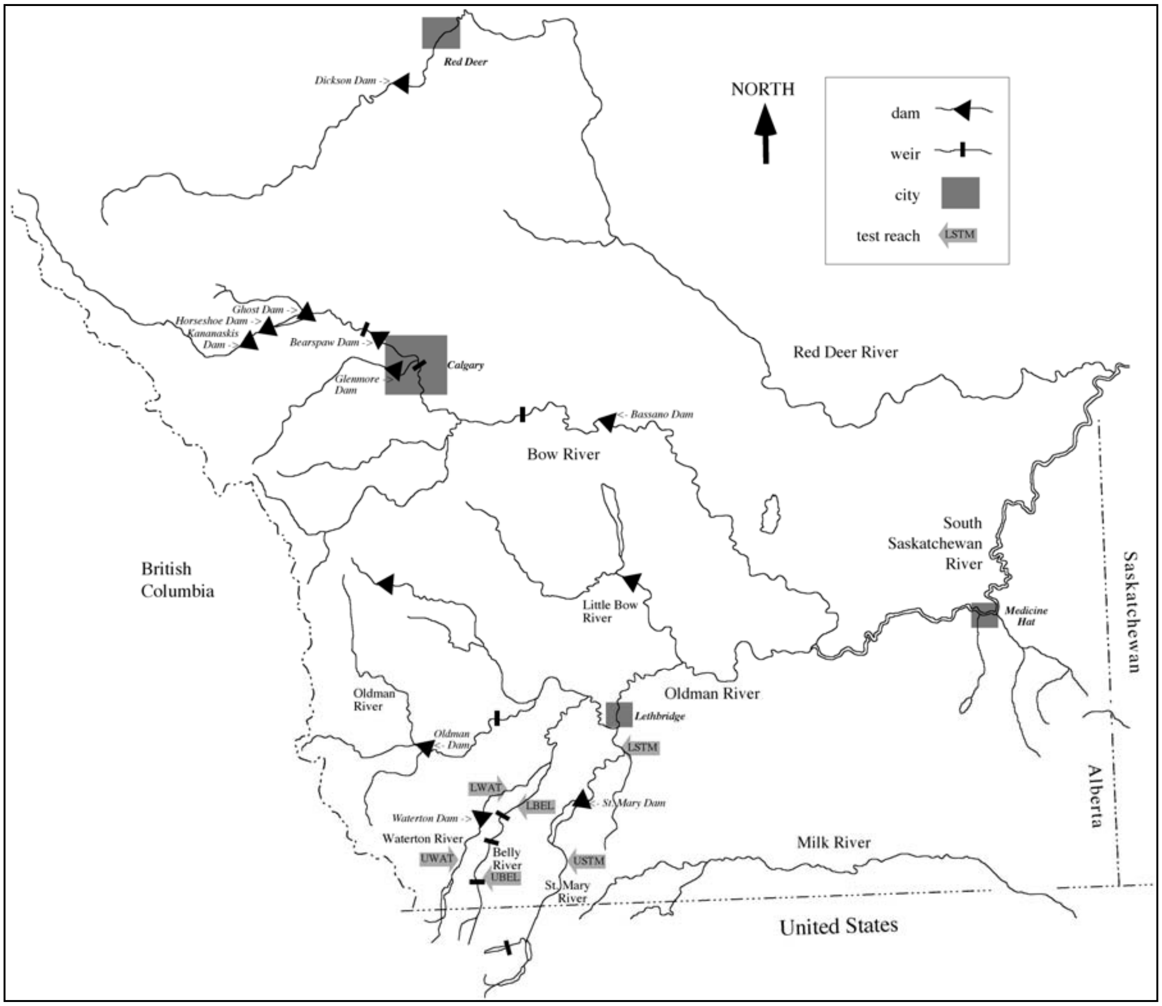

Figure 7.7. Major flow regulating structures and PRC calibration reaches in the SSRB (UWAT/LWAT = upper/lower Waterton River, UBEL/LBEL = upper/lower Belly River, USTM/LSTM = upper/lower St. Mary River).

7.6.1 Flow modifications that affect riparian cottonwoods

Many different flow regimes have been implemented along river reaches in the SSRB. Accordingly, the effects on riparian cottonwood forests have been varied. Careful analysis of these flow regimes and their effects identify trends that have been beneficial or detrimental to riparian cottonwoods. These findings were compared with the proposed PRC to evaluate its potential as a prescription to restore and maintain the long term health of riparian cottonwood forests downstream from flow regulating structures in the SSRB, and possibly within other regulated river basins.

Because riparian cottonwoods are adapted to natural patterns of streamflow, regulated flow regimes will affect downstream riparian cottonwoods in different ways depending on how flows have been altered from their natural condition. Depending on the extent of change to the magnitude, timing, frequency and duration of natural flow, the impact on downstream vegetation may vary from slight to severe and from temporary to permanent. Symptoms of acute stress due to sudden, extreme changes in streamflow tend to involve premature leaf senescence (yellowing), branch dieback, or tree death. The effects of more chronic stress due to gradual, long term changes in streamflow may not be evident for many years, and may involve reduced branch or radial growth, and diminished reproduction leading to widespread changes of population structure. Considering that a cottonwood's lifespan may exceed 100 years, symptoms measurable in less than 10 to 20 years indicate catastrophic impacts.

Reduced or prolonged low flows

Flow regulation in the SSRB may involve diverting a significant portion of natural streamflow offstream. The implication for riparian cottonwoods is greatest when diversion to meet water demands is high during periods of already naturally low streamflow.

Riparian cottonwoods are adapted to naturally occurring low flows. However, they may not be able to tolerate increased drought stress if the frequency or duration of low flows is increased. Additionally, if flows are reduced below natural minima, the occurrence of acute drought stress and tree mortality will be increased.

The extent and permanence of the damage caused to riparian cottonwood forests by drought stress tends to correlate with the severity and duration of the stress condition. Occasional, slight drought stress may cause no appreciable long term harm to these forests, because the trees have the opportunity to recover from slight setbacks in subsequent years. Forests exposed to more frequent or severe stress may suffer more widespread and long term consequences, including progressive forest deterioration and recruitment failure.

In addition to maintaining healthy cottonwood forests, preventing flow reductions below natural minima is also likely to encourage the recovery of drought-stressed and declining forests. The severity of the damage will largely determine the potential for recovery, but as long as living trees are present, protection of base flows will promote tree survival and associated forest recovery.

Increased low flows

If high flows are stored for more gradual release during drier periods, natural low flows will be supplemented. Initially, increases to low flows may enhance riparian cottonwood health, by reducing the incidence of drought stress and promoting survival of trees in otherwise marginal areas. Thus, permanent increases to low flows are likely to result in some degree of population expansion. However, long term changes to the extent of flow variability may also have negative consequences. During occasional periods of low flow, cottonwood roots are encouraged to grow deeper to access moisture. These deep roots tend to protect cottonwoods from drought stress during subsequent dry periods. This resiliency may be lost as root penetration is limited in response to the elevated water table provided by prolonged, supplemented low flows. Consequently, as their roots become shallower, cottonwoods may suffer increased drought stress by low flows that were previously tolerable.

In situations where riparian forests have become accustomed to elevated low flows, natural minima are no longer adequate for maintaining downstream cottonwoods. Abrupt reduction back to natural low flow levels could cause drought stress, especially to trees in areas of forest expansion facilitated by the elevated low flows. To limit drought stress for these forests, a higher minimum low flow needs to be maintained indefinitely. Alternatively, the forest may be restored to its natural state by gradually reintroducing natural flow variability over a period of several years. Consequently, areas of forest expansion may return to being only marginally suitable for cottonwoods, so some stress and decline might be expected in those areas.

Stabilized moderate flows

Flow regulation may involve the moderation of high and low flows, resulting in a more constant level of flow.

Moderated flow regimes do not accommodate the life strategy of cottonwoods, as these trees are adapted to naturally dynamic streamflows. Stabilized, moderate flows are likely to lead to the combined effects of decreased high flows and increased low flows. Stabilized streamflows tend to limit the elevational extent of the riparian forest above the water's surface as the cottonwood root systems become habituated to the stabilized water level. Consequently, the forest will become less resilient to drought stress caused by future low flows.

The dynamics of high and low streamflows also drive channel forming processes that involve the erosion and deposition of sediment. In contrast, stable moderate streamflows tend to cause channel stabilization as point and lateral bars become stagnant. As a result, sediments are not transported as regularly and vegetation tends to encroach to the water's edge. This gradual elimination of barren nursery sites for cottonwood seedling establishment will threaten the long term viability of the affected riparian forests. Seedlings that manage to establish under a stabilized streamflow regime may be prone to drought stress because root elongation that connects them to the water table during unusual periods of lower flows is not encouraged.

Prospects for the restoration of cottonwood forests affected by stabilized flow regimes are good. A full recovery could be expected in most cases where a natural range of flow variability was gradually reintroduced, allowing the forest to re-acclimatize over a period of years.

Reduced, delayed, or eliminated peak flows

Natural streamflow can be inadequate to satisfy human demand during dry periods, so flow regulating structures may be operated to compensate by storing water during wetter periods for release during dry periods. The resulting reduction or elimination of peak flows impacts riparian cottonwoods in various ways, depending on the degree and timing of flow modification.

An occasional reduction to peak flows is not likely to cause drought stress to cottonwoods, because these flows usually surpass the levels required to maintain healthy tree growth. If reduced flood flows fail to recharge the riparian water table, trees in higher, more marginal areas would have an increased risk of drought stress. However, an occasional peak flow reduction may promote the health of trees at lower elevations by lessening the scouring effects associated with flood flows.

Frequent reduction, delay, or complete elimination of peak flows is detrimental to the long-term health of riparian cottonwood forests. Natural flood flows drive channel processes involving erosion and deposition that prepare nursery sites required for successful seedling recruitment. The natural magnitude and timing of flood flows encourage establishment of seedlings higher on streambanks, thereby lessening the chances they will be washed away or buried during subsequent, moderate streamflows. Thus, modifications to peak flows may disrupt the frequency and pattern of natural cottonwood reproduction, resulting in reduced long-term viability of the affected riparian forests.

To remedy situations where peak flow modifications have already impacted cottonwood forest seedling regeneration, natural peak flows can be reintroduced. Provided an adequate seed source is still available, the natural frequency and occurrence of cottonwood seedling recruitment will be restored immediately. Forests that are exhibiting accelerated declines may need greater than natural rates of recruitment to expedite recovery.

Abrupt changes and pulsed flows

Riparian cottonwoods are adapted to the natural patterns of streamflow variability. Artificial changes in the rate of change of flows can have many effects on downstream forests. Changes that affect cottonwoods include abrupt flow increases or decreases and flow pulsing. The effects of these changes depend on their magnitude, duration, frequency, and timing relative to the pattern of natural streamflows.

Artificially rapid flow declines can lead to cottonwood drought stress. This may occur if the water table is reduced below the effective rooting zone too rapidly for root growth to keep pace. Young seedlings are most susceptible to this disturbance because their roots are not deeply established. However, saplings and even mature trees may become stressed if flow declines are severe. Cottonwoods may become increasingly less stress resilient if root elongation is not encouraged by gradual water table declines.

The destabilizing effect of repeated bank de-watering and re-watering can lead to increased erosion and channel incision. Susceptibility to such deterioration, due to changes in river stage, increases with stream gradient and progressively finer-textured substrates. Excessive bank erosion can perpetually reset the cottonwood seedling establishment process and accelerate the removal of saplings and established trees. In addition to the effects of horizontal streambank erosion, vertical downcutting or incision of the channel can lower the riparian water table. This can cause stress or die-back to trees in drier, higher areas, and result in narrowing of the forested riparian zone.

The regular, daily pulsing of flows characteristically produced downstream from hydropower generating facilities can produce artifacts in channel geomorphology and associated riparian forests. For example, repeated pulses of similar magnitude will tend to cause erosion and deposition on a limited portion of the floodplain. This may lead to artificially structured streambanks that are either more or less stable than the natural state. Consequently, this will influence the availability and location of barren sediments necessary for cottonwood seedling establishment.

The severity and permanence of impacts resulting from abrupt flow changes or repeated flow pulsing can be highly variable. The prognosis for restoration is similarly variable. While riparian cottonwoods are able to re-colonize areas relatively quickly, (within years or decades) when suitable conditions are restored, degradation of channel geomorphology tends to be a more permanent impact lasting decades or centuries. In most cases, the more severe the impact, the longer the period required for recovery.

7.6.2 PRC flows for test reaches in the Oldman River Basin

Six reaches of the Southern Tributaries of the Oldman River were analyzed. Two test reaches were defined along each of the Belly, Waterton, and St. Mary rivers in the Oldman River Basin. These included an upstream and downstream reach relative to the Belly River diversion weir, the Waterton Dam, and the St. Mary River Dam (Figure 7.7). The upstream and downstream reaches are also referred to as upper and lower respectively, and have been abbreviated throughout these discussions as UBEL and LBEL, UWAT and LWAT, and USTM and LSTM (upper and lower Belly, Waterton, and St. Mary rivers, respectively). The approximate location of each test reach is indicated in Figure 7.7.

All available actual (recorded) and naturalized (reconstructed) weekly streamflows, (generally during the period from 1912 though 1995,) were acquired for each test reach from Alberta Environment (2001b). Descriptions of how naturalized flows were reconstructed are found in

Alberta Environmental Protection (1998). The station locations and the types and periods of flow records used for each reach are summarized in Table 7.5. The weekly 125% bankfull flow for each test reach was estimated based on historic weekly flows during weeks when an instantaneous flow of 125% bankfull magnitude (Table 7.5) occurred at least once. Bankfull values for each reach were provided by Alberta Environment, Water Management Operations, Lethbridge.

Table 7.5. Weekly and bankfull flows used to calculate the PRC along test reaches in the Oldman River Basin (* indicates that flows for several weeks of that year are not available).

Reach	Station	Location	Weekly flow record available		Instantaneous 125% Bankfull (m^3/s)	Weekly 125% Bankfull (m^3/s)
			natural (estimate)	actual (recorded)		
UBEL	05AD005	Mountain View	1912-95	1912-95		50
LBEL	05AD002	Standoff	1912-95	1912-31*, 1949-85*	100	65
	05AD041	Glenwood		1986*-95		
UWAT	05AD003	Waterton Park	1912-95	1912-31*, 1948-95	180	117
LWAT	05AD008	Standoff	1912-95	1916-31*, 1935-66	205	175
	05AD028	Glenwood		1965-95		
USTM	05AE027	US/Canada border	1912-95	1912-95		140
LSTM	05AE006	Lethbridge	1912-95	1912-95	200	180

Abbreviations: UBEL = upper Belly River, LBEL = lower Belly River, UWAT = upper Waterton River, LWAT = lower Waterton River, USTM = upper St. Mary River, LSTM = lower St. Mary River.

Weekly PRC flows were calculated for each of the six test reaches using the available records of naturalized flows and the five criteria outlined in Figure 7.8.

The PRC flow was calculated for each weekly naturalized flow in the 1912-1995 dataset, using a series of logical decisions. If the exceedence of the naturalized flow was less than 90%, the lesser of naturalized flow or 125% bankfull flow was prescribed for the PRC. If both 65% of the naturalized flow and the 50% return interval-shifted flow were less than the naturalized 90% exceedence flow, the formula prescribed the lesser of naturalized 90% exceedence flow or 125% bankfull flow. Otherwise, the PRC was prescribed as the greater of 65% naturalized flow or the 50% return interval-shifted flow, to a maximum of 125% bankfull flow.

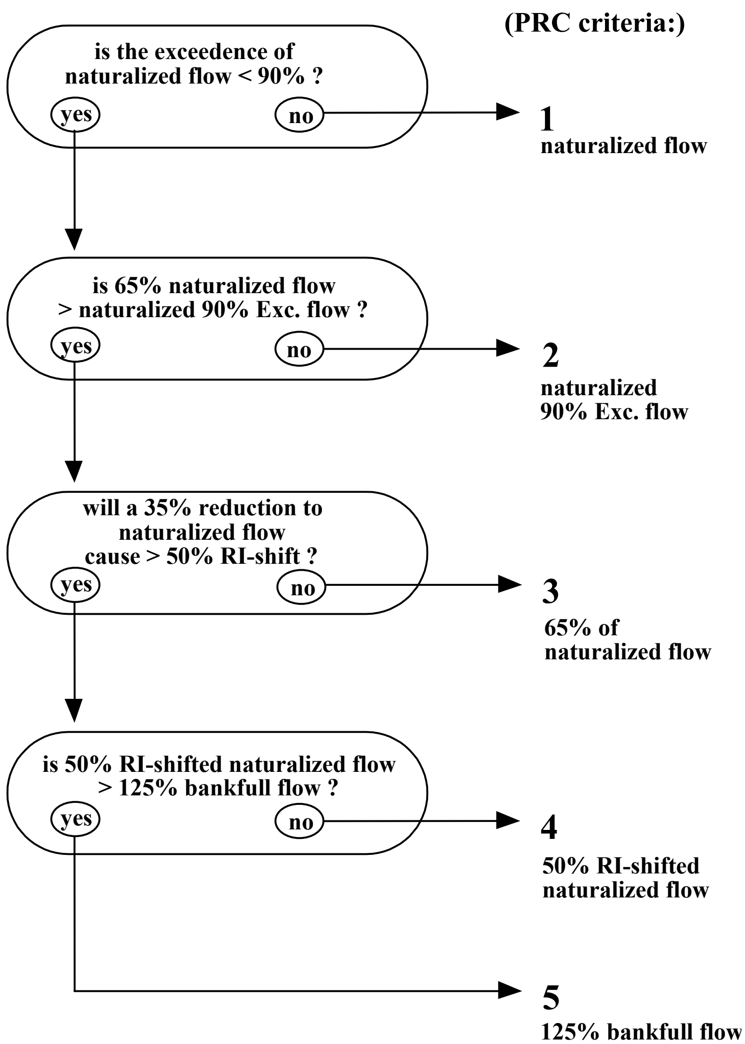

Figure 7.8. Flow-chart of criteria-based decisions for calculating PRC flows.

Evaluating PRC flows along test reaches

To estimate the potential long-term effect of a PRC based flow regime on riparian cottonwoods, the calculated PRC flows were compared with actual regulated flow regimes that have had known impacts on associated riparian poplar forests.

It should be noted that although the St. Mary River Dam has operated somewhat longer than the Waterton Dam, the St. Mary River Dam has still only influenced approximately the last half of the flow record represented (since 1951). For this reason, the severity of modifications to natural flow exceedences have probably been underestimated in representations featuring the full period of record (1912-1995).

Suitability of PRC flows along the Belly River

Selected annual weekly hydrographs comparing actual and PRC flows along upper and lower portions of the Belly River are provided in Figure 7.9. Similar depictions of natural versus actual flows are provided in Figure 7.10.

The regulated flow regime along the Belly River has not had strongly negative effects on downstream riparian woodlands (section 3.6.2). However, there has been an increased incidence of chronic drought stress symptoms in forests downstream from the Belly River Diversion Weir (Reid et al. 1992). Because increased frequency and duration of low flows are the most likely cause, further reductions to low flows should be avoided. Otherwise, the pattern of flow regulation downstream from the BRDW appears to be adequate for sustaining downstream riparian cottonwood forests in this context.

The flow regime along the lower portion of the Belly River that would have resulted if PRC flows were implemented during the period of record differ in two main ways from the flows that were actually recorded during the same period. Firstly, the PRC would permit greater reductions to extremely high flows than actually occurred. The affected peak flows have natural exceedences of less than about 5% (>1:20 year recurrence interval), and would equate with over-bank flooding. Considering the magnitude and infrequency of these extreme events, these high flows probably exceed the basic moisture requirements for keeping established cottonwood trees healthy. Instead, as described in Section 8.3, extremely high flows may be necessary for driving the geomorphic processes that set the stage for episodic, widespread cottonwood seedling recruitment events. In theory, the PRC's threshold peak flow of 125% bankfull discharge (Table 7.6) seems a reasonable limit for high flow events. It should allow some over-bank flooding to continue to occur at a natural frequency that would preserve processes key to seedling recruitment. However, the stage relationships of bankfull and 125% bankfull discharge must be verified in the field to fully evaluate the implications of completely eliminating peak flows beyond this threshold.

The second main difference between the actual flow and the PRC flow regimes along the Belly River is that the actual flows feature greater reductions to extremely low flows (85-100% exceedence) than the PRC. Although this difference seems subtle, comparisons of annual hydrographs particularly during low flow years, show that the PRC's protection of minimum flows is important for preventing extended periods of extremely low flow, as occurred during 1977 (Figure 7.9 and 7.10). Following the PRC would not prevent extremely low flows, but rather would simulate the natural frequency, magnitude and duration of low flow periods. In this way, the PRC's protection of minimum flows would reduce the occurrence of chronic drought stress reported downstream from the BRDW.

Historically, there has been very minor flow modification upstream from the BRDW (Figure 7.10). Riparian cottonwood forests in this reach are considered to be in relatively pristine condition. Implementation of PRC flows along this reach would result in the same types of flow modifications as downstream, except at lesser magnitudes proportional to the naturally smaller volumes of flow (Figure 7.9). The similarity in the contexts between upstream and downstream forests, suggest their moisture requirements would be essentially the same. Therefore, PRC flows should be acceptable for sustaining riparian cottonwoods along the Belly River as a whole. However, in reducing natural flow variability, the PRC flow regime is likely to result in a minor degree of reduced diversity in the floodplain landscape over a long period of time.

Table 7.6. Average naturalized flow exceedences of 125% bankfull flow for each test reach during peak flow weeks (Julian weeks 21-27).

Test Reach:	Weekly 125% Bankfull Flow (m^3/s)	Average Naturalized Weekly Exceedence of 125% Bankfull Flow
UBEL	50	6.4 %
LBEL	65	2.8 %
UWAT	117	7.2 %
LWAT	175	4.0 %
USTM	140	6.4 %
LSTM	180	2.6 %

Abbreviations: UBEL = upper Belly River, LBEL = lower Belly River, UWAT = upper Waterton River, LWAT = lower Waterton River, USTM = upper St. Mary River, LSTM = lower St. Mary River

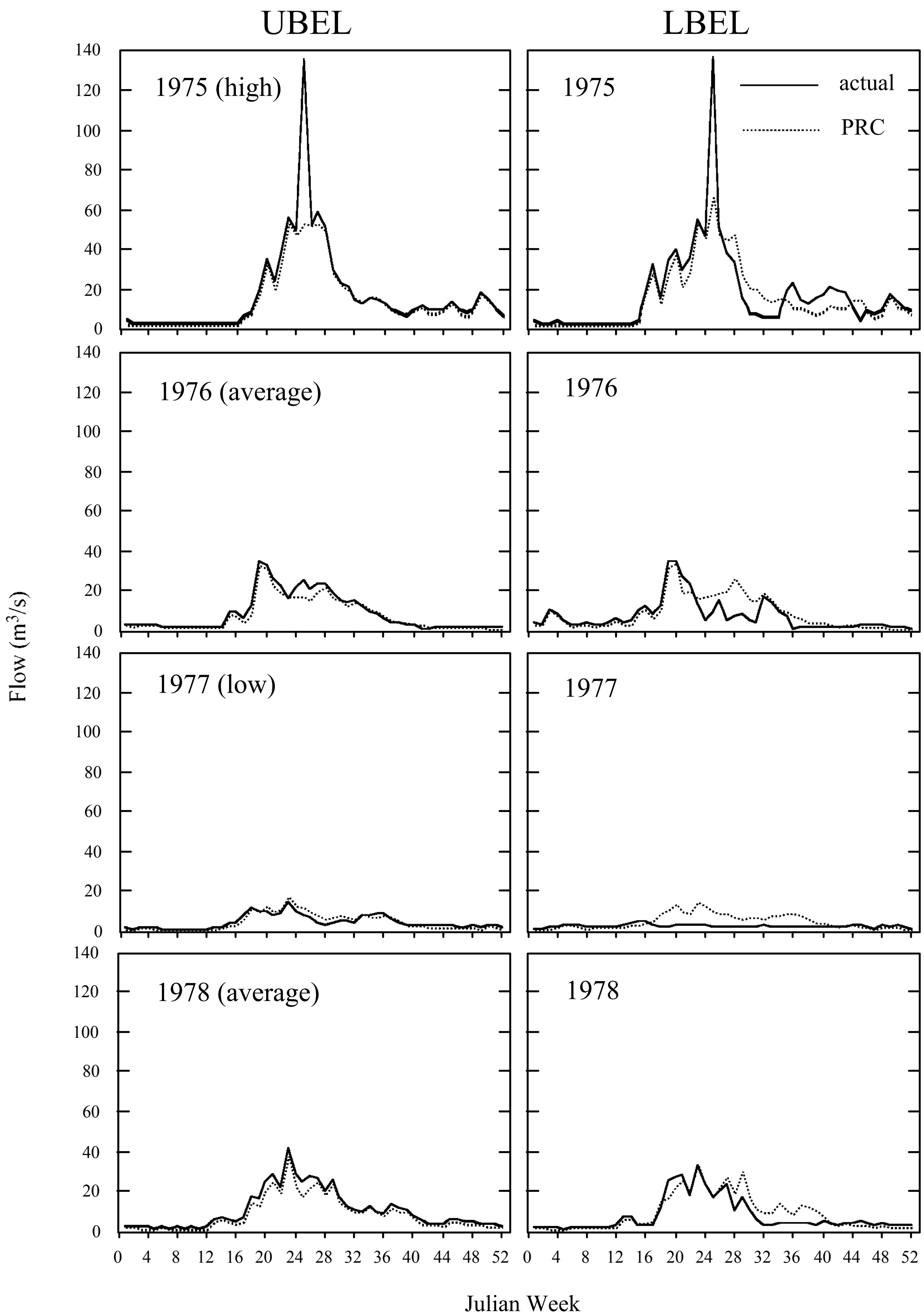

Figure 7.9. Actual and PRC weekly flows during a high flow year (1975), a low flow year (1977), and two average flow years (1976 & 1978) along the upper (left) and lower (right) reaches of the Belly River (at Mountain View and Standoff respectively).

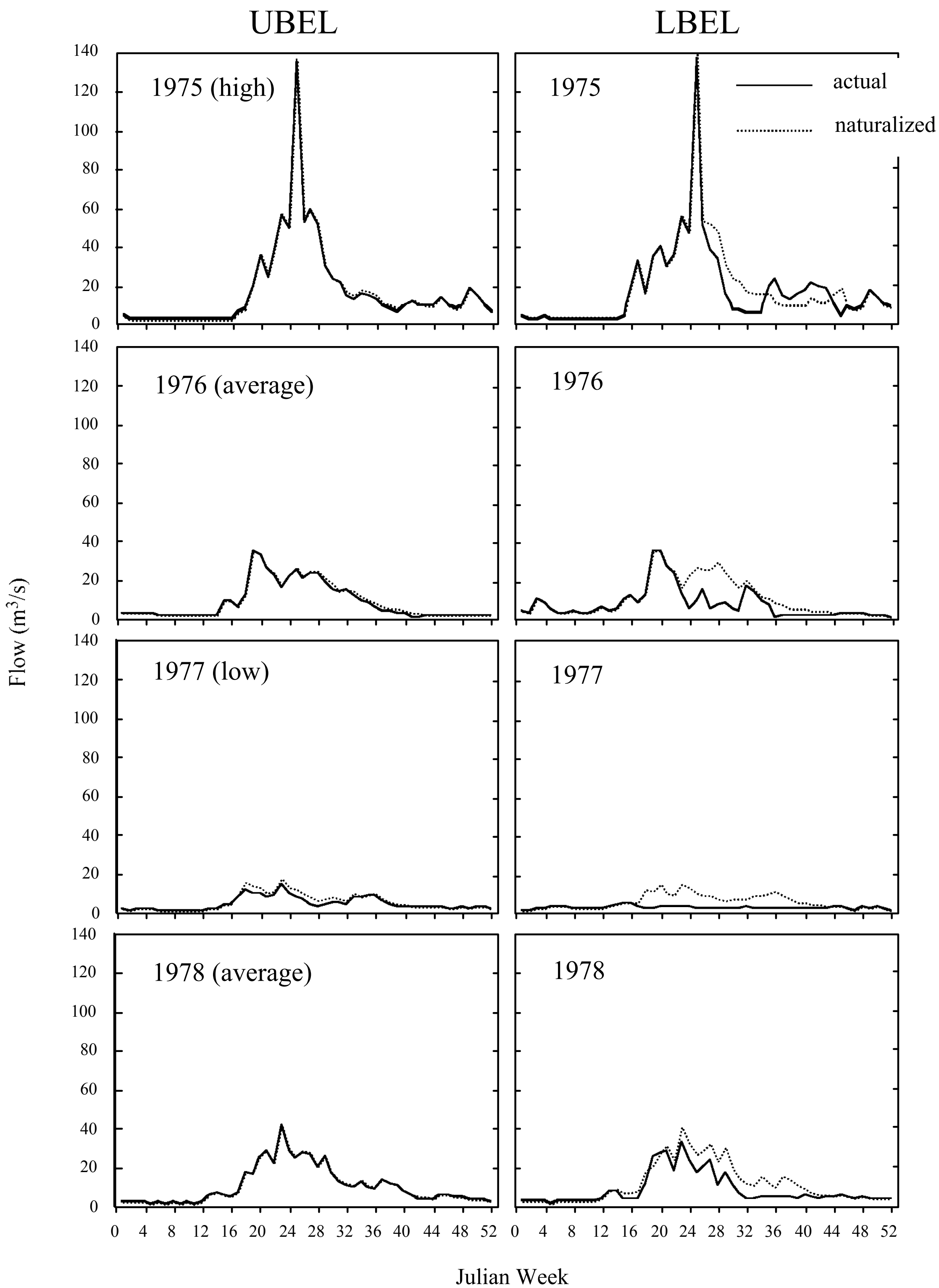

Figure 7.10. Naturalized and actual weekly flows during a high flow year (1975), a low flow year (1977), and two average flow years (1976 & 1978) along the upper (left) and lower (right) reaches of the Belly River (at Mountain View and Standoff respectively).

Suitability of PRC flows along the Waterton River

Selected annual weekly hydrographs comparing actual and PRC flows along upper and lower portions of the Waterton River are provided in Figure 7.11. Similar depictions of natural and actual flows are shown in Figure 7.12.

The regulated flow regime generated by the Waterton Dam has had measurable negative impacts on downstream riparian forests (detailed in Section 3.6.2). Symptoms of these impacts include acute and chronic drought stress, reductions to the mature canopy, and conditions detrimental to seedling recruitment. Regime modifications associated with these impacts include inadequate flows during the growing season, depressed natural low flows, and abrupt reductions following annual peak flows.

The pattern of flow that would have resulted if the PRC had been implemented along lower portions of the Waterton River from 1912 to 1995 differs in several ways from the actual regime that occurred during this period. As was the case along the Belly River, the PRC permits large reductions to extremely high flows (1975 in Figure 7.11). The PRC's upper flow limit of 125% bankfull discharge equates to flows with natural exceedences of generally less than 5% (Table 7.6). As was the case for the Belly River, the long-term geomorphological consequences of eliminating flows beyond the 125% bankfull magnitude need to be more fully investigated. The PRC would permit peaks somewhat greater than bankfull discharge to occur at relatively natural frequencies and would enable more gradual declines following these peak annual flows than has occurred historically (Figure 7.11). If delivered properly on a daily time-step, this modified pattern of flow should still be sufficient to recharge the riparian water table and promote the 'fringe' recruitment of cottonwood seedlings (producing narrow bands of seedlings that parallel the channel at a common stream-stage elevation).

With respect to improving the status of riparian cottonwood forests below the Waterton Dam, the most important difference between PRC and actual historic flow regimes along the Waterton River relates to natural low flows (90-100% exceedence). The actual reductions made to these natural low flows exceed amounts prescribed by the PRC. It should be remembered that the Waterton Dam has been in operation since 1964, and so has only influenced the latter 40% of the flow-record analyzed (1912-1995). Although a larger than average proportion of low flow years have occurred since 1964, the operation of Waterton Dam has caused very large reductions to already naturally low flows (Figure 7.12). By preventing reductions to already naturally low flows in the 90 to 100% exceedence range, implementation of PRC flows would have reduced the acute and chronic drought stress that is presently widespread downstream from the Waterton Dam (section 3.6.2).

The flow regime upstream from the Waterton Dam has remained relatively unaltered from its natural state (Figure 7.12). Flow reductions prescribed by the PRC (Figure 7.11) would produce PRC flows similar to those downstream from the Dam, except that they would be proportional to the smaller magnitude of natural flows along the upstream reach. Because the physical context of the floodplain and the distribution of riparian forests above and below the dam are similar, the PRC flow regime is expected to be suitable for sustaining cottonwoods along the Waterton River as a whole. However, PRC associated reductions to natural flow variability could result in a slightly reduced diversity in the floodplain landscape over a long period of time.

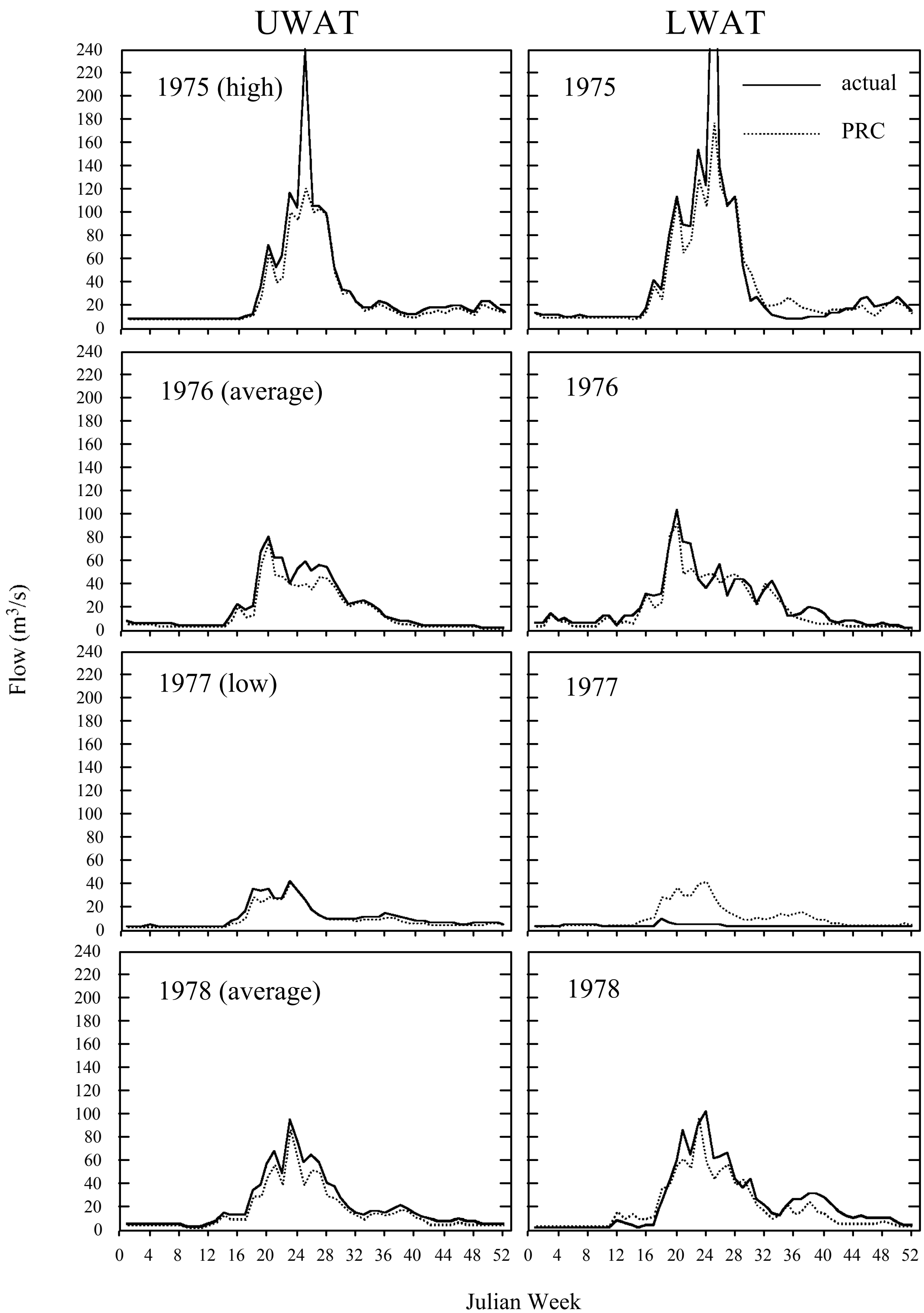

Figure 7.11. Actual and PRC weekly flows during a high flow year (1975), a low flow year (1977), and two average flow years (1976 & 1978) along the upper (left) and lower (right) reaches of the Waterton River (at Waterton Park and Glenwood respectively).

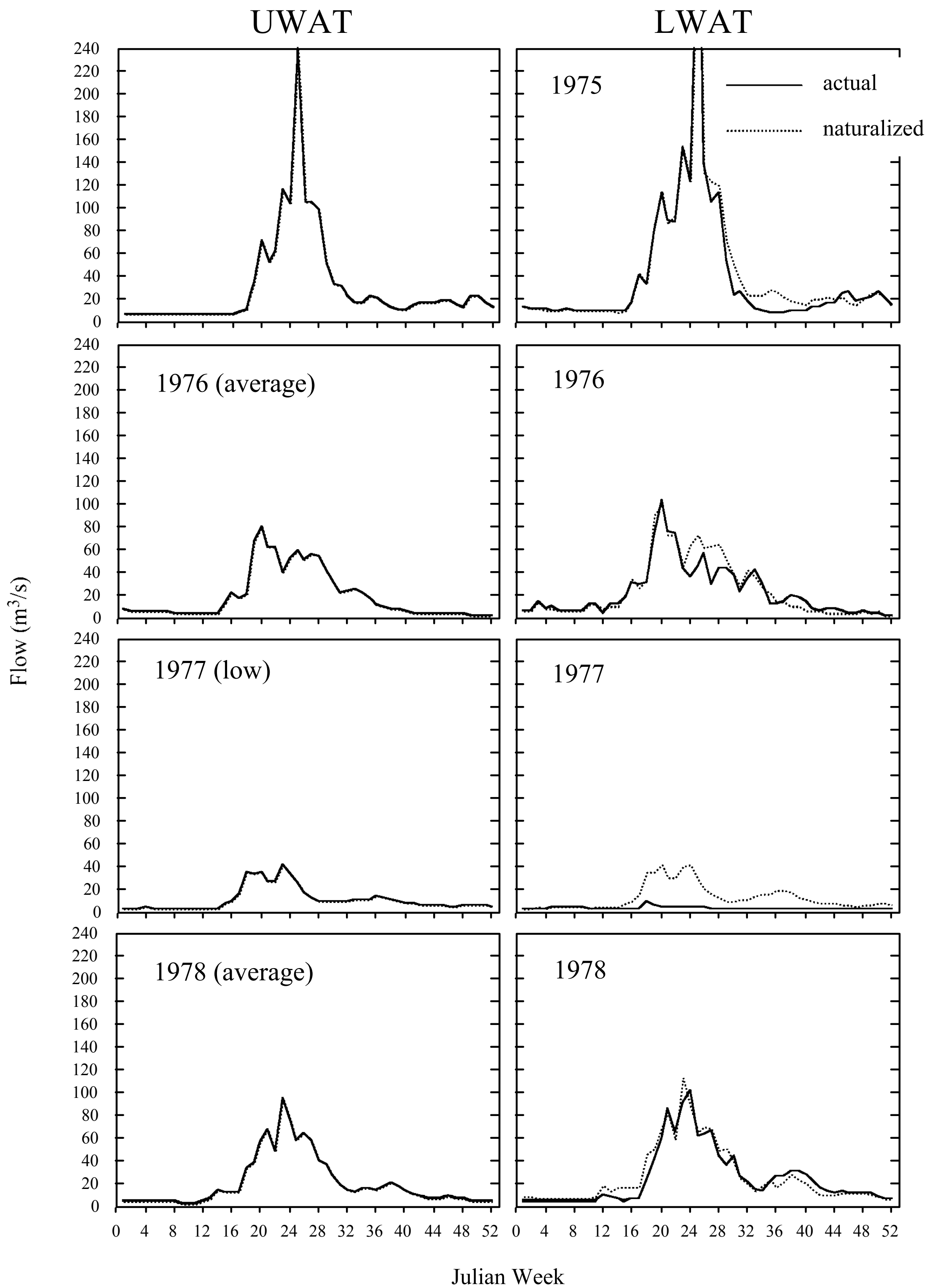

Figure 7.12. Naturalized and actual weekly flows during a high flow year (1975), a low flow year (1977), and two average flow years (1976 & 1978) along the upper (left) and lower (right) reaches of the Waterton River (at Waterton Park and Glenwood respectively).

Suitability of PRC flows along the St. Mary River

Selected annual weekly hydrographs comparing actual and PRC flows along upper and lower portions of the St. Mary River are provided in Figure 7.13. Similar depictions of natural and actual flows are shown in Figure 7.14.

The regulated flow regime downstream from the St. Mary River Dam has been associated with the near collapse of its associated cottonwood population (section 3.6.2). Symptoms include signs of acute and chronic drought stress, significant reductions in forest abundance, and the failure of seedling recruitment. Flow regime modifications implicated by these impacts include inadequate flows during the growing season, depressed naturally low flows, abrupt reductions following annual peak flows, and altered timing of high flow events.

If the PRC had been implemented along the St. Mary River from 1912 through 1995, the resulting flow regime would differ substantially from that which actually occurred. In general, the PRC would have permitted greater reductions to extremely high peak flows, less severe reductions to moderate flows, and no reductions to extremely low flows. Additionally, because the PRC is based on natural flow exceedences, it would have incorporated a more natural seasonal pattern of high and low flows than actually occurred (Figures 7.13 and 7.14).

The elimination of flows greater than 125% bankfull discharge affects peak flows with exceedences of less than about 5% (Table 7.6). These extremely high flows surpass the magnitude necessary for recharging the riparian water table and creating nursery sites for cottonwood seedling establishment. However, less direct effects of extreme peak flows may involve the geomorphic complexity of the floodplain landscape by influencing rates of channel migration or sediment transport. The long-term consequences of eliminating flows beyond 125% bankfull magnitude need to be more fully investigated.

The PRC would allow high flows that were reduced to 125% bankfull to occur at relatively natural frequencies and would provide more gradual declines following these peak annual flows than has occurred historically (Figure 7.13). If delivered properly, this pattern of flow should be sufficient to recharge the riparian water table and provide adequate flow to promote seedling recruitment. While high to moderate flows are important for seedling establishment, the subsequent rate of flow decline is also essential to ensure seedling survival. Recent efforts to produce gradual rates of decline following peak flows, by careful management of daily operations, have been successful in promoting initial seedling establishment along the lower portion of the St. Mary River (Rood and Mahoney 2000).

Compared with the actual flow regimes recorded along the upper and lower portions of the St. Mary River, the flow regime created by the PRC would be considerably more favourable to sustaining healthy riparian cottonwood forests. In particular, flow reductions permitted by the PRC would be less severe, and their timing and frequency across flow magnitudes would follow a more natural pattern of flow (Figures 7.13, 7.14).

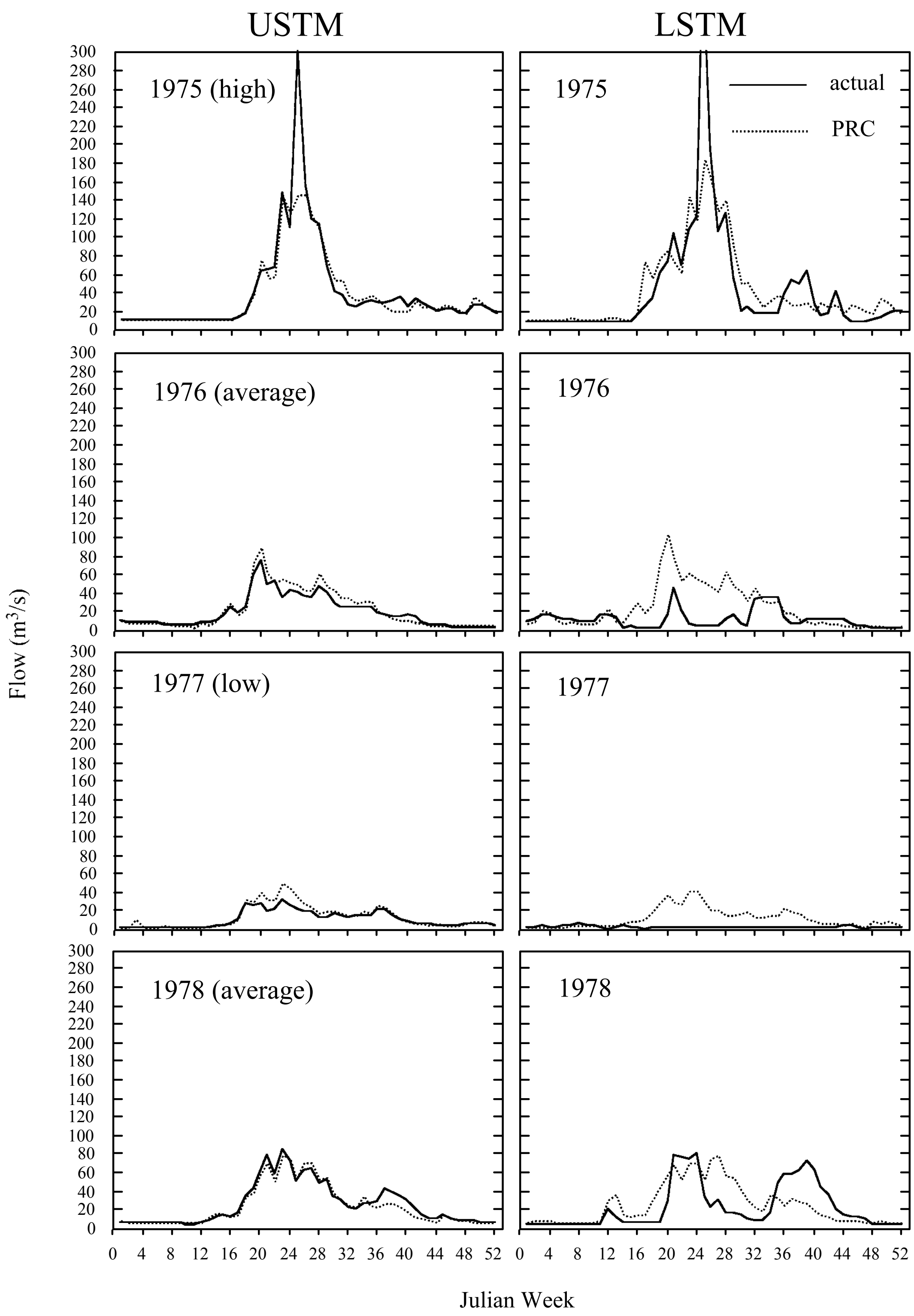

Figure 7.13. Actual and PRC weekly flows during a high flow year (1975), a low flow year (1977), and two average flow years (1976 & 1978) along the upper (left) and lower (right) reaches of the St. Mary River (at the US/Canada border and Lethbridge respectively).

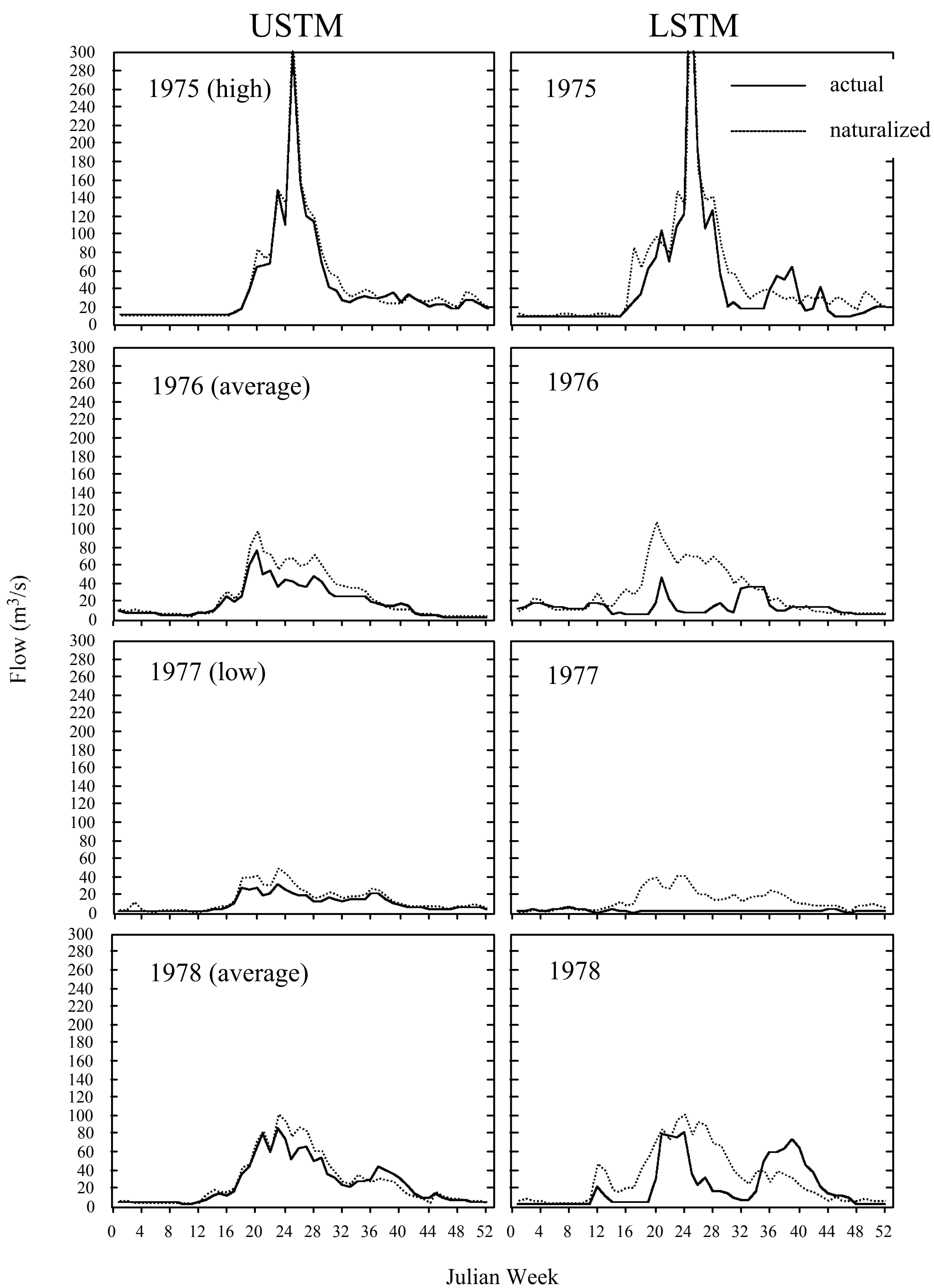

Figure 7.14. Naturalized and actual weekly flows during a high flow year (1975), a low flow year (1977), and two average flow years (1976 & 1978) along the upper (left) and lower (right) reaches of the St. Mary River (at the US/Canada border and Lethbridge respectively).

Overall suitability of PRC flows

The comparative evaluation of PRC flows, as they relate to naturalized and actual flow regimes along the six test reaches, indicates that PRC flows would maintain riparian cottonwood forests along these reaches. PRC flows are expected to provide more favourable conditions along the three downstream reaches, and identify an acceptable flow regime along the three upstream reaches.

The impact of regulated flow regimes on riparian cottonwoods along the downstream reaches of the Belly, Waterton, and St. Mary rivers have been relatively neutral, moderately negative, and severely negative, respectively (Table 7.7).

Table 7.7. A) Documented changes to cottonwood abundances in the Oldman River Basin from the 1950s to the 1980s, along reaches upstream (upper) and downstream (lower) from the Belly River diversion weir (operational since 1935), Waterton River Dam (1964), and St. Mary River Dam (1951). The standard error for lineal measures is approximately < ± 5% and for area measures is about ± 20% (bold values indicate highly significant changes). **B)** Summary of magnitude of changes in cottonwood abundance using ranked categories (>10% = +2, 10 to 5% = +1, 5 to -5% = 0, -5 to -10 = -1, -10 to -20 = -2, <-20% = -3).

A)	**Percent change in the abundance of cottonwoods along:**					
	non-regulated reaches			**regulated reaches**		
	UBEL	UWAT	USTM	LBEL	LWAT	LSTM
Rood and Heinze-Milne 1989						
- 2D area (1961 to 1981)	-4.6	-6.1	-4.7	-0.1	**-22.9**	**-47.8**
Reid et al. 1992						
- lineal distance (1951-1985)	-7.4	-5.8	-7.2	+0.4	-9.0	**-73.7**
- lineal distance (1961-1981)	-4.5	-8.0	-7.1	-0.9	**-20.4**	**-45.4**
- 2D area (1951 to 1990)	-13.1	+4.7	-4.8	**+21.2**	+2.6	**-40.0**
Rood et al. 1995						
- 2D area (1951 to 1985)	-9.1	+1.9	-0.5	**+52.2**	+3.5	**-61**
- lineal distance (1951 to 1985)					-9.0	**-68**

B)	**Ranked change in abundance:**					
	non-regulated reaches			**regulated reaches**		
	UBEL	UWAT	USTM	LBEL	LWAT	LSTM
lineal distance:	-1	-1	-1	0	-2	-3
2D area:	-1	0	-1	+2	-1	-3
absolute value of total:	2	1	2	2	3	6
extent of change:	moderate	slight	moderate	moderate	severe	extremely severe

Abbreviations: UBEL = upper Belly River, LBEL = lower Belly River, UWAT = upper Waterton River, LWAT = lower Waterton River, USTM = upper St. Mary River, LSTM = lower St. Mary River

Along all three rivers, reduction of low flows has been associated with drought stress and declines in cottonwood forests. PRC flows address this situation by preventing reductions below naturally low flow levels. This flow adjustment should correct the symptoms of drought stress observed along the lower part of the Belly River. The PRC otherwise resembles the actual regulated flow regime along this reach.

Along the downstream reach of the Waterton River, reductions affecting medium and larger flows have also been implicated with negative impacts on riparian cottonwoods. The PRC would improve this situation by moderating those reductions. The combination of protected low flows and moderated reductions to larger flows along the Waterton test reach would be expected to remedy its declining condition.

Along the severely impacted lower part of the St. Mary River, natural flow variability has also been significantly altered. The PRC approach should correct this problem because it is based on natural flow variability. Thus, combined with protecting low flows and moderating reductions to larger flows, the more natural pattern and timing of flow variability proposed by the PRC should prevent further deterioration and enable the rehabilitation of riparian forests along the lower reach of the St. Mary River.

The part of the PRC that cannot be adequately evaluated, based on comparisons with the implemented flow regimes for these test reaches, is the reduction of peak flows that exceed 125% bankfull. It is not possible to infer the effects of such a change, because none of the flow regimes along the test reaches have been modified in this way.

7.7 Evaluating the PRC Criteria

7.7.1 Relative contribution of each PRC criterion

Results of comparisons between PRC flows and actual flow regimes along the selected test reaches (section 7.6) have generally supported the utility of the PRC for sustaining riparian cottonwood populations. A more detailed validation of the PRC is possible through the individual assessment of each of the five PRC criteria (Figure 7.8) whose exceedence curves form the basis of the final PRC (Figure 7.15). Each individual criterion influences a particular range of flows in the final PRC (Figure 7.16, Table 7.8). To evaluate each criterion, the flows in the affected exceedence range have been compared with the corresponding regulated flows implemented along the various test reaches. Based on these comparisons, flows proposed by each PRC criterion have been assessed relative to the effects they are likely to have on downstream cottonwood health as suggested by trends reported along the various test reaches. A summary of these assessments is presented in Table 7.9.

Table 7.8. The ranges of flow affected by each PRC criterion.

PRC Criteria:	Range of affected naturalized flow exceedence:
1) Naturalized Flow	100 - 90% Exceedence
2) Naturalized 90% Exceedence Flow	90 - 60% Exceedence
3) 65% of Naturalized Flow	50 - 70% Exceedence
4) 50% RI-shifted Naturalized Flow	5 - 60% Exceedence
5) 125% Bankfull Flow	0 - 10% Exceedence (during weeks 21 - 27)

Table 7.9. Summary comparing recorded flows along each test reach to flows required by each individual PRC criterion (++ exceeds PRC, + meets PRC , - fails PRC, and - - severely fails PRC).

(PRC Criteria)	UBEL	UWAT	USTM	LBEL	LWAT	LSTM
1. Natural Flow	-	+	-	- -	- -	- -
2. Natural 90% Exceedence Flow	+	+ +	-	- -	- -	- -
3. 65% Natural Flow	+ +	+ +	+	-	-	- -
4. 50%RI-shifted	+	+ +	-	-	-	- -
5. 125% Bankfull	+ +	+ +	++	++	++	++
Overall Ranking :	2	1	3	4	4	5
Change in forest abundance (Table 7.7)	moderate	slight	moderate	moderate	severe	extremely severe

Abbreviations: UBEL = upper Belly River, LBEL = lower Belly River, UWAT = upper Waterton River, LWAT = lower Waterton River, USTM = upper St. Mary River, LSTM = lower St. Mary River

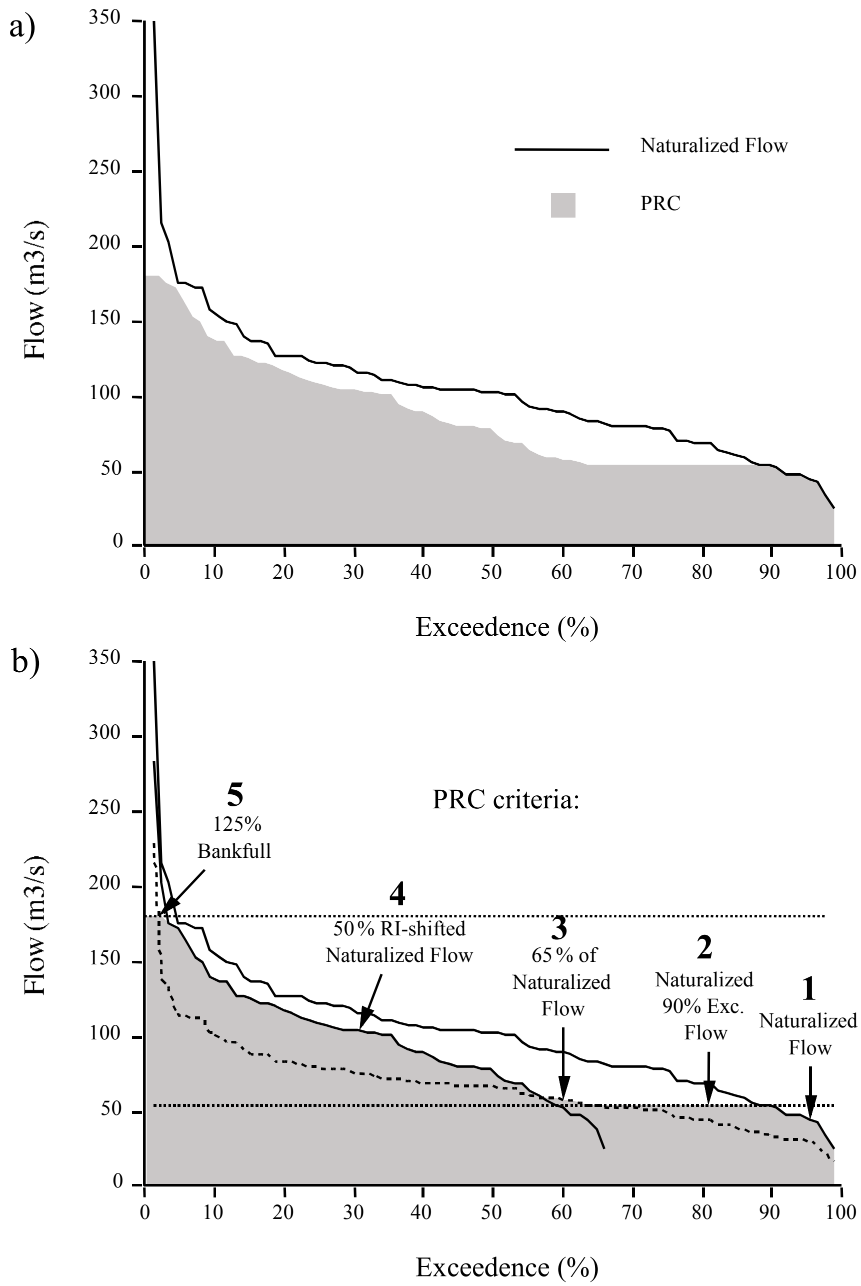

Figure 7.15. a) Example of a weekly PRC and a naturalized exceedence curve for flows along the St. Mary River near Lethbridge during Julian week 24, and **b)** individual exceedence curves for each criterion of the PRC.

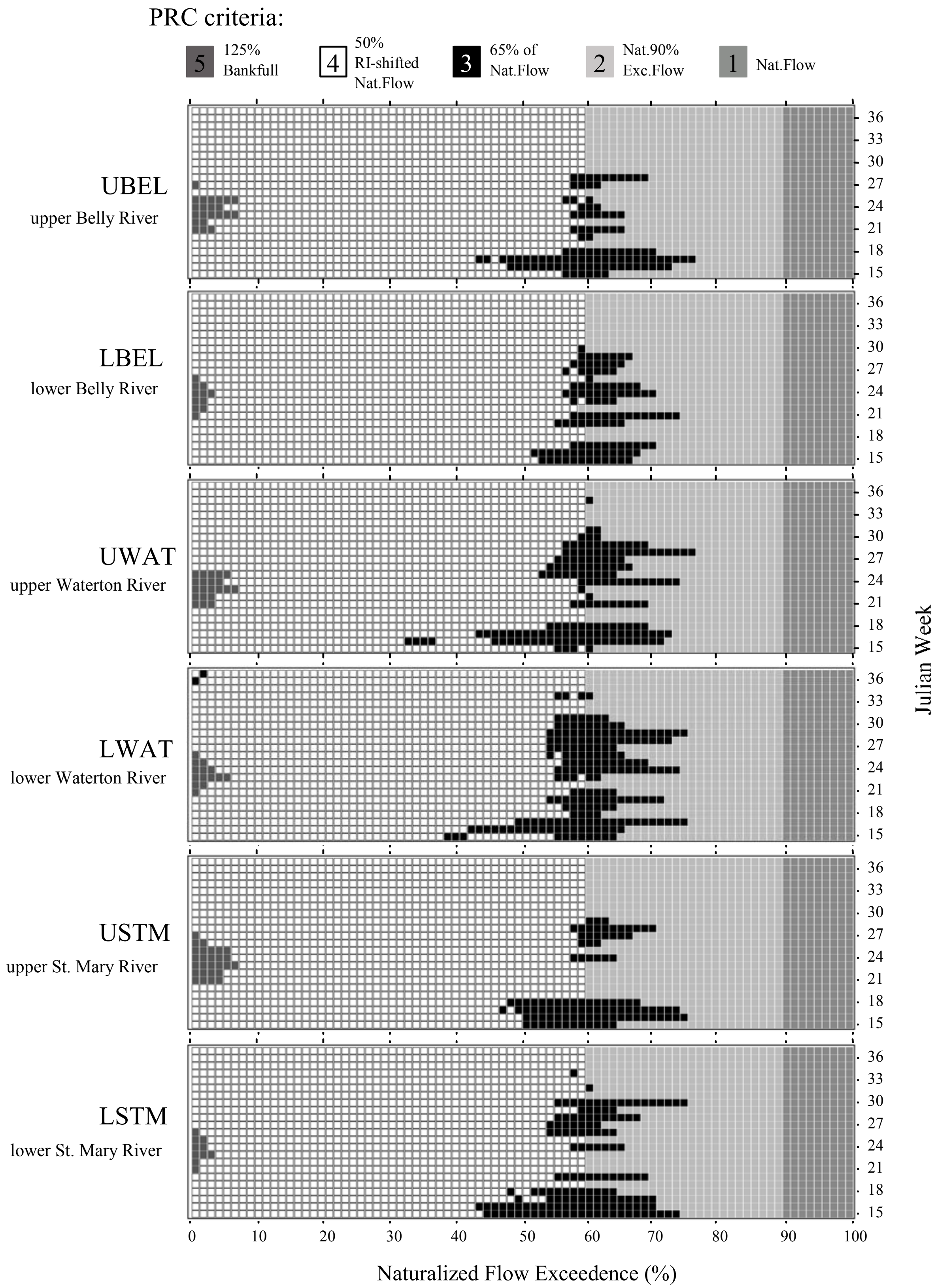

Figure 7.16. Ranges of naturalized flow affected by each PRC criterion for each test reach.

7.7.2 PRC criterion 1: Naturalized flow

PRC criterion 1 prevents reductions to natural low flows that have exceedences between 90 and 100% (Figure 7.16, Table 7.8). Natural 90% exceedence flows generally qualify as base flows because they are met or exceeded (on average) in 90% of years. The averaged magnitudes of reductions that have actually been made at each test reach within this category of minimum flows are summarized in the shaded portions of Figure 7.17. The PRC proposes no reductions to flows with natural exceedences in this range. Thus, the change to weekly flows (y-axis) would be 0% (dashed line) for exceedences between 90 and 100% (Figure 7.17b).

The upper reach of the Waterton River is unregulated, having no significant alterations to its flows, including those in the range from 90 to 100% naturalized exceedence. Thus, its flows meet the requirements for PRC criterion 1 (Table 7.9). In contrast, regulation along the other five test reaches has caused reductions ranging from about 20 to 95% to the already low flows, in the range from 90 to 100% natural exceedence (Figure 7.17b). The three downstream test reaches have been particularly severely impacted by greater than 80% reductions to these natural low flow events. This trend corresponds with the frequencies of acute drought stress reported along the lower reaches compared with the less-regulated upstream reaches, and suggests that this range of reduction to low flows is not acceptable in the PRC.

The magnitudes of flow reductions affecting natural 90 to 100% exceedence flows are generally comparable along the upper St. Mary and upper Belly rivers, ranging from about 20 to 40% reduction. However, signs of drought stress have been reported for cottonwoods along the upper St. Mary River and not along the upper Belly River. This disparity appears to be related to differences in flow reductions across the rest of the exceedence range (exceedences of < 90%), because overall weekly flow reductions along the upper St. Mary have been more severe than along the upper Belly (averaging 25% versus 10% respectively, un-shaded portion of Figure 7.17a). This trend suggests that although the maintenance of low flows is critical to cottonwood health, moderate and higher flows are also important. Additionally, the size and geomorphic context of the Belly River is quite different from that of the St. Mary River (Table 7.10) and these differences may affect the ultimate resiliency of each system to similar levels of flow reductions.

The moderate rate of 20 to 40% flow reduction affecting low flows along the upper Belly River, combined with lesser reductions (about 10%) to flows with exceedences less than 90%, are associated with no discernable drought stress in the affected riparian forests. However, along the upper St. Mary River, the same moderate rate of 20 to 40% flow reduction, extended over the full range of flow exceedences, has contributed to symptoms of drought stress. Considering that criterion 3 of the PRC allows marginally greater reductions (35%) than those experienced along the upper St. Mary River (30%) for moderate flows with 50 to 70% exceedence, reductions of more than 30% to low flows should be avoided. This will prevent reproducing the drought stress observed along the upper St. Mary River.

Criterion 1 of the PRC is conservative, permitting 0% reduction to flows between 90 and 100% natural exceedence. Based on the available evidence, reductions of up to about 30% may be acceptable if flows are conserved across the rest of the exceedence range. Conversely, the complete protection of these low flows would probably compensate to some extent for reductions made to moderate and higher flows.

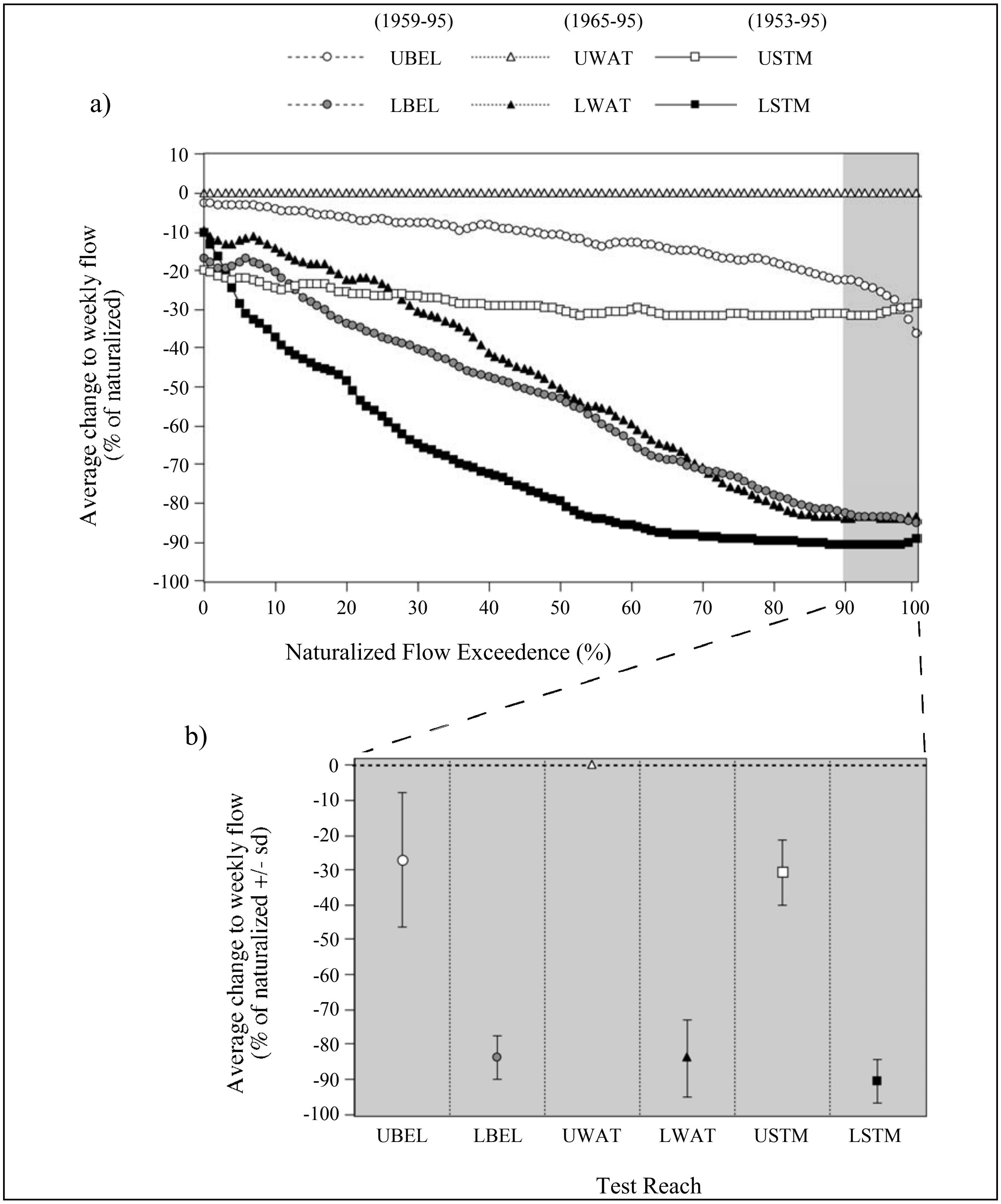

Figure 7.17. a) Average change from naturalized to actual weekly flows for each 1% exceedence interval during the growing season (Julian weeks 15-37) for a series of flow-regulated years. **b)** Summary of changes to flows between 90 and 100% naturalized exceedence (shaded areas), corresponding with flows affected by PRC criterion 1 along each test reach (UBEL/LBEL = upper/lower Belly River, UWAT/LWAT = upper/lower Waterton River, USTM/LSTM = upper/lower St. Mary River).

Table 7.10. Assessments of riparian forest abundances along various tributaries of the SSRB in the 1880s, 1950s, 1980s, and late 1990s using historic surveys and aerial photographs (reach equivalents in this study: SM1 = upper St. Mary River, SM2 = lower St. Mary River, BL1 = upper Belly River, BL2 = lower Belly River, W1 = lower Waterton River).

			-----------1980s-----------						General
		Length	Floodplain	Channel	Riparian Poplar Density:				Change
River:	**Reach:**	**(km)**	**Width (m)**	**Type**	**1880s**	**1950s**	**1980s**	**1997-99**	**1880-1999**
St. Mary	SM1	25.4	300-700	FM	3 to 5		4	4	
	SM2	115.51	200-(1000)	CM	2		1	1	-
Belly	BL1	28.82	300-500	FM	3 to 5		3	3	-
	BL2	48.81	500-1200	FM	2		5	5	+
(below inflow	BL3	37.59	1000-1500	FM-BR	3 to 5		4	4	
of Waterton R.)	BL4	34.74	700-1500	FM	3 to 5		3	3	-
Waterton	W1	75.31	500-700	FM	3 to 5		3	3	-
Oldman	OM1	17.26	200-500	FM	3 to 5	2	2	2	-
	OM2	98.82	1500-1700	BR-FM	3 to 5	5	5	5	+
	OM3	21.28	200-1000	ST	3 to 5	2	2	2	-
	OM4	61.93	500-2000	FM-CM	3 to 5	4	4	4	
	OM5	78.64	300-2000	CM-FM	2	2	2	2 to 3	
	OM6	62.08	300-700	ST-CM	2	1	1	1	-
S. Sask.	S1	197.2	200-3000	ST-CM-FM	2	2	2	2	
	S2	35.95	200	ST		1	1	1	
	S3	54.89	200-750	ST-CM		1	2	1 to 2	+
Red Deer	R1	22.86	200-300	CM		3	3	2	-
	R2	32.06	300-400	CM		2	2	2	
	R3	32.13	200-400	CM-ST	1	3	3	3	+
	R4	39.98	100	CM-ST	2	2	2	2	
	R5	16.48	300-500	CM	2	3	3	3	+
	R6	78.23	500	CM	3 to 5	4	4	4	
	R7	37.14	200-300	CM-ST	1	3	3	3 to 4	+
	R8	51.33	500-1300	CM-FM	2	3	4	3 to 4	+
	R9	18.45	300-500	ST-CM		3	3	3	
	R10	37.99	1000-1500	FM-BR		3	3	3 to 4	
Bow	B1	42.58	300-1500	FM-CM	3 to 5	3	3	3	-
	B2	38.86	500-1500	FM-BR	3 to 5	4	4	4	
	B3	48.14	500-2500	FM-BR	3 to 5	4	5	5	
	B4	36.26	500-1000	FM	3 to 5	3	3	3	-
	B5	60.38	200-500	ST	1	2	2	2	+
	B6	55.79	200-500	ST	1	1	1	1	
	B7	41.39	200-500	ST	1	1	1	1	
	B8	23.22	200-500	ST	2	2	2	2	

(1880-1980 content adapted from Bradley et al. 1991)

Channel Type categories:
FM = freely meandering ST = straight
CM = confined meandering BR = braided

Density categories:
1 = none / negligible
2 = sparse 4 = dense
3 = moderate 5 = very dense

7.7.3 PRC criterion 2: Naturalized 90% exceedence flow

PRC criterion 2 allows flows to be reduced only to the naturalized 90% exceedence flow. This criterion generally affects flows with naturalized exceedences between 90 and about 60% (Figure 7.16, Table 7.8). A comparison of regulated (actual) weekly flows and natural 90% exceedence flows is summarized for each test reach in Figure 7.18. The shaded portions in this figure encompass the exceedence range that is generally affected by PRC criterion 2 (natural 60 to 90% exceedence). Flows greater than the 90% exceedence flow are recorded as positive values; flows less than the 90% exceedence flow are negative.

The six test-reaches show considerable variation relative to 90% exceedence flow levels (Figure 7.18b). On average, 60 to 90% exceedence flows along the upstream reaches of the Waterton and Belly rivers have remained greater than natural 90% exceedence flows. The same group of flows along the upper portion of the St. Mary River has averaged about 15% less than the 90% exceedence flow level. Flows along the lower reaches of the Belly and Waterton rivers have had reductions between 50 and 80%, relative to natural 90% exceedence flow levels. Flows along the lower reach of the St. Mary River average even less, showing 90% reductions below natural 90% exceedence flow levels. The magnitudes of reductions below natural 90% exceedence flow levels correspond closely with the increasingly poor state of riparian forest health across the six test reaches (Table 7.7).

Declining riparian cottonwood health along the lower test reaches suggests that the 50% or greater reductions in streamflow below natural 90% exceedence flows (in the range from 60 to 90% exceedence) recorded along the lower reaches will not support riparian cottonwoods. Similar to the logic developed in evaluating PRC criterion 1, a 'safe' level of reduction for flows affected by criterion 2 is likely between that recorded along the upper part of the Belly River (where forests are healthy) and the upper St. Mary River (where forests are showing symptoms of drought stress). The PRC criterion 2 proposal of 0% reduction to 90% exceedence flows (dashed line in Figure 7.18b) falls within this range and is thus justified. Reductions greater than 10% are discouraged to avoid duplicating the stressed condition of riparian cottonwoods along the upper reach of the St. Mary River.

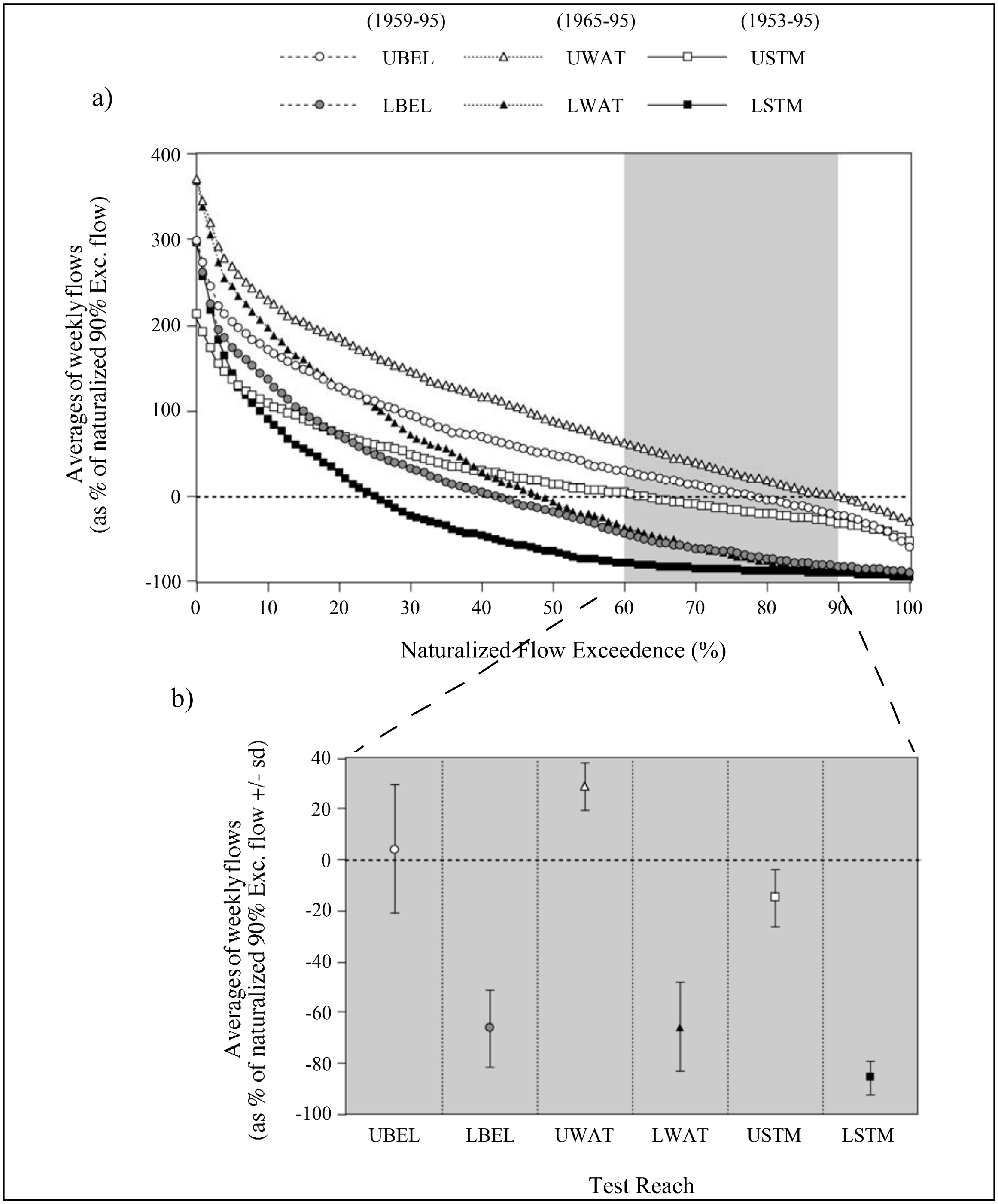

Figure 7.18. a) Average actual weekly flows relative to naturalized 90% exceedence flows for each 1% exceedence interval during the growing season (Julian weeks 15-37) for a series of flow-regulated years. **b)** Averages of actual weekly flows relative to naturalized 90% Exc. flows between 60 and 90% naturalized exceedence (shaded areas), corresponding with flows affected by PRC criterion 2 along each test reach (refer to Figure 7.17 for abbreviations).

7.7.4 PRC criterion 3: 65% of naturalized flow

PRC criterion 3 proposes a 35% reduction to flows with natural exceedences between about 50 and 70% (Figure 7.16, Table 7.8). The average magnitude of reductions that have been actually made at each test reach within this category of flows is summarized in the shaded portions of Figure 7.19 (the 35% reduction permitted by criterion 3 is indicated by the dashed line). All the upper test reaches have averaged less than this 35% reduction (Figure 7.19b). Flow reductions along the upper St. Mary closely parallel the 35% value. Flow reductions recorded along the lower Belly and lower Waterton reaches range between 40 and 80%. Along the lower St. Mary, reductions are even more severe, ranging from 80 to 90%.

As was the case for PRC criterion 1 and 2, flow modifications recorded along the upper reach of the St. Mary River probably coincide with the threshold of reduced flows that can still maintain healthy cottonwoods. The 35% flow reduction permitted by PRC criterion 3 is slightly more severe than the average 30% reduction that has occurred along the upper St. Mary reach. Combined with the conservative approaches of criterion 1 and 2, this more moderate reduction may still be reasonable in the PRC. However, reductions greater than 40% are expected to be increasingly detrimental, as evidenced along the lower reaches of the Waterton River and the St. Mary River in particular.

Although setting a valid limit to the level of flow reduction that will maintain the health of riparian cottonwoods, the value for criterion 3 should also provide a gradual 'bridge' between the exceedence curves of criterion 2 and 4 (Figure 7.15b). This will ensure that the natural pattern of flow variability intrinsic to the natural functioning of the system will also be preserved. In about one third of growing season weeks, criterion 3 does not register in the PRC (Figure 7.16). In these instances, the intended gradual transition between criterion 2 and 4 is absent. The adjustment of criterion 3 from 65% to 70% naturalized flow may correct this anomaly and also lessen flow reductions that would otherwise be equivalent to the marginal flow conditions along the upper St. Mary River.

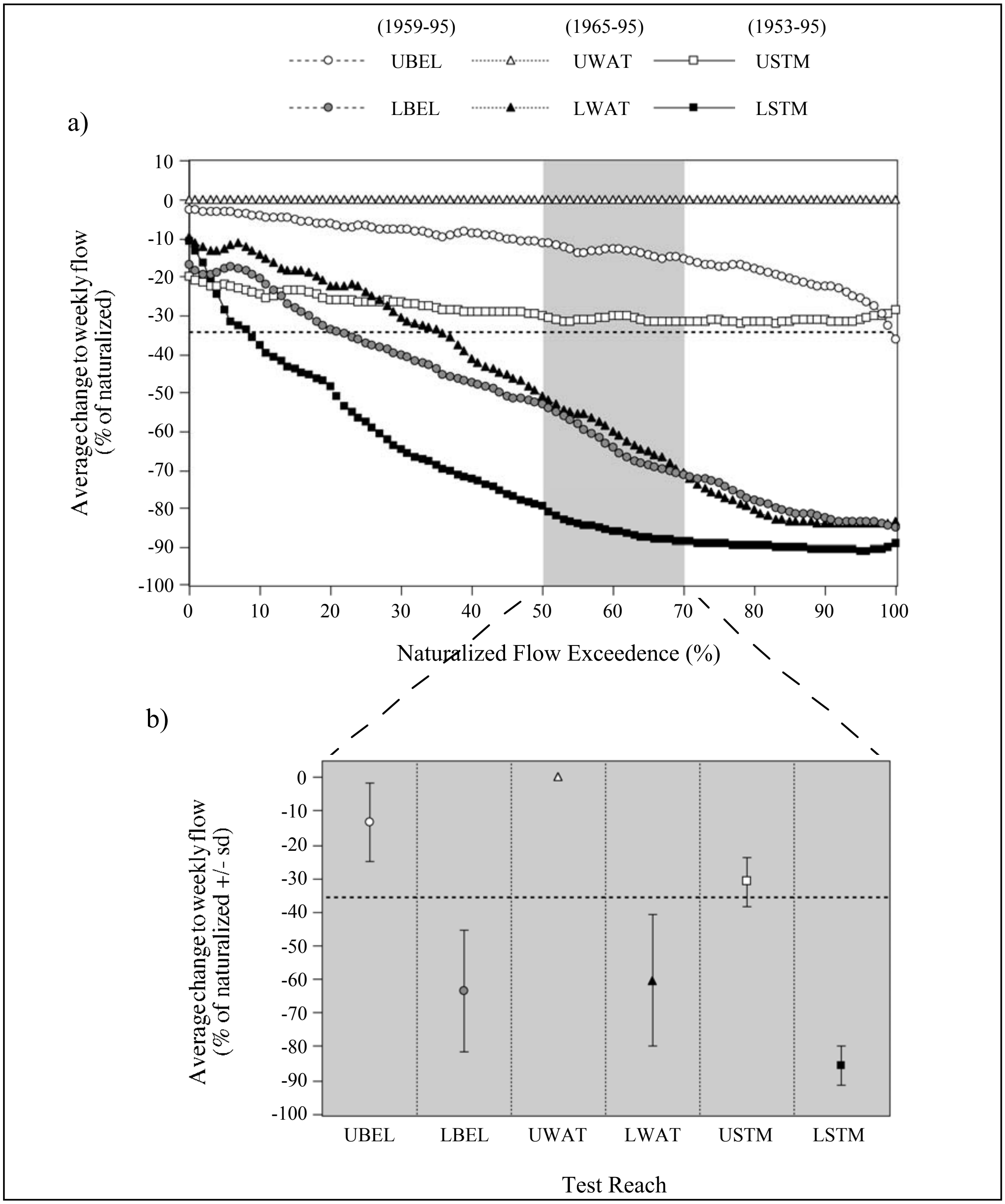

Figure 7.19. a) Average change from naturalized to actual weekly flows for each 1% exceedence interval during the growing season (Julian weeks 15-37) for a series of flow-regulated years. **b)** Summary of changes to flows between 50 and 70% naturalized exceedence (shaded areas), corresponding with flows affected by PRC criterion 3 along each test reach (refer to Figure 7.17 for abbreviations).

7.7.5 PRC criterion 4: 50% return interval-shifted naturalized flow

PRC criterion 4 would allow flow reductions equivalent to a 50% increases of return interval. This criterion defines the broad portion of the PRC between about 5% and 60% naturalized exceedence (Figure 7.16), and so affects mainly average and greater weekly streamflows. The actual RI shifts recorded during a selection of flow regulated years along each test reach are summarized in Figure 7.20. Here, the range of influence of criterion 4 is shaded. The threshold RI shift of 50% is indicated by a dashed line.

RI shifts have been consistently greater along the lower reach compared with the upper reach of each river. The RI shifts recorded along the lower St. Mary have been the most severe, averaging greater than 200% (Figure 7.20b). Shifts along the lower Belly, lower Waterton, and upper St. Mary have been moderately severe, averaging between 100 and 200%. RI shifts along the upper Waterton and upper Belly have been much smaller, averaging less than 50%. Thus, increasing magnitude of RI shifts correlates with decreasing riparian forest health along the test reaches (Table 7.7).

RI shifts are not solely responsible for trends in decreasing riparian forest health. Among the six test reaches, declines in cottonwood abundance and general health have been most closely associated with reductions to low flows. A test reach where low flows remain completely unchanged, while moderate and larger flows are altered, is not available to isolate the effects of modifications to greater flows. However, lower flows (naturalized 60 to 100% exceedence) along the upper reaches of the Waterton, Belly, and St. Mary rivers have been less altered than along the lower reaches (Figures 7.17, 7.18). In particular, the slight reductions that have been made to these low flows along the upper Belly and upper St. Mary reaches are similar, making these reaches good candidates for evaluating the effects of changes made to larger flow events.

Riparian cottonwoods along the upper reach of the Belly River are in reasonably good health, whereas those along the upper reach of the St. Mary River show signs of stress and increased seedling mortality (Reid et al. 1992). Considering that the slight reductions to low flows along both reaches have been relatively similar, this difference in cottonwood health and reproductive success could be related to differences in modifications to larger flows. The large RI shifts of 100 to 300%, relative to naturalized return intervals that have been recorded along the upper St. Mary River, suggest a threshold of tolerable reductions to larger flows. The shifts of less than 50% recorded for the upper Belly River probably represent a more acceptable range (Figure 7.20). Because the 50% RI shift permitted by the PRC (dashed line in Figure 7.20) is slightly greater than shifts recorded for the upper Belly River, this value is likely acceptable in the overall PRC. Due to the scarcity of controls among the test reaches, it is not possible to determine with certainty a level of flow reductions beyond the 50% RI shift threshold that would be safe for maintaining riparian cottonwoods.

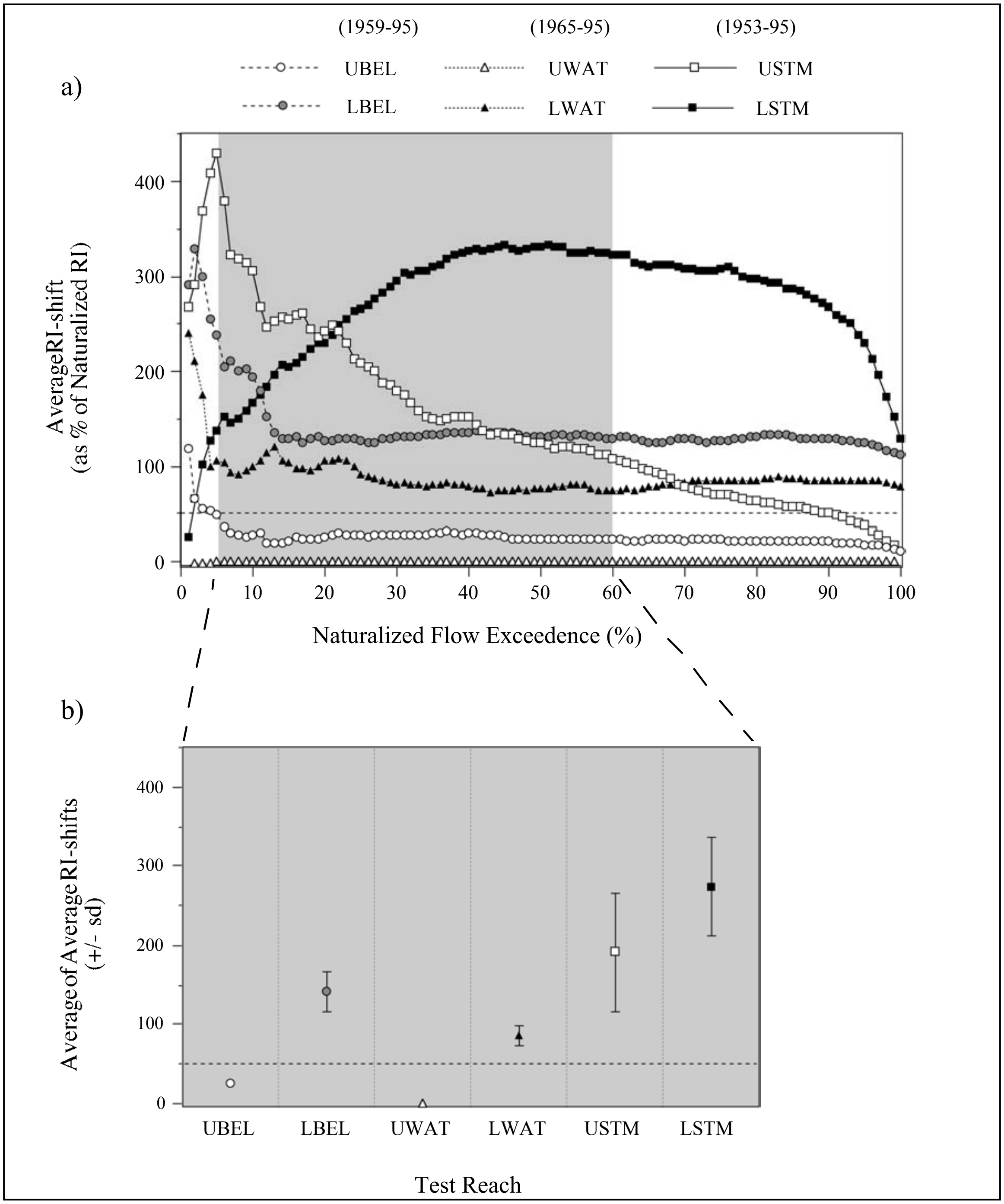

Figure 7.20. a) Average return interval shifts from actual to naturalized weekly flows for each 1% exceedence interval during the growing season (Julian weeks 15-37) for a series of flow-regulated years. **b)** Summary of changes to return interval shifts of flows between 5 and 60% naturalized exceedence (shaded areas), corresponding with flows affected by PRC criterion 4 along each test reach (refer to Figure 7.17 for abbreviations).

7.7.6 PRC criterion 5: 125% bankfull flow

PRC criterion 5 would permit high flows to be limited to the weekly equivalent of instantaneous 125% bankfull discharge (Figure 7.16, Table 7.8). Instantaneous bankfull discharge is the flow magnitude required to completely fill the active channel. This value varies across reaches as it relates to the physical dimensions of the cross-section of each channel.

A weekly equivalent for 125% instantaneous bankfull discharge was required in criterion 5 to accommodate the PRC weekly exceedence curve. The weekly time-step used in the PRC is not compatible with the naturally shorter duration of greater than bankfull flows that often last only one to three days. This complicates the selection of a weekly equivalent for instantaneous 125% bankfull flows. For the purposes of this report, weekly 125% bankfull flow values have been estimated based on historic data where flows of instantaneous 125% bankfull magnitude occurred at least once. The instantaneous 125% bankfull value and its weekly equivalent, used in calculating the PRC, are presented in Table 7.5 for each test reach. Based on these weekly estimates of 125% bankfull flow, PRC criterion 5 would affect flows with naturalized exceedences less than 10% (Table 7.6) during weeks of peak annual streamflow, usually Julian weeks 21 through 27 (Figure 7.16) that correspond with the last week of May through the first week of July.

Natural peak flows equivalent to 125% bankfull magnitude or greater occur infrequently along the Southern Tributaries of the Oldman River (< 1 in 10 year recurrence during peak flow weeks). Considering the relatively short period of available flow records (< 50 years), the evaluation of this value based on the test reaches is problematic. Historic reductions to natural peak flows greater than 125% bankfull have occurred to a limited extent along the test reaches (Figure 7.21). Test cases where this criterion has not been met are not available for analysis because flow regulation has not generally reduced these peak flows below the 125% bankfull level (Table 7.9). Thus, it is not possible to verify the 125% bankfull value directly along the test reaches. Even the most severely impacted reach, the lower St. Mary River, has not had peak flows reduced to this extent. A qualitative approach, to overcome the lack of specific quantitative data, has been used to assess the level of peak flows necessary for preserving functional riparian forests.

The importance of peak flows to cottonwoods (as detailed in Section 7.4.3) is mainly related to riparian water table recharge and the geomorphic processes that prepare nursery sites for cottonwood seedling establishment. As such, long-term reductions to these peak flows may cause drought stress to trees in marginal areas and to seedlings or saplings that lack well-established root systems. Reductions to peak flows may also interrupt natural patterns of nursery site formation, resulting in less frequent opportunities for successful seedling establishment. Because channel and floodplain topography and the elevational distribution and composition of riparian forests are highly variable, the choice of a maximum peak flow could have complex and varied effects on riparian and aquatic ecosystems. The implications of 125% bankfull as a maximum flow needs to be further investigated. Therefore, the physical parameters that define cottonwood requirements for high flows need to be investigated along each test reach to better define acceptable reductions for peak flows in each case.

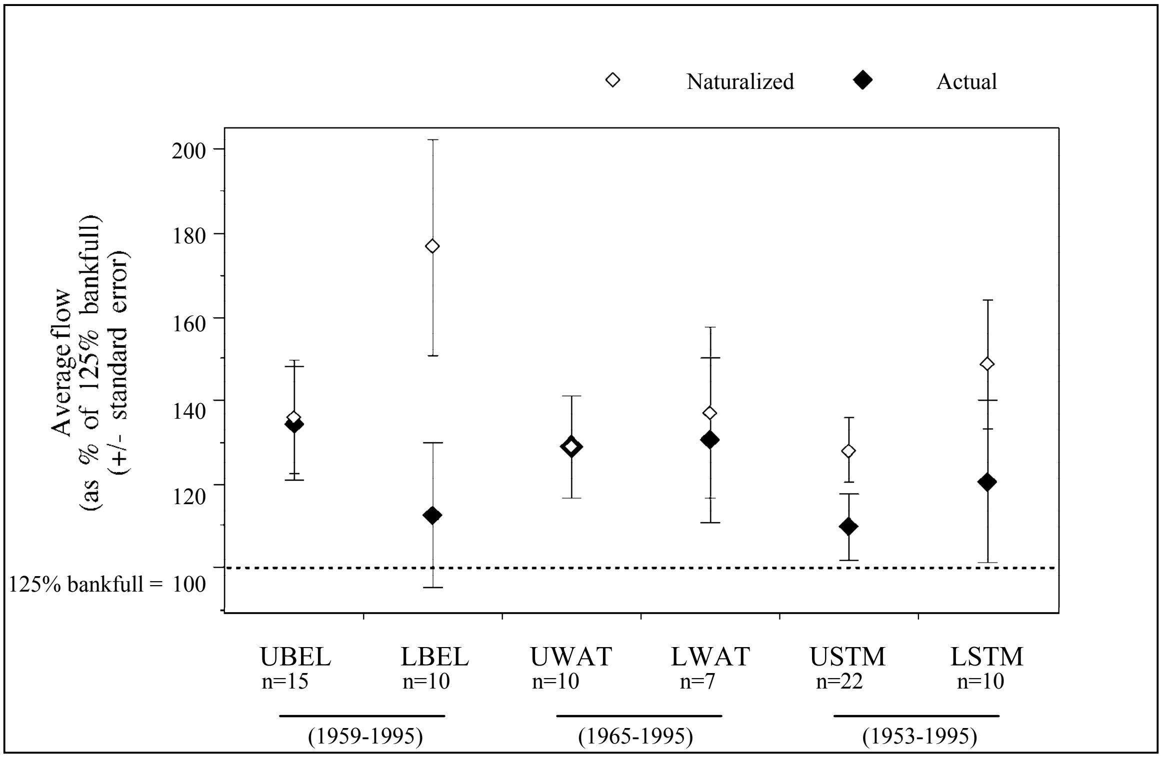

Figure 7.21. Comparison of naturalized weekly flows greater than 125% bankfull with their corresponding actual weekly flows (recorded during flow-regulated years for each test reach). The number of flows incorporated into each set of averages is indicated under the x-axis labels. (UBEL/LBEL = upper/lower Belly River, UWAT/LWAT = upper/lower Waterton River, USTM/LSTM = upper/lower St. Mary River).

7.7.7 Summary of evaluation of PRC criteria

PRC criterion 1 protects flows below the naturalized 90% exceedence level. Occasional, slight reductions (<30%) to flows in this exceedence range alone might not be seriously harmful. However, combined with moderate reductions to larger flows, there is an increasing likelihood of inducing chronic drought stress in downstream forests.

PRC criterion 2 would prevent reductions below naturalized 90% exceedence flow. Similar to the case for criterion 1, occasional, slight reductions below the 90% exceedence threshold may not have serious consequences. However, reductions greater than 10% may not be acceptable.

The assessment of PRC criterion 3 suggests that although the 35% reduction might be adjusted to 40% without harming riparian forests, such a reduction would prevent PRC criterion 3 from providing a gradual transition between criteria 2 and 4. The resultant exceedence curves would have an unnatural step function imposed in this range. This would somewhat negate the effort to maintain the inter-annual variation of the natural system. Thus, the 35% flow reduction allowed by criterion 3 should only be altered in concert with a similar adjustment in the exceedence curve for criterion 4.

PRC criterion 4 permits flow reductions equivalent to a 50% increase in return interval. Based on the trends in riparian poplar health along the test reaches, this value seems generally acceptable. Due to the variability among the reaches, it is not clear if a further reduction would still be adequate for maintaining healthy downstream forests. Without additional evidence from other test-reaches, the limit of 50% increase in RI should be maintained.

PRC criterion 5 would permit peak flows to be limited to 125% bankfull. Considering that actual reductions to flows beyond this magnitude have been relatively minor along the test reaches, the appropriateness of the 125% bankfull value as a maximum in the PRC cannot be verified using these test cases. This criterion is the only part of the PRC that is defined by an absolute value calculated without reference to the historic flow record. The 125% bankfull value is recommended only as an initial approximation. It requires further consideration on a reach-specific basis. The high flow criteria may be better estimated through other evaluation metrics, such as those for maintaining channel dynamics (Section 8).

The individual assessments of the five PRC criteria (summarized in Table 7.9) have generally supported their use in the PRC approach to meeting the flow requirements of riparian cottonwoods in the SSRB. Trends observed along the test reaches suggest that only minor revisions to any of the criteria used in calculating the overall PRC could be made safely.

7.8 Applicability of PRC flows for other systems:

As discussed previously, the details of a PRC-based recommendation may be altered by the particular fluvial, hydrological, geomorphic, and biological characteristics of a river. The foregoing discussion is related to a specific area within the South Saskatchewan River Basin. Although the evaluation of the PRC indicates it is appropriately suited for implementation within the Oldman River sub-basin, the diversity of fluvial systems within the South Saskatchewan River Basin suggests the detailed criteria may not be directly applicable to all reaches. A general assessment of the availability of site-specific data required for the PRC approach for each reach being evaluated in the SSRB WMP is provided in Figure 7.22. The riparian evaluation is based on the availability of hydrology data, such as the bankfull discharge, as well as site-specific poplar biology information.

The Red Deer River sub-basin can be considered to be the fluvial system most distinct from the Oldman River sub-basin. Should an assessment of the PRC with respect to the Red Deer River indicate it is reasonably suited for implementation there, it might considered acceptable for implementation in the South Saskatchewan River Basin in general.

Recent work by Cordes et al. (1997) identified several hydrological characteristics that must be met to sustain the long-term viability of the riparian forests along the Red Deer River. Included within their evaluation were the following recommendations to help mitigate the decline of cottonwoods along the Red Deer River:

- Preserve the magnitude, timing and duration of greater than 1 in 5 year flood flows and attenuate large floods to no lower than 1 in 20 year discharge (the minimum flood flow that is required for maintaining recent levels of regeneration);
- Do not modify very high floods, of greater than 1 in 50 year magnitude (flows are necessary for widespread regeneration);

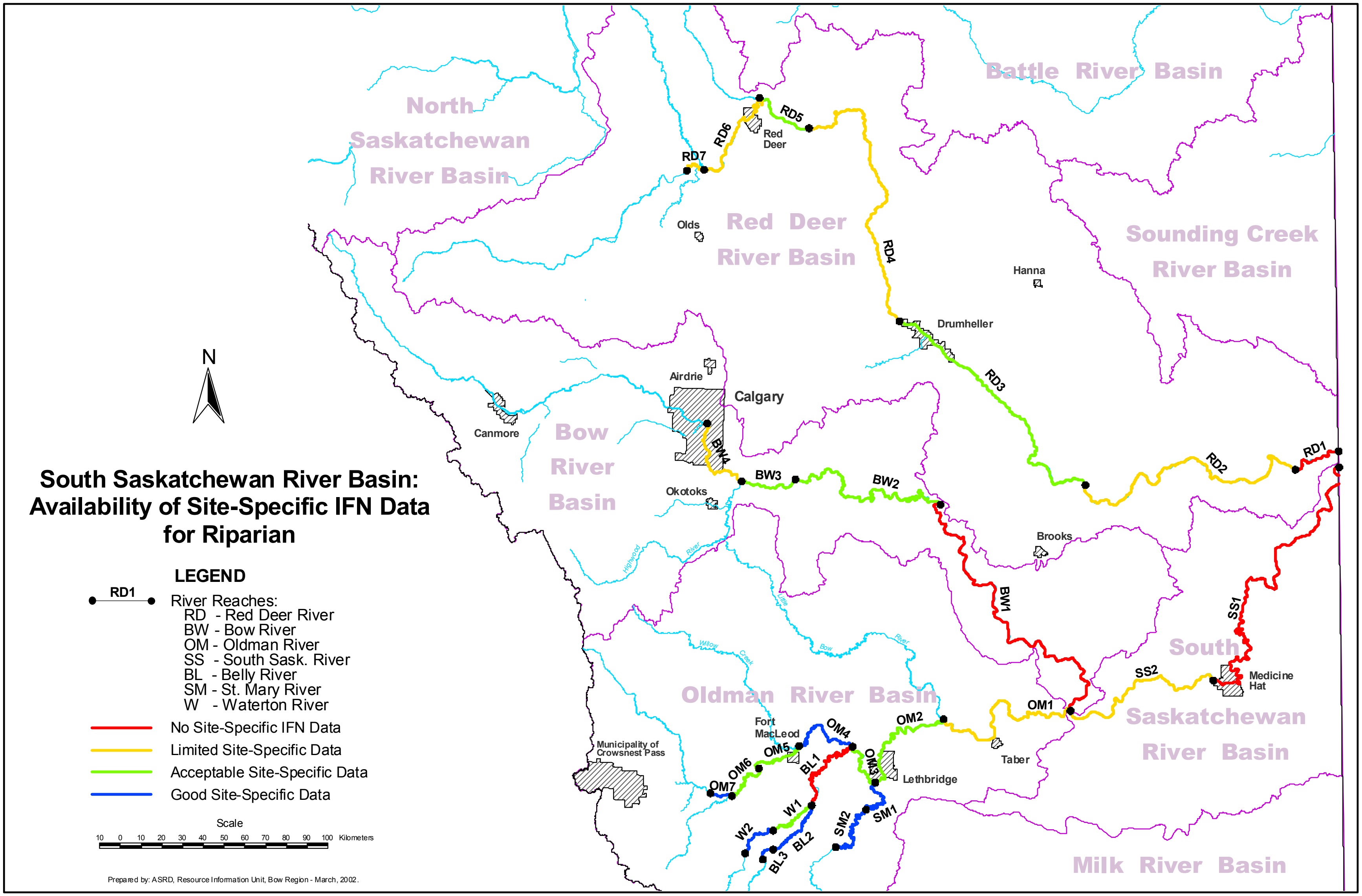

Figure 7.22. Availability of site-specific data required to develop a PRC for every reach in the SSRB WMP evaluation.

- Following greater than 1 in 10 year floods, leave flows unaltered for the rest of that year and the next, to maintain moisture levels for seedling survival; and
- Always maintain minimum flows during the ice free period to prevent stress.

In his critique of Cordes et al. (1997), Rood (1997) re-emphasizes the importance of the 1 in 10 to 1 in 100 year flood flows for floodplain processes and cottonwood seedling recruitment along the Red Deer River. Additionally, Rood (1997) suggests that a gradual rate of flow decline, following the peak of flood flows, may be as important or more important than the magnitude of the flood peak. A flow decline rate of 2.5 cm per day should allow seedling root growth to keep pace with the receding water table (Mahoney and Rood 1998), thus improving seedling survival by reducing the incidence of drought stress. Rood (1997) also suggests that clonal propagation may provide a natural buffer to compensate for periods that are less conducive for seedling based regeneration.

Considering the above values, the PRC approach to determining IFN for riparian cottonwood forests seems appropriate for managing cottonwood forests along the Red Deer River. The PRC has provisions for protecting minimum flows, natural seasonal flow variability, and some degree of flooding. Probably the most important issue for cottonwoods along the Red Deer River is the inadequate level of seedling replenishment. Successful seedling recruitment generally requires high springtime flows, to prepare nursery sites, followed by gradual flow recessions to promote seedling root growth and prevent drought stress. The PRC should provide sufficient flows for daily operations to be successful in providing these types of conditions at a natural frequency.

In the case of the Red Deer River, reductions to peak flows have been associated with insufficient seedling replenishment. Thus, it would be essential to verify the 125% bankfull limit to peak flows. The 125% bankfull values for the test reaches are generally equivalent to a 5% weekly exceedence flow (Table 7.6). These 1 in 20 year flood discharge events approximate the flood levels advocated by Cordes (1997).

Additional detailed work is required to confirm the suitability of the PRC approach for supporting riparian cottonwoods within the Red Deer River sub-basin. This initial assessment suggests the PRC would be a good first step in providing instream flows to meet the needs of riparian cottonwoods along this river in particular, and within the South Saskatchewan River Basin in general.