Appendix I

Riparian Vegetation Methods for the Watershed Flow Evaluation Tool

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RIPARIAN VEGETATION METHODS FOR THE WATERSHED FLOW EVALUATION TOOL

A report to the Non-Consumptive Needs Committee of the Colorado Basin Roundtable

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EXECUTIVE SUMMARY

Riparian vegetation is a key element of riverine ecosystems, providing many ecological, aesthetic and economic benefits, including terrestrial wildlife habitat structure, food resources, stabilizing geomorphic properties along banks and floodplains, and energy subsidies to aquatic and terrestrial ecosystems (Pusey and Arthington 2003). Riparian vegetation composition, structure and abundance are governed to a large degree by river flow regime and flow-mediated fluvial processes (Merritt et al. 2009). Streamflow regime exerts selective pressures on riparian vegetation, resulting in adaptations to specific flow attributes (Merritt et al. 2009), and riverine species have evolved life history strategies primarily in direct response to natural flow patterns (Bunn and Arthington 2002). Widespread modification of flow regimes by humans has resulted in extensive alteration of riparian vegetation communities (Merritt et al. 2009). Altered flow regimes may cause changes in plant species richness (Jansson et al. 2000, Nilsson and Svedmark 2002), plant growth and productivity (Stromberg & Patten, 1990), community composition (Merritt & Cooper, 2000; Merritt & Wohl, 2006) and loss of riparian forests (Rood & Mahoney, 1990; Braatne et al., 2007).

The Roaring Fork Pilot WFET (Watershed Flow Evaluation Tool) developed a quantitative relationships between flow alteration and riparian vegetation using many literature sources (Wilding and Poff 2008). The source literature covered a diverse range of vegetation types, including cottonwood, willow and herbaceous plants. In response to feedback received on the pilot as well as peer-review comments received during and after an expert workshop, this report refines the approach and narrows the application of the flow-riparian relationship. Specific changes and refinements to the methods used in the Roaring Fork pilot include:

1) Flow-ecology relationships are now described for three riparian types: i) cottonwoods on low- and moderate-gradient, meandering (open, or unconfined) rivers, ii) cottonwoods in moderate-gradient rivers of confined valleys and high-gradient rivers in unconfined valleys, and iii) willows in low-gradient, unconfined valleys.
2) Quantitative flow-ecology relationships were developed only for the two cottonwood types. Despite some evidence of willow dependence on floods (Cooper et al. 2006), we lacked

sufficient data to quantify this dependence over a range of flow alteration. For willows, the flow ecology relationship is described only conceptually.

3) Flow-ecology relationships are now applied only in the specific elevation ranges and select geomorphic settings where that relationship is expected to exist.
4) A new, large data set on cottonwoods (Merritt and Poff 2010) allowed for development of a robust quantitative flow-ecology relationship for cottonwoods in low-gradient, unconfined geomorphic settings.
5) Flood magnitude alteration is calculated only in the 30% of years with the highest mean annual flow.
6) No hydrographs are developed based on break-points between risk classes, in contrast to the Roaring Fork pilot.

Riparian Flow-Ecology Curves Recommended for Application in the Colorado WFET

Cottonwood in Unconfined (wide valley) settings

Geomorphic setting where applied: Moderate-energy unconfined, Low-energy floodplain, and Glacial trough. *Elevation where applied*: <9600 feet

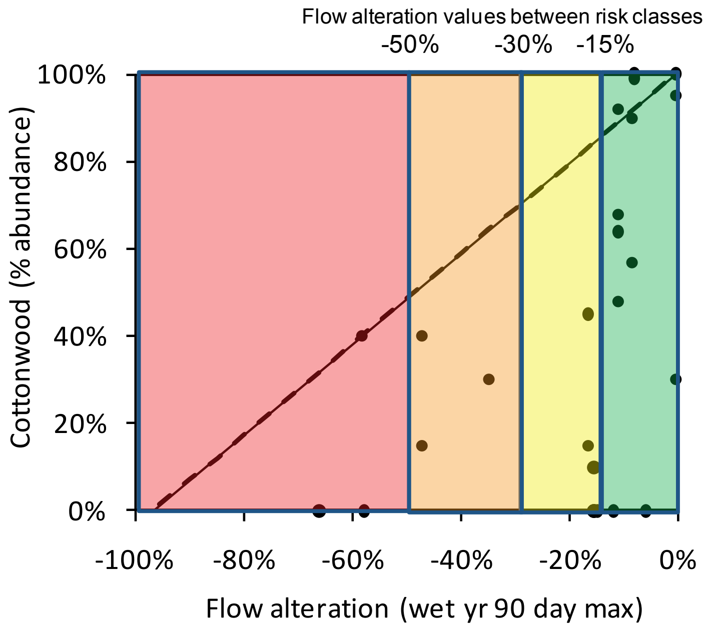
Two quantitative flow-ecology relationships exist for cottonwood in unconfined settings, one for adult cottonwood abundance and the other for cottonwood recruitment.

Adult cottonwood – The hydrologic metric for adult cottonwood is the change in average 90-day maximum flow in wet years only between current and undeveloped scenarios. "Wet years" are those in the top 30th percentile for mean annual flow in the undeveloped flow time series. Cottonwood abundance is calculated as:

- If flow alteration is >0% (i.e. flow augmentation) then cottonwood abundance = 100%
- If flow alteration is ≤0% then %abundance = 1.038 x %flow alteration + 1.005.

Risk classes:

Risk Class	Flow alteration	Justification for change to next higher risk class
Low	0 to -15%	Natural break in data—beyond flow alteration of -15%, no abundance greater than approximately 45%.
Moderate	-15% to -30%	Twice the risk of 'low'.
High	-30% to -50%	Natural break in data—only one non-zero value at flow alteration beyond ->50%
Very High	-50% to -100%	No data beyond flow alteration of more than -70%.



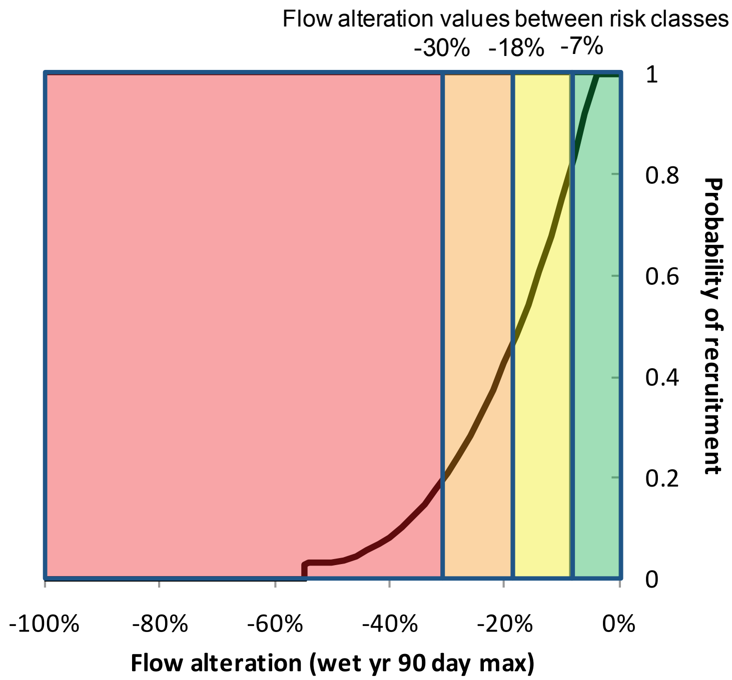
Flow-ecology relationship and risk classes for adult cottonwood in low- and moderate-gradient, unconfined settings.

Cottonwood recruitment – The hydrologic metric is the same as for adult cottonwood and is also calculated for only wet years. The probability of cottonwood recruitment is calculated as:

- If flow alteration is 0% to -4% then recruitment = 1.
- If flow alteration is -4% to -55% then recruitment = 2.91 x %flow alteration^3 + 7.27 x %flow alteration^2 + 5.26 x %flow alteration + 1.21.
- If flow alteration -55% to -100% then recruitment = 0.

Risk classes:

Risk Class	Flow alteration	Justification for change to next higher risk class
Low	0 to -7%	At flow alteration of -7%, probability of recruitment is reduced to 0.9.
Moderate	-7% to -18%	At flow alteration of -18%, probability of recruitment is reduced to 0.5.
High	-18% to -30%	At flow alteration of -30%, probability of recruitment is reduced to 0.2.
Very High	-30% to -100%	At flow alteration of -30% to -55%, probability of recruitment is less than 0.2.



Flow-ecology relationship and risk classes for cottonwood recruitment in low- and moderate-gradient, unconfined settings.

Cottonwood in Confined settings

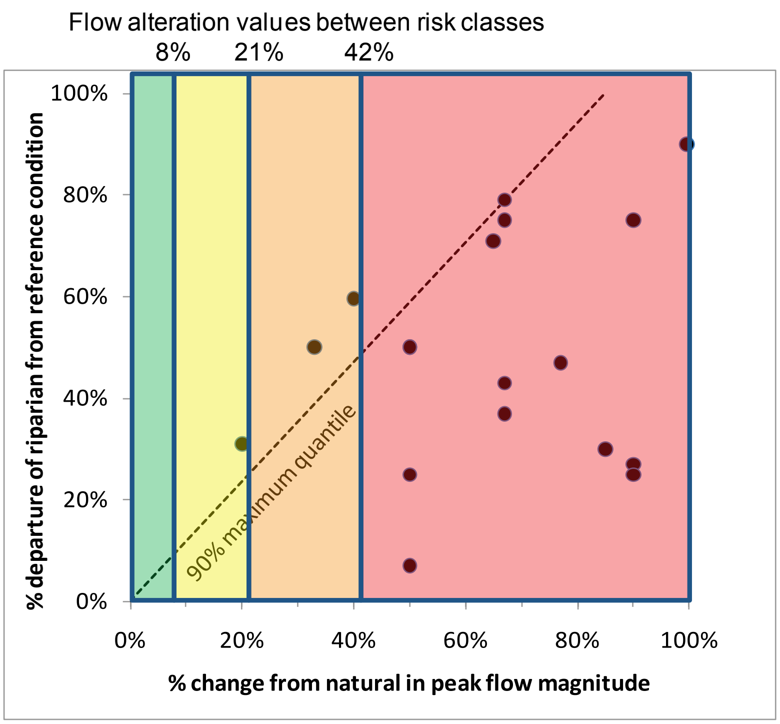
Geomorphic setting where applied: Moderate-energy confined. *Elevation where applied*: <9600 feet

% Departure of riparian from reference conditions: Calculated using Method 7 from Wilding & Poff (2008). Unlike the previous two cottonwood metrics, this metric is calculated using data from all year types. The hydrologic metric is calculated as:

$$\%\ \text{departure from reference condition} = \frac{\text{Annual Peak Daily Flow}_{\text{current}} - \text{Annual Peak Daily Flow}_{\text{baseline}}}{\text{Annual Peak Daily Flow}_{\text{baseline}}}$$

Risk classes:

Risk Class	Flow alteration	Justification for change to next higher risk class
Low	0 to 8%	At flow alteration of 8%, expected departure from reference condition is 10%.
Moderate	8% to 21%	At flow alteration of 21%, expected departure from reference condition is 25%. Maximum measured departure in this range is 31%.
High	21% to 42%	At flow alteration of 42%, expected departure from reference condition is 50%.
Very High	42% to 100%	In this range, measured departure from reference is at least 20% and as high as 90%.



Flow-ecology relationship for cottonwood in moderate-gradient confined settings and high-gradient unconfined settings.

Willow in Unconfined settings

Geomorphic setting where applied: Moderate-energy unconfined, low-energy floodplain, Glacial Trough. *Elevation where applied*: >8000 feet

Willow shrubland:
Evaluate %alteration of peak-flow (annual 1-day maximum or wet year 30-day maximum). We do not have data that describes the manner in which willow shrublands change as flow changes. Importantly, it is possible that beaver mitigate the negative impacts of reduced peak flow. See the Willow section of this report for discussion of willow response to flow alteration and hypothesized models.

Risk Classes: Due to the conceptual nature of this flow-ecology relationship, no risk classes are recommended.

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INTRODUCTION

The riparian zone is the area adjacent to a stream, and is distinguished by the influence of flood disturbance and more water in general than surrounding land. It represents a critical area for wildlife, including those inhabiting surrounding land and the stream itself (for an introduction see Gregory et al. 1991, Naiman and Décamps 1997, Patten 1998). The focus here is on riparian vegetation, which, among other things, provides critical habitat for terrestrial species (for example, game species and neotropical migrants), provides the carbon and energy that supports aquatic food webs, plays essential roles in supporting streambank and in-channel habitats, and has tremendous aesthetic value (Pusey and Arthington 2003).

The Watershed Flow Evaluation Tool (WFET) describes relationships between flow and river species and ecosystems. Wilding and Poff (2008) used many literature sources to develop a single quantitative relationship between flow alteration and riparian vegetation (Wilding and Poff 2008). The source literature used by Wilding and Poff (2008) covered a diverse range of vegetation types, including cottonwood, willow and herbaceous plants. This current report describes the development of additional methods--focusing on cottonwood forest and willow shrubland—that are described using recently published data, applied to specific geomorphic settings, and that have been subjected to additional peer review.

Flow ecology relationships are described quantitatively where sufficient data allowed reliable modeling of the relationship and qualitatively or conceptually in other cases. It is important to recognize that the complexity of river ecosystems precludes modeling all aspects of the system. While quantitative riparian flow-ecology relationships are available only for cottonwood, basic ecological principles suggest that the flow regime necessary to sustain cottonwood and willow is also expected to sustain the physical biological processes that support the broader riparian ecosystem, including processes of disturbance, nutrient cycling, and water flows. Cottonwood are therefore offered as an indicator of flow adequacy for riparian ecosystem as they are pervasive in the Colorado River basin and good data exist to describe the flow-ecology relationship.

The mechanisms by which establishment and growth of cottonwoods depend on flow are well established (Friedman et al. 1995, Scott et al. 1996, Auble and Scott 1998, Mahoney and Rood 1998, Cooper et al. 1999, Karrenberg et al. 2002, Shafroth et al. 2002, Rood et al. 2007, Stromberg et al. 2007). Recruitment from seed in wide valleys is particularly well understood. Floods create bare surfaces (from erosion or deposition) and remove competing plants, providing moist, sandy and unshaded conditions for seed germination. In semi-arid areas, flow recession must be gradual enough for the roots of seedlings to keep pace with dropping water levels (less critical in humid regions). The magnitude, frequency and timing of flows (within and between years) all come into play for a successful recruitment event. The right flow conditions are therefore required for seedling growth, but are not necessarily sufficient for survival to the age of reproducing adults. It may be three years before the roots of seedlings achieve reliable access to groundwater, assuming they are not eaten, burned or washed away (Auble and Scott 1998, Cooper et al. 1999, Polzin and Rood 2006, Rood et al. 2007). Asexual recruitment (i.e. suckering) has also been described in flow-related mechanistic terms (Roberts 1999, Polzin and Rood 2006). Cottonwood survival and growth depends on base flows in addition to flood flows (Stromberg and Patten 1991), but the base flow relationship is not described in this report because we lack sufficient data to develop a generalized relationship between base flows and cottonwood health

GEOMORPHIC SETTING IS MORE IMPORTANT THAN SPECIES

To understand the role of species, reproductive traits and geomorphic setting in determining flow dependence of cottonwood and willow, experts were invited to attend a Riparian Workshop and provided valuable input as well as direction for the literature review. Within Colorado there are several species of *Populus* that depend on the river to varying degrees (all species except aspen - *Populus tremuloides*). The sub-genus Section classification of *Populus* is more useful than species level classification, in the context of this report, as it better distinguishes the reproductive strategies of *Populus*. The section *Aegiros* (broadleaf cottonwoods) includes subspecies of *P. deltoides* (subspecies *monilifera*, commonly known as Rio Grande cottonwood and plains cottonwood) and *P. fremontii* (subspecies *wislizenii*, commonly known as Fremont cottonwood). These grow at lower elevations in Colorado (<6500 ft) and reproduce primarily from seed (Rood et al. 2007).

The other *Populus* section, *Tacamahaca*, is represented in Colorado by *Populus angustifolia,* commonly known as narrowleaf cottonwood. Literature for black cottonwood (*Populus trichocarpa*[1]) was also reviewed as this *Tacamahaca* section species helps us understand the transition of cottonwood traits (particularly fluvial reproductive traits) in response to geomorphic (valley shape) and temperature gradients between semi-arid plains and high mountains (Gom and Rood 1999). Narrowleaf cottonwood are found at higher elevations (5,200-9,600 ft; Carsey et al. 2003) than broadleaf cottonwoods, with *angustifolia-deltoides* hybrids (*P. x acuminate*, Eckenwalder 1984) occasionally abundant at overlapping elevations (5200-6,500 ft; Carsey et al. 2003).

Asexual reproduction is often dominant or co-dominant for narrowleaf cottonwood, in contrast to *Aegiros* cottonwood that rely on sexual reproduction through seed dispersal (Rood et al. 1994, Rood et al. 2007). Asexual reproduction in narrowleaf is predominantly through root-suckering, where injury can trigger "new" trees to grow from the roots of existing adults (rather than from broken or abscised branches, Rood et al. 2003). Root-suckering can be triggered by

[1] Also referred to as *Populus balsamifera* subsp. *trichocarpa*.

floods (Polzin and Rood 2006), and so can resemble sexual reproduction in *Aegiros* cottonwood. Root-suckering is expected to be a more effective reproductive strategy where the growing season is short (high elevations) and channel forming floods are less frequent (Patten 1998, Rood et al. 2007). Other disturbances can trigger asexual reproduction (colluvial movement on coupled slope slides, fire, herbivory; Rood et al. 2007), and this may negate consideration of flow alteration for recruitment of narrowleaf cottonwood in highly-coupled steep streams (narrow valleys and canyons), (Samuelson and Rood 2004).

Narrowleaf cottonwood is similar to broadleaf cottonwood in many respects, but successful recruitment is often associated with larger flood events (5-15 yr, compared to 2-5 yr events for *P. deltoides*). This distinction in the flow response appears to be a consequence of climatic and geomorphic gradients, which dictate a shift in reproductive strategies at higher elevations. Baker (1990) estimated good "seedling years" for narrowleaf cottonwood every 3.4 years on average, but "stand-origin years" for adult trees were less frequent at 10-15 years (true seedlings were not distinguished from root suckers). This study was completed on a confined section of the Animas River downstream of Silverton[2]. More frequent floods (e.g. 3 yr return) facilitate seedling germination, and this is probably sufficient for recruitment in wide valley settings where meandering can carry the river away from last year's seedlings (Rood et al. 2007). But, in the steeper, more confined rivers where narrowleaf cottonwood often occur, meandering is confined so the river is more likely to scour last year's seedlings. Bigger floods are therefore required to create bare colonization sites that are high enough above the frequently disturbed channel (Auble and Scott 1998, Polzin and Rood 2006). The coarser bed material in steep, confined valleys (>>2% slope, valley width <7x bankfull width) also necessitates a larger flood event to initiate bed movement (Ryan 1997). Growing seasons are short at higher elevation, further reducing the success rate of seedlings because of slow growth (Kalischuk et al. 2001). Seedling reproduction is therefore a riskier strategy in this setting, raising the importance of root-suckering for stand survival (Rood et al. 2007). Polzin and Rood (2006) suggested flow recession and low flows are less important for successful recruitment in the northern Rocky Mountains compared semi-arid areas farther south, because river flow is less likely to constrain seedling survival in cool moist environments.

Both sections of cottonwood depend on flow in a similar manner in wide valleys, where rivers are free to meander, shift and change (Patten 1998). In this setting we find the largest cottonwood forests and also the most flow-dependent forests (Gregory et al. 1991, Scott et al. 1996, Willms et al. 2006, Rood et al. 2007). Snowmelt is critical for cottonwood in this setting, with floods recurring every 3-5 years that provide the right conditions for germination and survival (Scott et al. 1996, Rood et al. 2007). This appears to hold true for root-suckering

[2] Study completed in the Animas Canyon. This has a 2% slope for the 10 km river section between 2390 and 2575 m elevation, and colluvial deposits are visible reaching the channel viewed from aerial photos in Google Earth.

species, as demonstrated for narrowleaf cottonwood forests on the Yampa River by Richter and Richter (2000), and seedling recruitment of black cottonwood in "parkland" reaches by Samuelson and Rood (2004).

The geomorphic and climatic differences do not simply discriminate where each species is found, they are directly responsible for the relationship between flow and cottonwood recruitment. Therefore geomorphic classification is a better indicator of flow dependence than the species or section of cottonwood. So rather than applying the flow-ecology method to a given species, we should instead develop methods that are specific to the geomorphic settings that favor fluvial dependence as a reproductive strategy in riparian cottonwood (Merritt et al. 2009). This approach is further supported by the converse situation where *P. deltoides* recruitment is associated with infrequent flood events (10 yr return) in confined valleys (Auble and Scott 1998). Therefore wide valleys with low slopes are more likely to support cottonwood stands that depend on flow for successful recruitment. The greater fluvial dependence also increases the importance of flow management for riparian health in this setting.

DEFINING THE GEOMORPHIC SETTING

The relationship of flow to riparian vegetation is best considered within a geomorphic context, as it is the valley landform that determines the occurrence of riparian vegetation (type and extent) and their response to change in flow over time (Gregory et al. 1991, Scott et al. 1996, Rood et al. 2007). Methods were therefore developed to classify reach geomorphology in the Colorado basin. In a parallel investigation, Bledsoe and Carlson (2010) developed a geomorphic classification system for Colorado streams at the reach scale (Table 1). Processes under consideration here include valley confinement, where unconfined valleys (>7 x the bankfull channel width) allow streams to reach a sinuosity >1.5 and produce a wider flood zone with lower water velocities – conditions conducive to developing extensive riparian vegetation. Groundwater tables in wide valleys are more dependent on stream flow, and therefore flow is more important for riparian vegetation in this setting (cf. confined - Dawson and Ehleringer 1991). Valleys strongly coupled with adjacent hillslopes (where the valley width is less than 2x the bankfull channel width) are narrow enough for slides and rockfalls to reach the stream channel, potentially overwhelming the effect of stream processes on riparian vegetation, especially given the narrow zone of flood influence. Valley slope is an important determinant of stream power, and therefore processes creating riparian habitat such as sediment transport (erosion and deposition). Low valley slopes are required for developing sinuosity and are often associated with wide valleys.

Table 1. Geomorphic classification of Colorado streams from Bledsoe and Carlson (2010).

Valley Class Name	Energy / Valley Gradient	Valley Bottom Width / Coupling / Confinement	Hillslope Gradient	Energy Potential
Headwaters	> 4%	< (2 L_D + W_{BF})	Both > 30%	High
High-energy Coupled	> 4%	< (2 L_D + W_{BF}) or < (L_D + W_{BF})	Both or at least one > 30%	High
High-energy Open	> 4%	> (2 L_D + W_{BF})	Both or at least one > 30%	High
Moderate-energy Confined	0.1-4%	< 7 W_{BF}	Variable	Moderate
Moderate-energy Unconfined	0.1-4%	> 7 W_{BF}	Variable	Moderate
Canyon	Variable	> 3 W_{BF}	> 70%	Moderate to High
Gorge	Variable	< 3 W_{BF}	> 70%	Moderate to High
Glacial Trough**	< 4%	> (2 L_D + W_{BF})	~ 10-% initially steepening to > 30%	Moderate to Low
Low-energy Floodplain	< 0.1%	> 7 W_{BF}	Generally < 30%	Low

L_D – length of debris runout W_{BF} - width of channel at bankfull stage

** Defined as valleys with the given characteristics, lying above the elevation of the most recent glacial activity

PEER REVIEW AND EXPERT INPUT TO RIPARIAN FLOW-ECOLOGY RELATIONSHIPS

We held an Expert Panel Riparian Workshop on February 25, 2010 to peer-review completed work and to provide guidance on future efforts. One of the aims of which was to seek expert input on appropriate geomorphic classes for riparian cottonwood forest. Geomorphic classes with steep slopes and small stream size would not support significant stands of cottonwood. In addition to the reduced occurrence of cottonwood in canyons, flow is less important for recruitment here because rockslides are probably more important drivers of recruitment (canyons are highly coupled to side slopes). Those classes with slopes <4% and uncoupled with side slopes were therefore considered candidate classes. The magnitude of flow events required for successful recruitment is a product of geomorphic context because smaller floods are better able to rework the finer sediment of meandering reaches (Rood et al. 2007). Braided rivers are generally absent from the Colorado basin, and are not captured by the proposed riparian methods because different ecological processes occur (e.g. braided river systems can respond to flow regulation with increased cottonwood forests as the channel narrows; Scott et al. 1996, Marston et al. 2005, Graf 2006).

Within the suitable elevation and geomorphic contexts for cottonwood, there will be reaches where *P. deltoides* are absent. For example, floodwalls (even low ones) cut off the riparian zone from the river and can render otherwise suitable geomorphic classes unsuitable (see Table 9 in Hauer et al. 2002). We considered it unlikely that these alterations could be mapped reliably across the landscape, or that they were particularly prevalent across the Colorado watershed. Channels that have incised (e.g. sediment starvation from impoundment) also abandon the floodplain, so are not as suitable as indicated by broad geomorphic setting. Heavy browsing and felling of cottonwood can also eliminate cottonwood from otherwise suitable habitats (Auble and Scott 1998, Beschta 2003, Samuelson and Rood 2004). At this point, societal values could also be overlaid in terms of where conservation of cottonwood forest is a priority. The basin roundtable may choose to consider these additional non-geomorphic constraints for site specific evaluations or priority areas, but these are not dealt with here at a watershed scale.

RISK CLASSES

Flow-ecology relationships are used to assess potential changes in the status of flow-related attributes such as fish or riparian vegetation. In the Watershed Flow Evaluation Tool, we use "risk classes" as an indicator of the probability that the status of a given attribute will change relative to a reference status as a result of flow management. The hydrologic regime of a stream or river is a "master variable" governing the condition of species and ecosystems (Poff et al. 1997), yet other factors (land use, water quality, etc.) can also affect the status of river attributes. As such, risk classes are not deterministic, that is a "high" risk class does indicate that the attribute will for certain be in a state that is far-removed from the reference state, but it does imply that the chances of the attribute being farther removed are higher because of flow alteration.

Demarcation of risk classes is both a data-driven science process and a social process. The science process uses patterns in data, understanding of mechanisms of ecological function, and ecological principles to demarcate class. The social process adjusts the scientists assessment of risk classes to factor in values of those stakeholders who are applying the flow-ecology relationships with thresholds that better reflect acceptable levels of biotic alteration.

METHODS USED TO DEVELOP RIPARIAN FLOW-ECOLOGY RELATIONSHIPS

Wilding and Poff (2008) developed a flow-ecology relationship for riparian areas in Colorado below 9600' elevation. This relationship is still recommended for cottonwoods in confined geomorphic settings. In this report, two new flow-ecology relationships are developed specifically for cottonwood in unconfined valleys, including one for abundance of adult cottonwood and one for cottonwood recruitment.

Since Wilding and Poff (2008) was published, a dataset has become available that focused on cottonwood and used standardized survey methods applied across many sites (Merritt and Poff 2010). This dataset was employed here to derive the two new flow-ecology relationships. Merritt and Poff (2010) developed relationships for cottonwood and tamarisk, but the flow metric was deemed incompatible with the WFET (requires instantaneous flow data). As such, we re-analyzed the data using flow metrics that can be derived using a daily flow time series from StateMod (CDWR and CWCB 2009) followed by analysis of this time series with the Indicators of Hydrologic Alteration (IHA) software package (Version 7.1.0.10, Richter et al. 1996).

FLOW DATA

Merritt and Poff (2010) used a multivariate indicator of hydrologic alteration termed the IFM (index of flow modification). This index condensed various metrics for peak flow and low flow in terms of their deviation from unregulated conditions for each site[3]. The index performs well in representing flow alteration while dealing with collinearity (non-independence) among the various flow metrics, but is not directly interpretable in terms of flow units. It also uses component flow metrics that are not compatible with StateMod (e.g. instantaneous return period flows, cf. daily time series generated for StateMod nodes). So for the present study, cottonwood data from the Merritt and Poff (2010) dataset was re-analyzed using flow metrics that can be produced using StateMod, and that relate directly to the flow management questions being asked of this investigation.

As an initial step, data were obtained from David Merritt (USFS) providing the USGS gage numbers used, demarcation of flow data into pre- and post- alteration (normally temporal, but occasionally spatial), and a broader range of flow metric data. The record for unregulated rivers was divided in half for calculation of a “pre“ and “post” period comparable to regulated rivers, thereby allowing for natural variability in streamflow over long periods of time (i.e. non-stationary climate). Streamflow data for the relevant sites were then downloaded from the USGS website to enable a new analysis. One site was omitted at this point because daily data are no longer available (Rio Grande USGS 08332010), presumably because of poor quality (estimated alteration here was extreme at 170% increase for the 90 day maximum, in deviation from nearby gages).

Years with missing data (>10 consecutive days) were omitted from the analysis, which typically only affected the first and last year of record, with the revised record summarized in Table 2. The long periods of flow record used by Merritt and Poff (2010) meant that omitting data-short years had little effect on flow metrics for most sites (Figure 1). The largest deviations in metrics were for the Rio Grande (deviants from 1:1 line in Figure 1). The gages used and periods of pre and post alteration were revised for the Rio Grande following the recommendations of a separate hydrologic analysis that specifically examined hydrologic alteration for the Rio Grande (Wesche et al. 2005). Their recommended divisions of the flow record were therefore followed (1942-70 for pre-Cochiti Dam, and 1975-2003 for post). Changes were also made to the selection of pre and post records for Rio Grande sites RG1 and RG2 (vegetation study sites). The

[3] Merritt and Poff (2010) performed a Principal Components Analysis on 8 flow metrics, from which the significant axes were used to calculate euclidean distance of each site from the centroid of unregulated rivers.

USGS gages 08361000 and 08362500 were used as the post alteration gages for sites RG2 and RG1 respectively (1975-2002 – post Conchiti period from Wesche report). Following the Wesche et al. (2005) recommendation, the USGS gage 08358500 for the period 1936-1958 was used as the pre-alteration record for sites RG1 and RG2 (cf. USGS gage 08358400 used as a spatial reference by Merritt and Poff 2010). This gage is at the same location as the gage used by Merritt and Poff (2010) (San Marcial) but has the advantage of predating Conchiti dam, as well as predating the flow division between a low flow conveyance and a flood channel at this site (now represented by USGS 08358300 & 08358400 respectively).

Omitting years with gaps in the flow record reduced the pre dataset for the Little Colorado at Woodruff (USGS 09394500) to just one year of data, and closer examination revealed unlikely spikes in the data (e.g. rising from 33 cfs to 10,000 cfs in one day). A similar 24-hour spike in flow is seen in other years on the exact same date (November 27) and also several times on December 4. Given the date repetition, these may have been an end of year release from Lyman Reservoir or, coincidentally, one of several known dam bursts that occurred at this site (though no record of their dates was found). These unseasonably high flows were therefore omitted as erroneous. To better represent the pre-alteration flows, the data that are available were pieced together. Flows were averaged for each day of the year across the period 1905-1920. Most days had 5 years data (ranging from 3 to 6 days) providing an improvement over the one year of complete record available. An additional year of data was produced by synthesizing a flow record from a nearby gage with overlapping record:

$$USGS09394500 = 0.315.USGS0938600^{1.2249} \qquad R^2 = 0.70 \text{ for 1906-1907}$$

The output of these revisions was a single average year of data that provided more robust flow metrics.

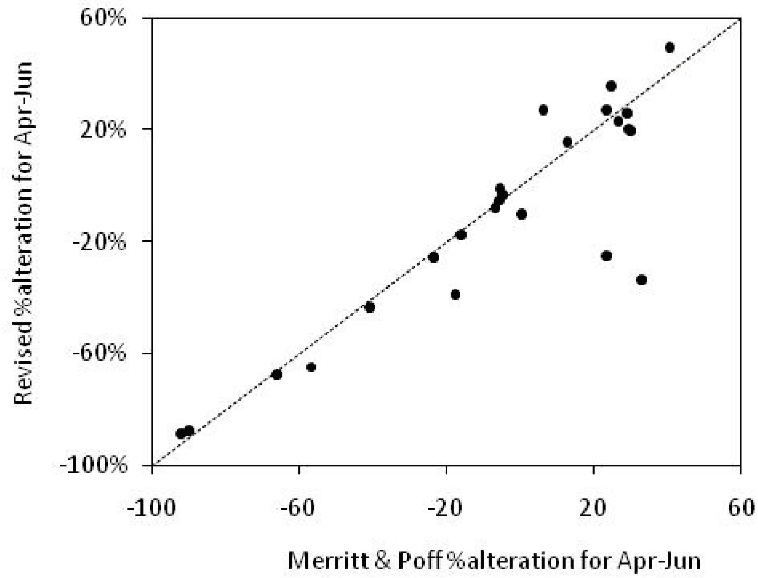

Figure 1. Comparison of revised and original flow statistics, comparing values used by Merritt and Poff (2010) and those recalculated for this investigation (omitting data short years and some change in gage sites used). The flow statistic being compared is the mean flow for April to June expressed as a percent alteration (post-pre/pre). The dashed line is a 1:1 line – the revised estimates that equal the original value will fall on this line.

Table 2. Hydrological record used to assess alteration of flow, including the USGS gage number, river and location, duration of pre- and post-alteration, intervening years that were omitted due to missing data ("Omit" column) and the vegetation monitoring sites that each gage record was applied to. See Merritt and Poff (2010) for additional information.

USGS Gage	River	Pre-alt.	Post-alt.	Omit	Vegtn. site no.
08330000	Rio Grande, Albuquerque, NM.	1943-1970	1975-2002		RGM7-1, RGN1-1, RGS1-5
08332010	Rio Grande, Bernardo Floodway, NM.	1958-1974	1975-2002		RG3 (omitted)
08361000	Rio Grande, Elephant Butte Dam, NM.	1936-1958 USGS 8358500	1975-2002		RG2
08362500	Rio Grande, Caballo Dam, NM.	1936-1958 USGS 8358500	1975-2002		RG1
08383500	Pecos River, Puerto De Luna, NM.	1939-1978	1979-2002		PEC-1 & 2
08384500	Pecos River, Sumner Dam, NM.	1913-1936	1937-2002	1926	PEC-3 to 5
09095500	Colorado River, Cameo, CO.	1934-1963	1964-2004		GJ-665 & 666
09128000	Gunnison River, Gunnison Tunnel, CO.	1911-1965	1966-2003		GUN-1 & 2
09163500	Colorado River, State Line, CO.	1952-1966	1967-2004		GJ-667 to 670
09169500	Dolores River, Bedrock, CO.	1918-1983	1984-2003	1971	DOL-2
09177000	San Miguel River, Uravan, CO.	1955-1978	1979-2003	1996	SM-1
09180000	Dolores River, Cisco, UT	1952-1983	1984-2003		DOL-1

09251000	Yampa River, Maybell, CO.	1917-1962	1963-2004		YAM-1 to 3
09384000	Little Colorado River, Lyman Lake, AZ.	1941-1970	1971-2003		LCR-34 to 35
09388000	Little Colorado River, Hunt, AZ.	1930-1949	1950-1972	1934, 1940	LCR-28, 29 & 32
09394500	Little Colorado River, Woodruff, AZ.	1905-1920	1930-2003	see report	LCR-15, 20 & 21
09402000	Little Colorado River, Cameron, AZ.	1948-1985	1986-2003		LCR6 & 10
09429100	Colorado River, Palo Verde Dam, AZ.	1957-1968	1989-2003		LC-T1 to T9, LC-T11 to T16
09431500	Gila River, Redrock, NM.	1931-1955	1963-2002		GILA1
09504000	Verde River, Clarkdale, AZ.	1916-1920	1966-2003	1917	VER-1 & 2
09506000	Verde River, Camp Verde, AZ	1935-1989	1990-2005		VER-3
09511300	Verde River, Scottsdale, AZ.	1962-1982	1983-2003		VER-6 & 7
10327500	Humboldt River, Comus, NV.	1895-1947	1948-2002	1910	HUM-1 to 5
10335000	Humboldt River, Rye Patch, NV.	1900-1932	1936-2002	1910, 11, 17 & 28	HUM-6 & 7
10351600	Truckee River, Derby Dam, NV.	1919-1957	1960-2002		TR-1 & 2

Following the Expert Panel Riparian Workshop several revisions to the draft riparian assessment were initiated. The first of these was a revision of flow metrics for predicting riparian response. Concerns were raised that relationships with annual floods may be a statistical artifact (see Baker 1990 for rationale). It was suggested that a flood peak with a return period of 3-5 years was more mechanistically linked to cottonwood recruitment and therefore population success, compared to annual floods (see Bradley and Smith 1986, Scott et al. 1996, Mahoney and Rood 1998, Rood et al. 2007). The Merritt and Poff (2010) analysis used instantaneous annual maxima series to generate 2, 10 and 25 year return period flood magnitudes. This cannot be generated by StateMod which is based on daily average data (not instantaneous flow). Following suggestions from the expert panel, additional metrics were calculated and analyses were done to compare various flow metrics based on a daily time-step to an instantaneous 5 year return period flood. The flow metrics used in this report are described in Table 3.

RE-ANALYSIS OF MERRIT AND POFF'S (2010) COTTONWOOD ABUNDANCE DATA

Abundance of cottonwood was assessed by Merritt and Poff (2010) as the proportion of plant occurrences in a series of transects. A 200 m long reach of river was selected and at every meter increment adult cottonwood occurrence (presence/absence) was observed for a perpendicular transect that ran across the entire floodplain. This provided 200x1 m wide transects from which to calculate %abundance, therefore:

% abundance = the proportion of 1m wide transects containing 1 or more adult cottonwood.

The reaches were replicated every 0.5 km. Analysis of the response of adult cottonwood abundance to flow alteration used quantile regression, following the methods stated in the original WFET report (Wilding and Poff 2008). These are restated here for completeness.

The mechanisms by which flow alteration affect stream ecosystems are complex, so a simple response to flow (1-dimensional) was not anticipated. A community could be limited by the chosen flow-metric (e.g. peak-flow), but other variables (unmeasured) often constrain the ecosystem and limit its response to flow. For example, cutthroat trout may reach higher biomass in deeper channels, but if introduced competitors (brook trout) are present then the trout population will be small regardless of depth (Dunham et al. 2002). Using quantile regression to define the upper bound is therefore expected to better represent the potential response to the chosen flow parameter (see Cade and Noon 2003). This also expresses complex relationships in an easily digestible form for end-user application, as compared to multi-dimensional models.

Table 3. Flow metrics used in this report. Metrics calculated by Merritt and Poff (2010) are indicated by a asterisk. Note: instantaneous values are not StateMod compatible.

Flow metric	Description
Instantaneous 2, 5, 10 and 25 year return period*	Instantaneous annual-maximum peak flows for 2, 5, 10 & 25 years (flows with annual probability of exceedence of 0.50, 0.20, 0.10 & 0.04). The Pearson Type III frequency distribution was fit to the logarithms of instantaneous annual peak flows. Used PeakFQ software. Calculate flow for pre-alteration period, then repeat for post alteration. Percent flow alteration calculated in Microsoft Excel ([pre-post]/pre).
Daily 5 & 10 year return period	Daily series annual-maximum peak flows (Oct-Sept water year) for 5 and 10 year return events years (flows with annual probability of exceedence of 0.20 & 0.10). Calculated using IHA software by changing the EFC small flood return period from 2 to 5 years to generate a pre-alteration value (output under SCO worksheet as "EFC small flood minimum peak flow"). IHA appears to use a Weibull plotting position: P = rank/(n+1). The post-alteration value was then produced using a single period analysis constrained to post-alteration data. Percent flow alteration calculated in Microsoft Excel ([pre-post]/pre).
April-June average*	Mean flow for the April-June period is calculated for each year using IHA software, then averaged across years separately for both pre and post alteration periods. Percent flow alteration calculated in Microsoft Excel ([pre-post]/pre).
monthly average for April, May, June and July	As per April-June average, but calculated individually for each month.
1-day maximum	Annual maximum flow from the daily flow series (Oct-Sept water year) calculated using IHA software. This is then averaged across years separately for both pre- and post-alteration periods in Microsoft Excel. Percent flow alteration calculated in Microsoft Excel ([pre-post]/pre).
3-day, 7-day, 30-day and 90-day maximum	As per 1-day maximum, but annual maximum flow series is calculated as a moving average over 3, 7, 30 and 90 day periods instead of 1-day (i.e. the actual period of averaging is allowed to vary between years and sites).
Wet year 1-day, 3-day, 7-day, 30-day and 90-day maximum	In Microsoft Excel, wet years were identified as those exceeding the 70%ile MAF (threshold calculated separately for pre-and post-alteration). The annual maxima series (1, 3, 7, 30 and 90 day moving average) is then reduced to wet years only, and flows averaged across wet years separately for both pre- and post-alteration periods. Percent flow alteration calculated in Microsoft Excel ([pre-post]/pre).

Quantile regression was used to identify these upper bounds, providing a coarse filter to isolate the potential response to each flow parameter (using Blossom statistical software; Cade and Richards 2007). This method minimizes the sum of absolute deviations (LAD - least absolute deviation), which are asymmetrically weighted by the quantile (e.g. 90%) for positive residuals and one minus the quantile for negative residuals (e.g. 1-0.9=0.1). Using absolute deviations (cf. squared deviations for conventional regression) reduces the effect of outliers. The 90% quantiles were judged as representing the upper-bound response adequately. The necessity of transformations was investigated, before carrying out linear quantile regression.

The significance of the relationships was tested (null hypothesis: slope =0) using a quantile rank score test to minimize assumptions regarding error distributions (cf. higher power parametric alternatives). The rank score test provides P-values that are calculated from the sign of the residuals (positive or negative), not their magnitude. The permutation version uses an F statistic with its sampling distribution approximated by permutation (Cade et al. 2006), with 5000 permutations used here.

Re-analysis of Merritt and Poff's (2010) cottonwood recruitment data

Recruitment of cottonwood was investigated using the binary recruitment data from the Merritt and Poff (2010) dataset. The presence of 2-5 year old saplings was recorded when surveying each 200 m long reach, producing a presence/absence record for each reach (cf. %abundance per reach for adult cottonwood). The quantile regression analysis used for adult cottonwood is therefore not applicable to the recruitment data. The analysis by Merritt and Poff (2010) employed the IFM (index of flow modification) to predict recruitment response, based on a mixed effect logistic regression model.

The purpose of the analysis was to select alternative flow metrics to the IFM that are compatible with StateMod (i.e. derived using daily time series data). A subset of informative flow metrics was selected based on results from the adult cottonwood analysis and riparian workshop (instantaneous 10-year return period flow, daily series 5-year return period flow, maximum 90-day flow, and wet year maxima – 1, 7 and 90 day, described in Table 3). A logistic Generalized Linear Model analysis was then run to further narrow the list of candidate flow metrics. Using AIC (Akaike's Information Criterion), the 5-year return period flow and wet year 90 day maxima were selected as the most informative flow alteration metrics (Table 4).

Table 4. A logistic Generalized Linear Model was run for each of the following flow alteration metrics as predictors of cottonwood recruitment. The wet year 90 day maximum and 5-year return period flow (daily series) were the best predictors based on AIC (smaller better). The multi-metric based IFM (index of flow modification) from Merritt and Poff (2010) is also tabulated for comparison (modeled for this table using the same sites as the other metrics). A lower AIC value and a lower p-value both indicate a better model.

	AIC (smaller better)	P-value of coefficient Pr(>|z|)
90 day max	113.0	0.0589
10 yr return flow (instantaneous)	111.7	0.0284
wet year 7 day max	109.6	0.0096
wet year 1 day max	106.1	0.0023
5 yr return flow (daily)	**105.7**	0.0018
wet year 90 day max	**103.6**	0.0010
IFM	*93.6*	*0.0002*

Maxent was used to model the response of cottonwood recruitment to flow alteration (Dudik et al. 2010). Maxent attempts to estimate the most uniform or spread-out probability function (i.e. the distribution with maximum entropy), subject to constraints that are determined by the environmental data. In effect it makes no assumptions about the distribution of, in this case, recruitment beyond the flow constraints we can observe. It is a non-linear method that follows Bayesian principles in deriving an appropriate probability distribution function from the dataset (Phillips et al. 2006), rather than assuming that commonly used probability functions will be adequate. The model settings used included a regularization multiplier of 1, bootstrap evaluation with replacement for at least 50 model replications and with presence sites added to background (otherwise using defaults). Because absence sites were used as background data (termed “target-group” background), the model is expected to achieve better predictions than a presence-only analysis would with random background reaches, as demonstrated by Phillips and Dudík (2008). The AUC statistic was used to evaluate Maxent model performance. This measures the area under the receiver operator curve, with a value of 1 ideal and values <0.5 indicating predictions no better than chance.

The relatively small number of occurrences (22 reaches with recruitment observed) increases the importance of the method used in determining predicted response to flow alteration. Maxent was used to re-assess the data because of its strength in dealing with small numbers of occurrences and lack of assumption about the shape of the response (Pearson et al. 2007, Phillips et al. 2006, Phillips and Dudík. 2008). This method does not account for the nested sampling design used by Merritt and Poff (2010) (cf. NLME models), instead considering each reach individually. So the two methods were compared (NLME logistic regression & Maxent) using recruitment response to IFM (index of flow modification). There were some differences between NLME logistic regression and Maxent predictions (Figure 2). On average, Maxent predicted slightly higher occurrence at intermediate flow alteration (IFM 0.2-0.5) which is also the range with greatest variability (the predictions of each replicate model depends on which sites are included). The lower bound (-1 standard deviation) of the Maxent response is closest to NLME predictions overall (Figure 2). Certainly Maxent appears a valid method for investigating the response of recruitment to alternative flow metrics, especially given the flexibility of the response function.

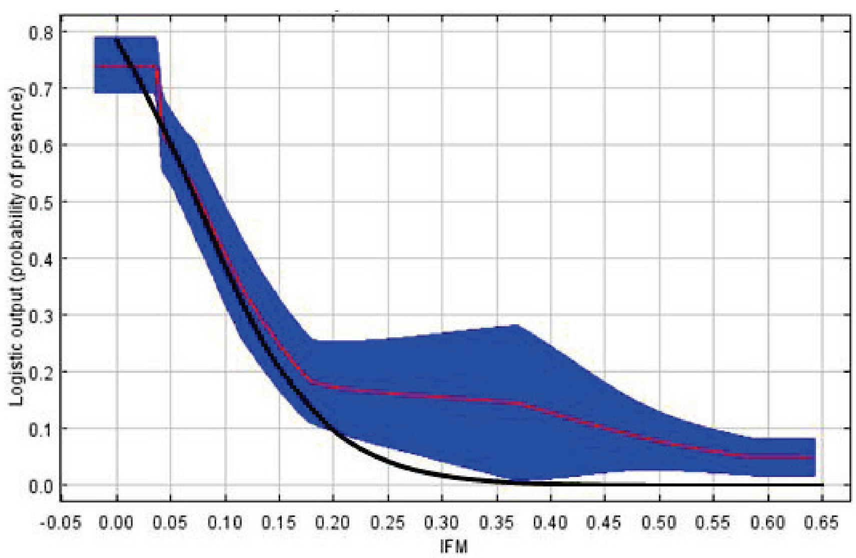

Figure 2. Probability of cottonwood recruitment in response to IFM (index of flow modification), comparing the predictions from NLME logistic regression (black line) to Maxent predictions (red line, with blue area ± 1 standard deviation generated from 50 bootstrap iterations). AUC = 0.806.

RIPARIAN RESULTS

RE-ANALYSIS OF THE MERRITT AND POFF (2010) DATA

Flow-ecology relationships for unconfined geomorphic settings: adult cottonwood

Among the metrics used by Merritt and Poff (2010) to describe peak flow, the 25 year return-period flow (instantaneous) had the highest R^2 value, which means it explained more of the variation in the data. However, as noted above, instantaneous values cannot be derived from StateMod. Therefore, additional flow metrics were calculated for this investigation to provide measures of peak flow that could be derived using StateMod (described in Table 3).

Cottonwood forest does not require high flows every year in order to achieve adequate recruitment. Therefore the flow data were re-analyzed using only wet-years. A wet-year was delineated as exceeding the 70th percentile mean annual flow. The pre-alteration percentile cannot be applied post alteration because regulation can reduce the chance of the threshold being exceeded (i.e. the number of wet years will be underestimated). In the absence of a reliable indicator of natural wet years, we used the post alteration 70th percentile, which is still indicative of precipitation assuming that flows are somewhat uniformly altered between years (or at least between wet-years). Each flow metric was then averaged only across wet years and compared pre- and post-alteration. An additional two sites were omitted from this analysis due to insufficient replication of wet years (USGS 09394500 & 09504000). Note that the quantile regression analysis was constrained to sites with reduced flows (i.e. only sites with flow alteration ≤ 0) as we are primarily concerned with flow *reduction*.

Compared to pre-workshop analyses based on annual maxima, the wet year analysis (Figure 3) gave a less significant correlation for 30 day maximum (p-value increased from 0.095 to 0.18), but improved the significance for the 90 day maximum (p-value reduced from 0.027 to 0.015). All else being equal, we might have expected reduced significance of results from the wet year analysis because of the reduced dataset (70% less flow records), so the improvement exceeds expectations. All metrics approach a 1:1 relationship (1% flow reduction associated with 1% less cottonwood), especially if attributing more weight to the statistically significant relationships ($p<0.05$). The original WFET riparian analysis (Wilding & Poff 2008) also approached a 1:1 relationship, lending weight to this level of riparian impact from flow alteration.

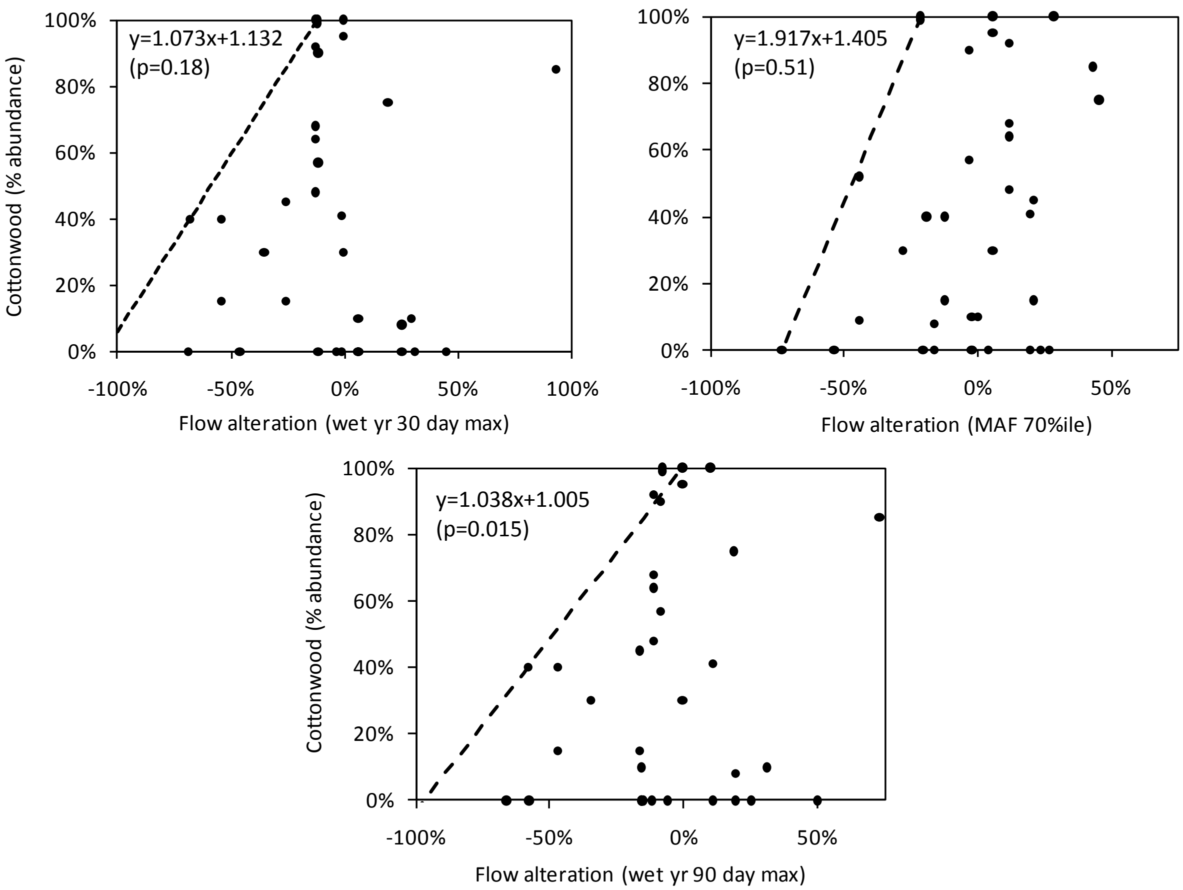

Figure 3. Cottonwood abundance response to peak flow alteration (30 day and 90 day max.) during wet years only (i.e. averaged over years exceeding 70%ile MAF). Necessary flow data was not available for three sites (USGS 08332010, 09394500, 09504000), hence were omitted. Alteration of the 70 percentile MAF (mean annual flow) is also presented (one datapoint at 143% alteration and 0 cottonwood is not shown on the MAF plot to achieve consistent axes). Note that all of these charts are comparable, indicating moderate to strong correlation among these flow metrics, but the 90 day maximum provides the best model.

The best predictor of a 5-year return period flood magnitude was investigated following recommendations from the Riparian Workshop. The instantaneous 5-year return period flood magnitude calculated by Merritt and Poff (2010) was used as the target metric. The daily series 5-year return period flow magnitude (produced using IHA software) gave the best correlation with the instantaneous estimate for the 5 year return period flow (also for the 10 and 25 year instantaneous flow). The next best correlate was the wet year 90-day maximum (Figure 4).

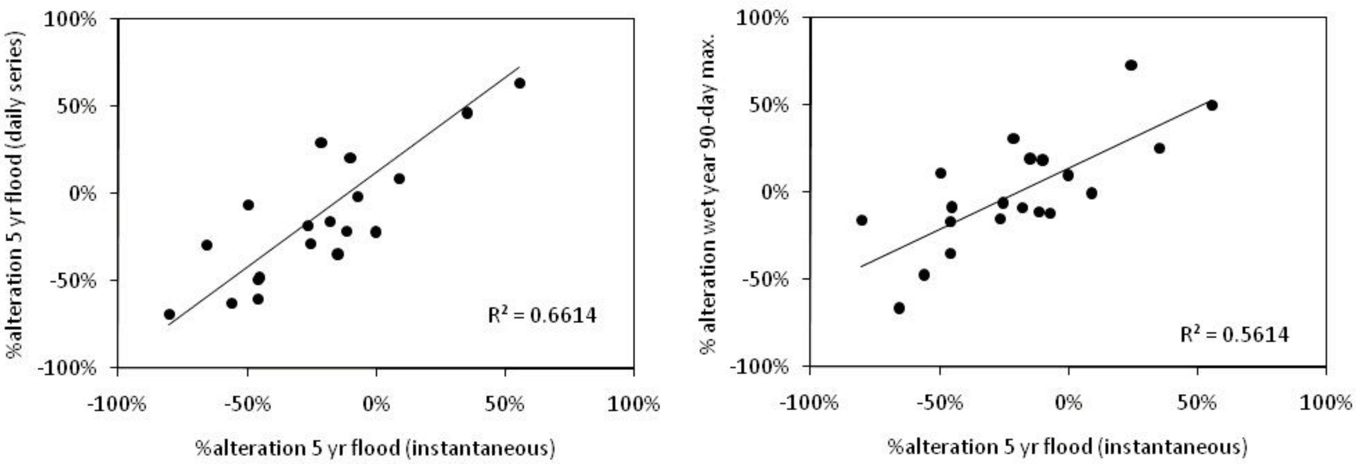

Figure 4. Correlation of two IHA metrics (daily series 5-yr return period flood and wet year 90-day max.) with the instantaneous 5 year return period flood.

Unfortunately the daily series 5-year return period flow is a poor predictor of cottonwood abundance, along with the wet-year 1-day and 7-day maxima (Figure 5). Visually, an underlying response can be seen (Figure 5), but the outliers are too pronounced to allow calculation of a valid relationship (p = 0.5). The instantaneous 5-year return period flow provided a relationship more consistent with other metrics, but was not significant (p=0.12).

The recommended function for evaluating the risk of flow alteration effects on cottonwood abundance is therefore based on the wet-year 90-day maximum flow. A response function was derived as the 90% quantile of the Merritt and Poff (2010) abundance data for adult cottonwood. The final recommended equation and risk classes are presented in the Executive Summary and need not be repeated here.

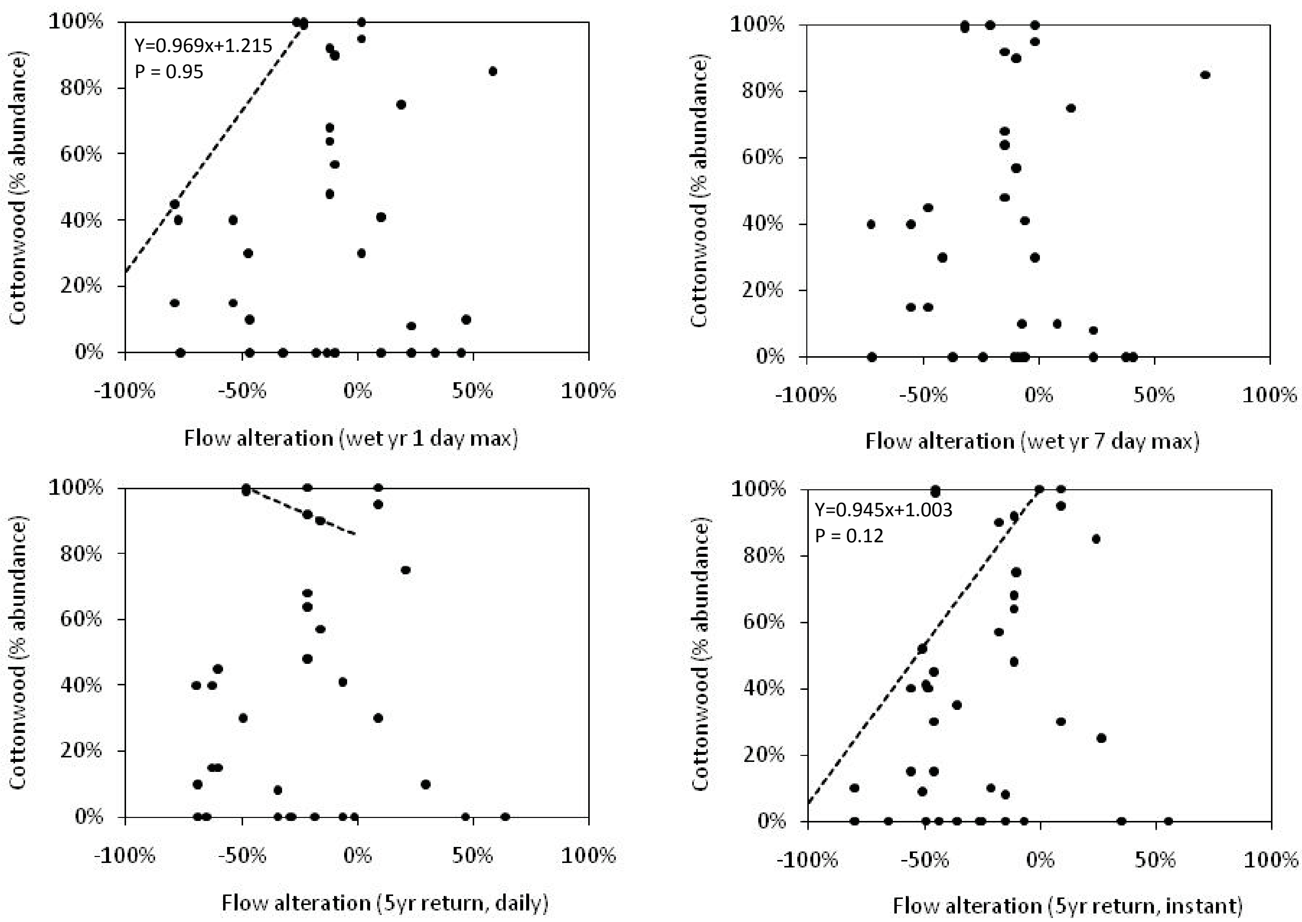

Figure 5. Adult cottonwood response to peak flow alteration. This plot includes two "wet year" average maxima (1-day and moving 7-day average), the daily series 5-year return period maxima and instantaneous 5-year return maxima. The dashed lines are 90% quantiles fit to the data (y=100% for 7-day).

Flow-ecology relationships for unconfined geomorphic settings: cottonwood recruitment

Recruitment of cottonwood was investigated using the binary recruitment data from the Merritt and Poff (2010) dataset. The occurrence of 2-5 year old saplings was recorded for each reach, hence this is a presence/absence dataset (cf. %abundance data for adult cottonwood). Two flow metrics were selected, as alternatives to the IFM, based on Statemod compatibility and predictive strength (wet year 90 day max, daily series 5 year return flow – see methods).

Maxent was used to analyze the data because of its strength in dealing with small numbers of occurrences and lack of assumption about the shape of the response (Phillips et al. 2006, Phillips and Dudík 2008). Using the wet year 90 day maximum predicts a reduced probability of recruitment when flow is reduced from natural, but not at sites with augmented flows (Figure 6). The other StateMod compatible flow metric (5 year return flow) was similar in the general form of the response to the 90-day max, with declining recruitment at reduced flows and stable recruitment under augmented flows (Figure 7). But the predictive performance using 5 year return flow is not as good and the predictions more variable (AUC=0.72, cf. 0.7 lower cutoff used by Phillips and Dudík 2008).

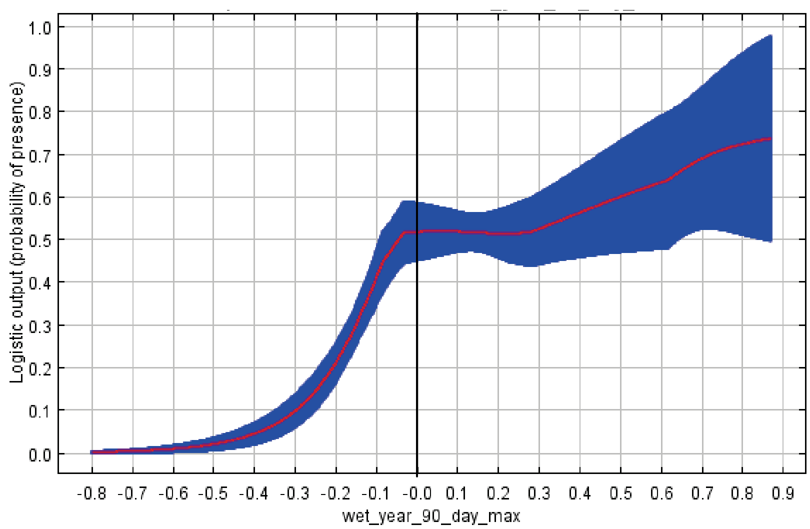

Figure 6. Probability of cottonwood recruitment in response to alteration of wet year 90-day maximum flow predicted using Maxent (mean response is the red line, with blue area ± 1 standard deviation generated from 100 bootstrap iterations). An unaltered flow is 0 on the x-axis (-0.5 represents a 50% reduction in flow). AUC = 0.775.

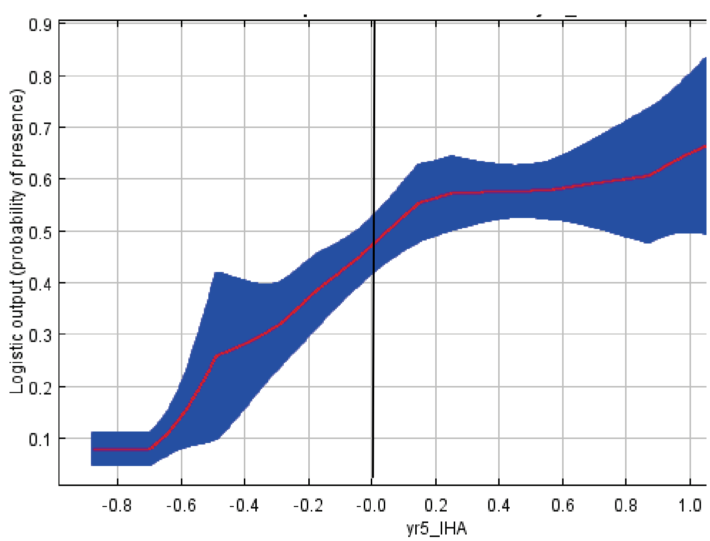

Figure 7. Probability of cottonwood recruitment in response to alteration of 5 year return flow predicted using Maxent (mean response is the red line, with blue area ± 1 standard deviation generated from 50 bootstrap iterations). An unaltered flow is 0 on the x-axis (-0.5 represents a 50% reduction in flow). AUC = 0.719.

The recommended function for evaluating the risk of flow alteration effects on recruitment of cottonwood is therefore based on the wet-year 90-day maximum flow. A polynomial response function was derived from the Maxent output to simplify implementation using post-processing in Microsoft Excel. This polynomial function adequately reproduces the flow-reduction portion of the model and is more easily applied than the multiple functions (or features) generated by Maxent. The final recommended equation and risk classes are presented in the Executive Summary and need not be repeated here.

Comparison of adult cottonwood and cottonwood recruitment curves

A comparison of the cottonwood curves for binomial recruitment versus adult abundance is therefore worthwhile in considering their application. Certainly predicted recruitment declines more steeply than the predicted abundance of adult cottonwood in response to reduced wet year 90 day maximum flows (Figure 8). Recruitment is needed to sustain cottonwood forest, but adult cottonwoods are present at sites that have a low chance of recruitment. Arguably, this could be interpreted as meaning some level of abundance of adult cottonwood can be supported by low rates of recruitment (e.g. 50% adult abundance was sustained by 4% of natural recruitment where flows are reduced by 50%). Alternatively, sites experiencing significant flow alteration may not be experiencing adequate recruitment and those adults that were observed are simply the remaining fraction of a forest that is slowly dying out. Certainly the recruitment function provides a more protective evaluation of risk of effects from flow alteration, with more certainty that the function describes flows that sustain cottonwood forest in the long term.

We anticipate that the wet year 90 day maximum flow is mechanistically linked to critical recruitment processes for cottonwood. The wet year 90 day maximum does not measure the duration of the effective discharge (flows that are effective in mobilizing sediment to create bare colonization sites, sensu Richter and Richter 2000), but this flow metric is expected to be correlated with the effectiveness of flood events. Nor does it capture the timing of flows relative to cottonwood seedfall. Equally so, representing 10 years of data with one 15-minute interval (instantaneous 10 year return flow) or 5 years of data with 1 day of recorded flow (daily series 5 year return flow) falls short of capturing all components of the flow regime necessary for recruitment. Results here suggest the wet year 90 day maximum does the best job, out of the individual metrics considered, of indicating the suitability of the broader flow regime. It is therefore an indicator of flow adequacy rather than a description of the complete flow requirements of riparian cottonwood. The latter would be required for site-specific flow prescriptions (see Mahoney and Rood 1998).

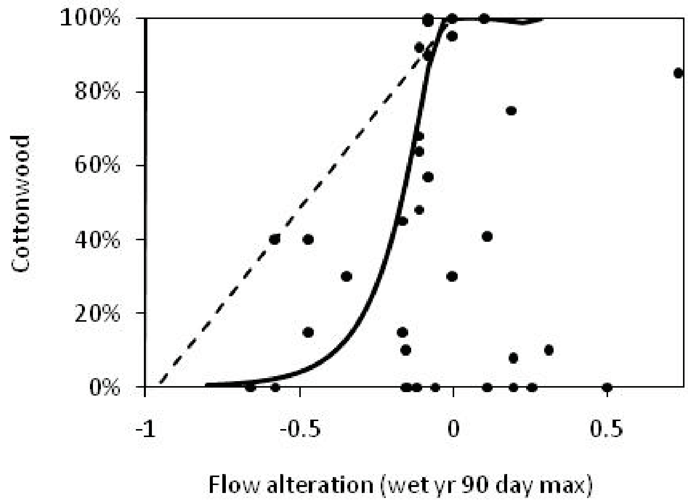

Figure 8. Comparison of adult cottonwood (dashed line and black dots, %abundance) to cottonwood recruitment (solid line, % of natural recruitment probability) in terms of their response to alteration of the wet year 90 day maximum flow.

COTTONWOOD FLOW-ECOLOGY RELATIONSHIP FOR CONFINED SETTINGS

The Merritt and Poff (2010) derived flow-ecology relationships are valid only in unconfined valleys, so a separate relationship is recommended for steeper, more confined geomorphic settings. Peer-reviewed research indicates that recruitment and growth of cottonwood in confined settings is related to flow, but the mechanisms of this relationship differ from unconfined settings (e.g. Roberts 1999, Stromberg and Patten 1991). There is some consensus in the literature that a less frequent flood drives recruitment in confined settings, typically in the order of 10-15 years recurrence, regardless of species (Table 5). Seedling establishment occurs more often in confined rivers (3-5 years), as it does in unconfined rivers. But survival to reproducing adults (i.e. recruitment) is unlikely from these smaller events in confined settings, so the bigger floods (10-15 yr return) are more of a necessity. Confined valleys are generally more prevalent at higher elevations where the climate is cooler and wetter. This reduces the dependence on receding flows to provide moisture for seedling growth (Polzin and Rood 2006), and large trees may instead source water from deeper groundwater originating from hillslopes (Dawson and Ehleringer 1991).

Confined valleys at lower elevations will be drier, and hence flow recession rates will be more critical for cottonwood here. This is a relatively harsh environment for cottonwood establishment, and it is therefore expected to support sparse cottonwood stands. The faster growth rate of *P. deltoides* seedlings may increase their chance of success at lower elevations, compared to narrowleaf cottonwood seedlings (Kalischuk et al. 2001). Seedlings are expected to be very dependent on surface water in this setting (Dawson and Ehleringer 1991), compared to root suckers from narrowleaf cottonwood that benefit from deeper groundwater (Krasny et al. 1988).

Table 5. Cottonwood stand recruitment data from confined rivers. Data were sourced from each article where available, otherwise were estimated from aerial photos in Google Earth.

Study	species	Valley slope	Confinement	Flood recurrence interval for recruitment	Flow alteration
(Scott et al. 1997, Auble and Scott 1998)	*P. deltoides*	0.05%	confined (valley width ~3x bankfull width)	9.3 years for adult recruitment from seed.	"attenuated peak flows by 14-23%"
(Baker 1990)	*P. angustifolia*	2%	Canyon (valley width ~2x bankfull width, colluvial deposits in channel)	10-15 years for adult recruitment, 3.4 years for seedlings that presumably failed.	"unregulated"
(Polzin and Rood 2006)	*P. trichocarpa*	0.6%	Confined (valley width 2 to 6x bankfull width)	100 yr for seedling recruitment; weak flood association for root suckers.	"run of river dam"
(Samuelson and Rood 2004) montane results	*P. trichocarpa*	3%	Confined (sinuosity <1.5)	5 yr for root sucker recruits, >50yr for seedling recruits.	Unregulated

In the absence of new data to describe cottonwood response in confined settings, *the recommended function for evaluating the risk of flow alteration effects on cottonwood in confined settings* is Method 7 from Wilding & Poff (2008). The final recommended equation and risk classes are presented in the Executive Summary and need not be repeated here.

Additionally, we recommend evaluating alteration of the 1-in-10 year 90-day maximum flow (i.e. direct consideration of degree of flow alteration). Large floods are important for cottonwood recruitment in this setting. We cannot quantify the degree of risk associated with alteration of this flow metric, but it could at least be used to narrow down the list of sites where further investigation of effects may be justified (e.g. sites where the 1-in-10 year 90-day maximum flow is reduced by more than 10%).

FLOW-RESPONSE FOR WILLOW (SALIX SPP.)

Willows (*Salix* spp.) are a diverse genus, and belong to same family as cottonwood (Salicaceae). Most members of this family are riparian/wetland specialists (Karrenberg et al. 2002), and willow are no exception. Among Colorado's 30+ species of willow, nearly all grow in moist habitats of wetlands and/or riparian areas (Weber and Wittmann 2001a, b). In Colorado, willow ecosystems (termed willow carrs) are often dominant in broad valleys (including unconfined and glaciated valleys) with low valley slopes (<3%) in montane and subalpine settings (Patten 1998, Rocchio 2006). Flow-ecology relationships were investigated in this geomorphic setting for a subset of species (*S. planifolia, S. geyeriana, S. monticola*, and *S. petiolaris*) because they dominate montane and subalpine willow carrs in Colorado (Carsey et al. 2003) and are known to depend on floods (Woods and Cooper 2005, Cooper et al. 2006). Willow carrs were divided by Carsey et al. (2003) into two types: tall shrublands (e.g. *S. geyeriana, S. monticola* from 7,700-10,300 ft) and short shrublands (e.g. *S. planifolia* from 8,300 to 12,000 ft).

Establishment and growth of most willow species depends on interactions between hydrology, geomorphology and animals, with bare, moist surfaces formed by floods being particularly important to establishment of plants and high water tables being important for long-term survival and growth (Krasny et al. 1988, Naiman and Décamps 1997, Karrenberg et al. 2002, Woods and Cooper 2005, Cooper et al. 2006, Westbrook et al. 2006). These aspects of the ecology of willows, including their reproductive mechanisms and strategies are similar to other members of the plant family Salicaceae, including cottonwood (genus *Populus*). Among the Salicaceae, many species reproduce sexually (i.e. by seed) or asexually (e.g. sprouting from broken branches). The importance of one means of reproduction versus another varies based on species and physical setting (Krasny et al. 1988). Sexual reproduction by seedfall was observed to be dominant for riparian willow at higher elevation (Cooper et al. 2006). The species considered here are capable of asexual reproduction, but this is rarely observed as an origin of mature riparian stands. Asexual reproduction is more important in wetlands than riparian shrublands (including species that inhabit both environments), though we do not understand the mechanisms of this transition.

Recruitment is expected to respond more immediately to flow alteration, compared to aerial extent of willow shrublands, because willow are relatively long-lived (>40 years, Cooper et al. 2006, Wolf et al. 2007). Cooper et al. (2006) demonstrated that willow recruitment depends on flooding events to create appropriate surfaces and hydrologic conditions - processes that are in many ways similar to those mechanisms supporting cottonwood recruitment at lower elevations. In particular, smaller flood events (annual return) were associated with recruitment in meandering rivers (point bars left behind by meandering), larger floods for recruitment of abandoned channels (2-5 yr return) and infrequent floods for recruitment of abandoned beaver ponds (>5 yr return). Flow alteration can impact channel processes of wide valleys at high elevations, as demonstrated by Ryan (1997) in the headwaters of the Colorado River, and it follows that flow alteration could affect willow establishment, growth, and survival. A decline in willow extent following flow regulation was observed in Arizona and Montana (Lite and Stromberg 2005, Marston et al. 2005).

Floods and streamflow are important drivers of willow ecosystems and the general processes are assumed to be similar to cottonwood. But there are several other major drivers that can overwhelm the response of willow to flow alteration. Beaver are major drivers of willow shrublands, as well as riparian-stream ecosystems as a whole (Naiman et al. 1986, Cooper et al. 2006, Rocchio 2006, Westbrook et al. 2006, Wolf et al. 2007, Westbrook et al. 2010), acting as a major disturbance of riparian areas through flooding, vegetation clearing and as a modifier of channel response to floods. Beaver ponds are important for raising groundwater levels above and below the dam. The bare surfaces exposed by failed beaver dams are important recruitment sites for willow that often extend the zone of flood influence and, consequently, willow shrubland (cf. no beaver dam). Beaver activities cause channel avulsion, which also produces bare surfaces. Beaver affect sediment deposition, increasing the quantity and proportion of fines in soils to the benefit of willow (by producing soils with better moisture retention). The loss of floods can therefore be mitigated by beaver to some extent, as they provide an alternate source of disturbance and reduce the dependence of groundwater levels on stream flow. But this limits the disturbance to one source and creates a system that is very susceptible to other stressors, such as overgrazing. People may actively remove beaver for the purposes of development (e.g. agriculture, diversion schemes). The loss of beaver can also result in channel incision as the stream adjusts to a new regime of sediment and water retention (Wolf et al. 2007). Channel incision can result in floodplain abandonment by the stream and subsequent loss of willow recruitment.

Willow shrublands are associated with shallow groundwater (Krasny et al. 1988, Gage and Cooper 2004). In some settings, groundwater is recharged primarily from adjacent hillslopes, rather than the stream. High recharge rates can originate from deep glacial till, hillslopes with highly fractured rock and longer hillslopes, particularly those with low slopes that drain more slowly. Typically, the higher the elevation the higher the magnitude of hillslope discharge as a consequence of precipitation-evaporation patterns in Colorado (Patten 1998). Groundwater does not directly influence recruitment processes (such as meandering and point bar migration), but groundwater does affect biomass of existing vegetation (Dwire et al. 2009) and vulnerability to grazing effects (Peinetti et al. 2001). Also, substantial groundwater inputs can mitigate effects of diversions depletions by rapidly recharging the stream below a diversion, and these inputs can provide opportunity for beaver activities that lead to recruitment. The less water originating from hillslopes the more dependent willow will be on streamflow. Intermittently flowing streams reflect low groundwater levels, and therefore may not support willow. Beaver dams can raise groundwater levels (Westbrook et al. 2006), increasing willow success in intermittent streams and drier valleys.

Flow-ecology curves

As this review demonstrates, much research has established the basic mechanisms by which willows depend on the flow regime, geomorphic setting and beaver activity. Nonetheless, specific quantitative descriptions of flow dependence of willow recruitment has not received the same level of research effort as cottonwood (see Lite and Stromberg 2005, Marston et al. 2005). The flow-ecology relationship for cottonwood in unconfined geomorphic settings provides a good starting point because the same channel processes are involved. In particular we see seedling establishment associated with point bar migration and channel cutoffs regardless of whether cottonwood or willow are the dominant riparian species. The results from Cooper et al. (2006) indicate similar recruitment processes in this setting, with the "effective" flood for recruitment being 2-5 years. In addition to similar channel forming processes, the strategies for reproduction and growth are similar across many of the Salicaceae (Karrenberg et al. 2002). The similarity extends to the timing of seed rain for willow and cottonwood (Niiyama 1990, Mahoney and Rood 1998, Cooper et al. 1999, Gage and Cooper 2005), which reaches a maximum on the receding limb of snowmelt peak flow (Figure 9).

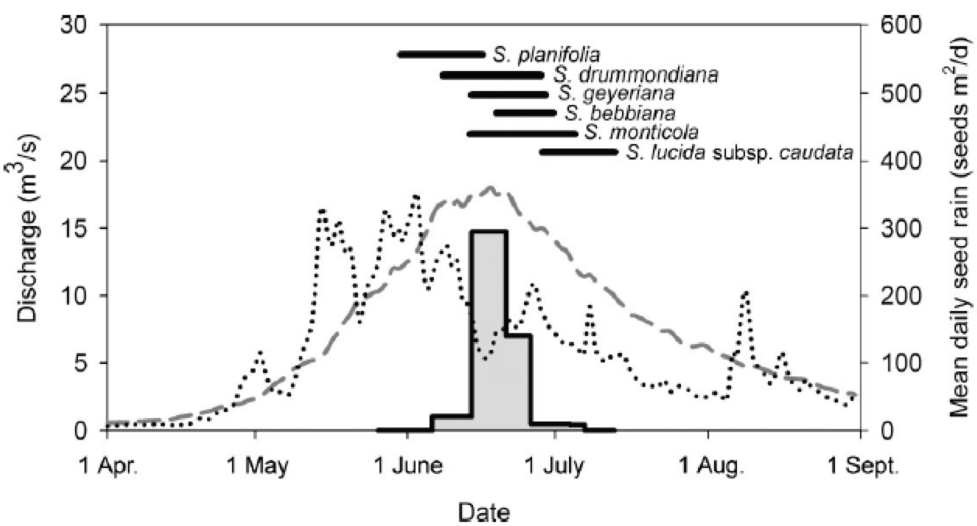

Figure 9. This figure, reproduced from Gage and Cooper (2005), describes the timing of willow seed rain (shaded columns) relative to snowmelt flow (dotted line – same year flow, dashed line – average flow). The seed-release period for individual willow species are also described by horizontal bars.

We can at least formulate hypotheses of the relationship between willow and flow alteration, and these hypotheses were developed into plots (Figure 10). These concern montane and subalpine willow shrublands in wide valley settings, including *S. planifolia, S. geyeriana, S. monticola*, and *S. petiolaris*. The first scenario (Scenario A) represents a largely intact system, with beaver widespread and low levels of grazing, clearance and developmental pressures. In this situation, beaver have the potential to mitigate much of the impact of flow alteration on disturbance regimes. The range of response for Scenario A is expected to vary depending on the degree of alluvial groundwater recharge from adjacent hillslopes (cf. streamflow recharge). High recharge from hillslopes is expected to offer some mitigation for the effects of flow alteration, because willow productivity/survival is less dependent on stream flow for groundwater recharge. As discussed previously, an absence of floods for Scenario A streams may support expansive willow cars, but is very susceptible to additional stressors.

Scenario B lacks severe grazing and developmental pressures (as per Scen. A), but also lacks beavers. In this scenario we expect willow shrublands to be most susceptible to flow alteration. Note that we do not expect the natural flow regime will be sufficient, in the absence of beaver, to maintain maximum potential for willow shrubland (i.e. willow maintenance is <1 at flow alteration of 0).

For Scenario C, direct pressure on willow from grazing and other development is high and beaver are expected to be largely absent as a direct or indirect consequence of development/grazing. In this scenario we do not expect to see extensive willow shrublands regardless of flow alteration (or lack of). Willow may be reduced to a narrow strip along the stream banks. Heavy grazing can trigger collapse of beaver-willow communities (Baker et al. 2005), with low groundwater levels increasing susceptibility to grazing effects (Peinetti et al. 2001).

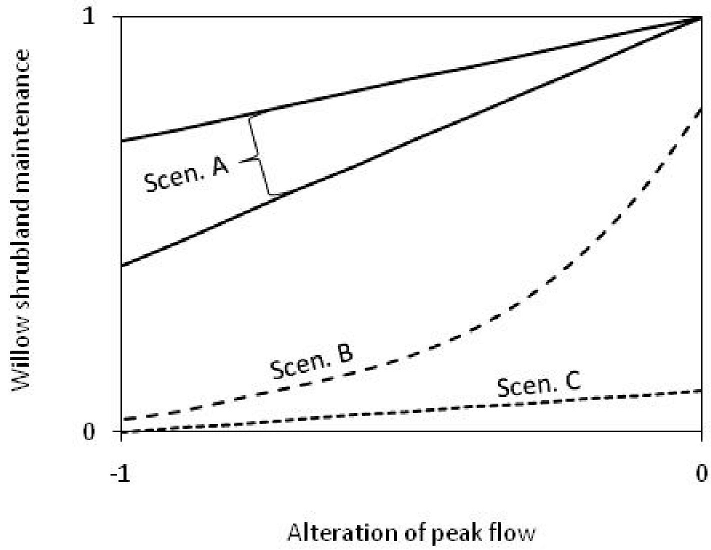

Figure 10. Hypothesized response of riparian willow to flow alteration under 3 scenarios. These concern willow shrublands in wide valley settings, including *S. planifolia, S. geyeriana, S. monticola*, and *S. petiolaris*.

> *Scenario A* – Beaver present, with an upper and lower range of response depending on degree of recharge of alluvial groundwater from adjacent hillslopes (low hillslope recharge for lower line).
> *Scenario B* – Beaver absent. High dependence on snowmelt floods for willow recruitment and ultimately for shrubland maintenance.
> *Scenario C* – Heavy grazing and or clearing of willow.

These different response scenarios suggest that application of flow-ecology curves should be targeted at a subset of the wide, low-to-moderate gradient valleys >8000 feet. Where beaver are active (Scenario A), particularly where there are significant groundwater inputs, willow shrublands are less likely to show a dramatic decline in response to flow alteration. Therefore, consideration of willow response to flow alteration is a low priority in these locations. Flow-ecology relationships could be applied to both Scenario B and Scenario C. In Scenario B (limited grazing and development, but without beaver), willows are expected to be most sensitive to flow alteration. In Scenario C (human activities trump ecological processes), unaltered flow indicates the potential for healthy willow ecosystems, but the realized extent of willow shrublands is limited by other factors. Identifying streams that lack beaver (Scenario B and C) across the Colorado basin (wide valley, montane-subalpine) would allow targeted application of flow-ecology relationships where flow alteration is most likely to constrain the potential extent of willow shrublands.

Because the data available to describe flow-ecology relationships for willow are limited, *we do not recommend a quantitative function for evaluating the risk of flow alteration effects on* willow. However, alteration in peak flows can provide a basis for general inferences about risk to willows, using the conceptual relationships described above.

The flow metric that could be used to describe peak flow alteration also deserves consideration. The flow metric used for cottonwood (90-day maximum) may be too long because streamflow patterns are expected to be less important for post-germination survival of willow at high-elevations compared to cottonwood in semi-arid areas (Patten 1998). Temperatures are cooler and available moisture is expected to be higher above 8000 feet (both atmospheric humidity and soil moisture), so willows may tolerate being disconnected from the water table. Woods and Cooper (2005) observed a correlation between willow seedling survival and soil moisture within 3 weeks of the snowmelt peak (the "steep recession limb of the snowmelt hydrograph"), but not later in the year and little apparent benefit from supplemental irrigation. Additionally, the growing season is short at high elevations, which constrains the maximum duration per year of streamflow influence on plant growth. Therefore, the 30-day maximum flow may be a better indicator metric, compared to the 90-day maximum used for cottonwood. The 1-day maximum flow is likely correlated with the 30-day maximum flow and thus could be informative as an indicator metric. The return period of flow events that are associated with recruitment of willow (3-5 years, Cooper et al. 2006) are equivalent to that described for cottonwood in wide valley settings. The consideration of only wet-years (years exceeding the 70%ile mean annual flow) for cottonwoods could also be used for willow.

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