# Review of Off-Channel Habitat Protection Under the Current Washington Forest Practices Rules

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Prepared by

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## Executive Summary

The current Washington Forest Practice Rules (FPR) (Washington Administrative Code 222-08) for fish bearing waters provide measures for protection of off-channel habitat (OCH). Concerns about whether the current water typing rule adequately protects OCH in small streams resulted in the formation of a science work group to review the rule to determine if it adequately defines, delineates, and protects OCH for fish. Here, we report on the findings of our work group. To assist with our review, we examined the literature and latest science in three major categories including: 1) importance of OCH to fish, 2) role of OCH in regulating aquatic productivity, and 3) literature to support using bankfull width, depth or height to define OCH. There is extensive scientific literature that demonstrates the importance of OCH for fish and other biota in both large alluvial rivers as well as smaller more confined streams such as those covered by the rule. In addition, there is extensive literature documenting the importance of OCH in regulating productivity of small streams and production of salmonids and other fishes. OCH under the current FPRs are defined primarily by bankfull width (BFW) and corresponding elevation at bankfull flow. Thus, whether bankfull elevation (BFE) is the appropriate flood elevation to delineate OCHs is the critical component of the OCH rule in question. There is extensive scientific literature to support use of BFW and BFE to delineate channels and floodplains. While the approach for defining OCH under the current rule seems logical, it is unclear if using BFE to delineate OCH leads to exclusion of some habitats or inadequate protection of OCH under the current rule. We outlined a handful of scenarios where the current rule may be excluding OCH, though it is not clear how common OCH is in the stream channels in question. Moreover, there is little existing research for quantifying (1) the proportion of OCH that would be excluded at BFE, (2) the flood return interval needed to capture a given percentage of the available OCH, or (3) the biological impact of not protecting all or different percentages of OCH. We close with recommended studies needed to address these key uncertainties.

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# Introduction

Off-channel habitats (OCHs) such as sloughs, alcoves, groundwater-fed side channels, beaver ponds, and wetlands permanently or seasonally connected to streams are important rearing and reproductive areas for fish, amphibians, and other biota (Welcomme 1979; Ward et al. 1999; Roni et al. 2006; Meyer et al. 2007). OCHs are particularly important for juvenile Pacific salmonids (*Oncorhychus* spp.) and there is broad literature documenting their importance particularly for juvenile coho salmon (*Oncorhychus kisutch*) (e.g., Scarlett and Cederholm 1984; Brown and Hartman 1988; Swales and Levings 1989; Morley et al. 2005). Floodplains and off-channel areas also typically provide high species richness, refuge from predators, and complex, highly-productive habitats for different life stages of salmonids and other vertebrates (Welcomme 1979; Fausch 1984; Gregory et al. 1991; Bayley 1995; Jeffres et al. 2008; Baldock et al. 2016). The current Washington Forest Practice Rules (FPR; Washington Administrative Code 222-08) for Type F[1] waters provide measures for protection of off-channel habitat. Under WAC 222-16-030, OCH is defined as part of Type F waters as follows:

***"Type F Water"*** *means segments of natural waters other than Type S Waters, which are within the bankfull widths of defined channels and periodically inundated areas of their associated wetlands, or within lakes, ponds, or impoundments having a surface area of 0.5 acre or greater at seasonal low water and which in any case contain fish habitat or are described by one of the following…*

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[1] The proposed water typing rules include Type S Water, Type F Water, Type Np Water, and Type Ns Water. Complete definitions can be found in Chapter *222-16-030. The interim water typing rules include Type 1 (S), Type 2 & 3 (F), Type 4 (Np), and Type 5 (Ns) and detailed definitions can be found in WAC *222-16-030.

*(e) Riverine ponds, wall-based channels, and other channel features that are used by fish for off-channel habitat. These areas are critical to the maintenance of optimum survival of fish. This habitat shall be identified based on the following criteria:*

> *(i) The site must be connected to a fish habitat stream and accessible during some period of the year; and*
>
> *(ii) The off-channel water must be accessible to fish.*

Until formal adoption, interim waters typing rules are in effect. The interim water typing rules (WAC 222-16-031) define Type 2 (Type F) waters and off-channel habitat more specifically as follows:

***"Type 2 Water"*** *means segments of natural waters which are not classified as Type 1 Water and have a high fish, wildlife, or human use. These are segments of natural waters and periodically inundated areas of their associated wetlands, which: ...*
*(e) Are used by fish for off-channel habitat. These areas are critical to the maintenance of optimum survival of fish. This habitat shall be identified based on the following criteria:*

> *(i) The site must be connected to a fish bearing stream and be accessible during some period of the year; and*
> *(ii) The off-channel water must be accessible to fish through a drainage with less than a 5% gradient.*

The current interim rules were meant to be used until detailed fish habitat water type maps mentioned in WAC 222-16-030 were available. The definition and delineation of OCH in the above rules are largely based on the Forest and Fish Report (FFR 1999). Whether the rules adequately define, delineate, and protect OCH has been identified as an area in need of additional examination. On October 1, 2015 per request of the TFW Policy Co-Chair, the Adaptive Management Program Administrator (AMPA) outlined a process to:

- Confirm the definition of off-channel habitat as it exists in the current forest practices rules
- Confirm the manner in which OCH is delineated under the current forest practices rules
- Make recommendations for a permanent Water Typing rule to be presented to the Forest Practices Board.

These recommendations included five tasks for the science track:

1. Collect and review current literature and protocols used to define processes for identifying OCH.

2. Determine if OCH is being omitted from FPAs under the existing definition used to define OCH in the interim water typing system rule and, if yes, describe these habitats in a manner that would facilitate coverage.

3. Review the existing definitions of bankfull width and bankfull depth in the forest practices rules and the FFR, and determine if using bankfull elevation in the definition would be more beneficial than bankfull depth in the determination of OCH. The rule currently defines bankfull width as ‘the measurement of the lateral extent of the water surface elevation perpendicular to the channel at bankfull depth’.

4. Review the OCH description developed during Policy field site visits to determine if this description meets the definition of OCH and adequately covers off channel habitat as currently described in rule, WAC 222-16-031. The site visits found "*Off Channel Habitat consists of waters connected to and draining into Type S and F waters by inundation at bank full elevation of the Type S or F water and encompassed by that area of inundation at bank full width and elevation*."

5. Define the flood return interval that defines 95% of OCH and the field methods used to delineate that flood return interval.

To address these tasks, it was recommended that a formal OCH Technical Working Group with expertise in fluvial processes and aquatic ecology be contracted to complete these tasks, including development of a final report and presentation of findings to TFW Policy.

## OCH Working Group Approach

On February 25, 2016 a contract was issued to Dr. Philip Roni to convene and lead the OCH Technical Working Group. Based on discussions with the AMPA and the tasks that the group was charged with, it was determined that the OCH Technical Working Group (Working Group) should include leading experts with experience in stream and salmonid ecology, off-channel and floodplain habitats, fluvial geomorphology and channel classification, riparian ecology and forest practice rules. The Working Group includes four experts who have written many key papers on off-channel habitats, channel typing, and salmonid and stream ecology and each have more than 20 years of experience in the field. In addition to Dr. Roni (Principal

Scientist, CFS), the team includes Dr. Peter Bisson (retired USDA Forest Service Researcher), Dr. George Pess (Research Scientist and Program Manager with NOAA Northwest Fisheries Science Center), and Dr. John Buffington (Research Geomorphologist, USDA Forest Service). All members of the working group have extensive experience working on salmon habitat and forestry issues in Washington State and the Pacific Northwest. Brief biographies of the OCH Working Group are provided in Appendix A.

The Working Group approach consisted of four steps. First, familiarize the Work Group with Washington Forest Practice Rules as they pertain to Type F (Type 2) waters and off-channel habitats, and the tasks the group has been asked to address. Second, convene in person meetings to go through each of the major tasks and provide recommendations, clarification and discussion of science to address, support or amend the current definition of OCH under the FPR. Third, conduct a site tour to view field examples of streams where OCH rules apply. Fourth, draft the report and present the findings to Policy. As instructed, the Working Group also conducted a review of the current literature related to OCH and to specific tasks.

This report summarizes the approach and findings of the Technical Work Group, including responses to these major tasks as well as recommendations for future studies that may be needed to refine or improve the current method of delineating OCH. The five tasks outlined above all focus on understanding if important OCHs are being excluded from protection. Rather than presenting the literature review in a separate section, we reviewed the literature and incorporated it into our findings and responses to key questions posed for each task.

## Current Literature on Importance of OCH

The literature on off-channel habitats, which is sometimes considered synonymous with floodplain habitats, is extensive and global in nature. Rather than review all literature on off-channel and floodplain habitats, we reviewed literature that was pertinent to forested streams in the Pacific Northwest (PNW). Moreover, since the FPR addresses the protection of OCH at two scales, one being OCH or floodplain habitats in larger streams which are covered by the channel migration zone (CMZ; WAC 222-16-010), and second with the focus on relatively small streams (generally 3rd order or less based on Strahler (1957) stream classification[2]), we generally focused on literature from small to medium-sized streams. We examined literature in three major categories including: 1) importance of OCH to fish, 2) role of OCH in regulating aquatic productivity, and 3) support for using bankfull width, depth or height to define OCH.

The quality and utilization of stream channels for fish vary seasonally and off-channel habitats are often occupied when conditions in the main stream channel become unfavorable (Peterson 1982a; Martens and Connolly 2014). As noted in the introduction, the importance of OCH to salmonids and non-salmonids fishes, amphibians and other aquatic biota has been well documented (Welcomme 1979; Ward et al. 1999; Henning et al. 2006; Olson et al. 2006; Roni et al. 2006; Branton and Richardson 2014). In the Pacific Northwest, these habitats are seasonally important to juvenile coho salmon and Chinook salmon (*O. tshawytscha*) (e.g., Scarlett and Cederholm 1984; Brown and Hartmann 1988; Swales and Levings 1989; Nickelson et al. 1992a; Morley et al. 2005), as well as resident (non-anadromous) salmonids such as cutthroat trout (*Oncorhynchus clarkii*) (Bustard and Narver 1975; Rosenfeld et al. 2000) and bull trout

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[2] Note these are approximately streams less than about 10 meters in bankfull width.

(*Salvelinus confluentus*) (Baxter et al. 1999; Bean et al. 2014). While they have received less attention, off-channel habitats are important areas for non-salmonid fishes (Moyle 2002; Wydowski and Whitney 2003; Henning et al. 2006; Markle *In press*). The vast majority of research on off-channel habitats has been on the floodplains of large to medium sized alluvial rivers (Bayley 1995; Richardson et al. 2005). We located more than 40 references that provided information on the importance of OCH to fish in the PNW in small to medium sized streams. Rather than a lengthy review of the literature, we summarize the key findings and provide a list of key references pertinent to the tasks at hand in Appendix B. While this is a relatively small body of literature compared to the research on large floodplain rivers globally, these papers consistently show the importance of off-channel habitats to production of stream-dwelling fishes (e.g., Peterson 1982; Swales et al. 1986; Hartman and Brown 1987; Nickelson et al. 1992a, b; Richards et al. 1992; Brown 2002; Morley et al. 2005; Ogston et al. 2014). All these studies were conducted in the PNW, making the work highly relevant to the current review.

OCHs are not necessarily common in the small to medium-sized streams covered by the OCH rules. This is in part because of the location of such streams in the landscape; typically occurring at higher elevations in constrained valleys with little floodplain development. Moreover, streams with wider floodplains are covered by other parts of the Forest Practices Rules (i.e., riparian management zone (RMZ) and CMZ). However, OCHs in small to medium sized streams can occur in areas where such habitats are relatively scarce and, thus, can be of disproportionate importance for rearing and refuge during certain periods. For example, OCHs provide refuge during high flow periods when water velocities in the main channel become too great for fish to maintain profitable feeding stations (Peterson 1982a; Fausch 1984). Without access to OCH, rearing salmonids and other fishes may volitionally migrate or be physically displaced downstream. Research on coho salmon in the Oregon Coast Range has demonstrated the importance of OCH to coho production, and how increasing the amount and accessibility of OCH can lead to large increases in parr and smolt production (Nickelson et al. 1992b; Solazzi et al. 2000). Furthermore, the presence of accessible, ecologically complex OCH in small and medium sized streams adds to the overall diversity of habitat types in the drainage system. This in turn facilitates the expression of freshwater life history variation (occupying multiple habitats at different times and places by different individuals in a population) – a "spreading the risk" habitat strategy believed to promote population resilience (Bisson et al. 2009).

The role of OCH in regulating aquatic productivity is well documented in alluvial streams with well-developed floodplains. OCHs are known to support increased growth and survival for juvenile coho and Chinook (Sommer et al. 2001 2005; Giannico and Hinch 2003; Jeffres et al. 2008; Ogston et al. 2014) as well as support higher densities of juvenile Chinook and coho salmon than many mainstem rivers or small streams as a result of more favorable water velocities, cover and habitat conditions, improved water clarity, a wider variety of food resources, and absence of predatory fishes (e.g., Reeves et al. 1989; Swales and Levings 1989; Nickelson et al. 1992; Solazzi et al. 2000; Rosenfeld et al. 2008; Ogston et al. 2014). OCHs are also important in regulating stream productivity by acting as storage reservoirs for organic matter (Webster and Meyer 1997), for nutrient cycling and primary production (Decker 1999; Richardson et al. 2005; Wipfli and Baxter 2010), for production of macroinvertebrates for fish consumption (Gregory et al. 1991; Bellmore et al. 2013), and thermoregulation for optimal growth (Baldock et al. 2016). While much of the literature comes from floodplains adjacent to large rivers, several of the studies referenced above were conducted in relatively small streams (e.g., Reeves et al. 1989; Nickelson et al. 1992; Solazzi et al. 2000, Richardson et al. 2005; Wipfli and Baxter 2010; Baldock et al. 2016). It is important to note that some of the ecological functions provided by OCH do not require fish to actually occupy a site. Organic matter storage and processing in fishless off-channel areas, even where surface flows are absent much of the time, are nevertheless an important component of the stream's food web (Bisson and Bilby 1998). Therefore, there are some off-channel sites that are never actually occupied by fish, but that constitute part of the stream environment that supports fish productivity.

## Use of Bankfull Width and Depth to Define OCH

The WAC 222-16-010 defines bankfull depth (BFD) and bankfull width (BFW) as follows:

*Unless otherwise required by context, as used in these rules:*

***"Bankfull depth"*** *means the average vertical distance between the channel bed and the estimated water surface elevation required to completely fill the channel to a point above which water would enter the flood plain or intersect a terrace or hillslope. In cases where multiple channels exist, the bankfull depth is the average depth of all channels along the cross-section. (See board manual section 2.)*

***"Bankfull width"*** *means:*

*(a) For streams - the measurement of the lateral extent of the water surface elevation perpendicular to the channel at bankfull depth. In cases where multiple channels exist, bankfull width is the sum of the individual channel widths along the cross-section (see board manual section 2).*

*(b) For lakes, ponds, and impoundments - line of mean high water.*

*(c) For tidal water - line of mean high tide.*

*(d) For periodically inundated areas of associated wetlands - line of periodic inundation, which will be found by examining the edge of inundation to ascertain where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland.*

The literature supporting the use of bankfull width (BFW), depth (BFD), and elevation (BFE) to delineate OCH can be divided into three main areas: 1) use of bankfull width and depth as a measure of stream size and floodplain extent, 2) use of bankfull depth as an indicator of flood return interval, and 3) use of bankfull elevation to determine extent of OCH.

Bankfull dimensions (width, depth) are standard measures of channel size in fluvial geomorphology and have a long history of use (e.g., Leopold et al. 1964; Leopold and Skibitzke 1967; Dunne and Leopold 1978; Harrelson et al. 1994). The bankfull flow is a frequent flood (occurring every 1-2 years on average, Williams 1978) that commonly transports the most sediment over time (Wolman and Miller 1960) and sets the long-term, average, morphology of floodplain rivers. The guidelines for determining bankfull dimensions outlined in the Forest Practice Board Manual (2004), which appear to be based largely on Pleus and Schuett-Hames (1998), are widely used and accepted approaches. However, determining bankfull dimensions from field observations is not without uncertainty (Johnson and Heil 1996; Buffington et al. 2009); there can, in fact, be a fair amount of variability in bankfull dimensions within a reach and from one observer to the next (e.g., Roper et al. 2010). Training and use of standard protocols reduce this uncertainty, but it should be recognized that delineation of OCH from bankfull dimensions has a certain amount of inherent uncertainty associated with it.

While it is logical to use bankfull dimensions for determining the extent of OCH as described under the FPR, the Working Group was unsure of the evidence to support the use of BFE to adequately delineate OCH. Therefore, we reviewed the literature for evidence supporting this approach and to understand the most appropriate elevation (bankfull or higher) for protecting OCH.

Although there is considerable literature about methods for determining bankfull depth and discharge (See Appendix B), only a handful of studies have looked at using bankfull characteristics (width, elevation or depth) to define floodplain, riparian habitats and associated flood return intervals. Verry et al. (2004) defined the riparian zone in terms of Rosgen's (1996) floodprone width (an approximation of the 50-year flood extent, which is empirically defined as the width of the valley measured at an elevation of twice the bankfull depth). Sullivan and Watzin (2009) used BFE to separate in-channel vs. floodplain habitats and related bankfull metrics to the level of channel−floodplain connectivity and fish assemblages (diversity) in the Champlain Valley, Vermont, although this was for larger river floodplain waterbodies.

In addition, there are a number of GIS approaches that have been used to predict BFE and floodplain extent from digital elevation models (DEMs) (e.g., Hall et al. 2007; Nagel et al. 2014). For example, Nagel et al. (2014) provide a freely available GIS program called the Valley Confinement Algorithm to define the extent and shape of unconfined valley bottoms. Hall et al. (2007) used a GIS approach to predict BFE and floodplain extent from DEMs to assist with salmon habitat mapping for the entire Columbia River Basin.  GIS approaches are attractive because they allow rapid assessment of entire watersheds and regions, but they should be viewed as first-order estimates that frequently have large errors and require field verification and algorithm training. Moreover, most of these approaches focus on larger floodplain rivers, rather than the relatively small and confined channels covered by the OCH rule.

A recent study by Vondrasek (2015) compared use of high-resolution LiDAR data and GPS surveys for modeling channel hydraulics and delineating riparian areas and off-channel habitats under dense forest canopy in two relatively unconfined streams (Snahapish River and Goodman Creek on the Olympic Peninsula). He found that LiDAR topography coupled with a simple hydraulic model allows one to both locate riparian areas and delineate discrete off-channel wetlands, tributaries and side channels. He also found that this LIDAR-based hydraulic model allows one to model flows in these areas to examine seasonal hydrologic connections to the main channel and how the extent of OCH varies with flood recurrence interval. However, a less intensive relative elevation model, that simply used the elevation above bankfull performed similarly to the LIDAR-based hydraulic model in delineating OCH (Vondrasek 2015). While his study was on streams that are larger and have more pronounced floodplains than those typically covered by the OCH rule, it does provide a useful case study for demonstrating how hydraulic models and remote sensing can be used to predict the extent of OCH that might be excluded under the interim rules based on BFE.

Although our literature review demonstrates that BFE has been used in delineating floodplain and off-channel habitats, we are not aware of any studies other than Vondrasek's (2015) that have assessed how the extent of OCH varies with discharge. Consequently, it is difficult to assess the adequacy of using BFE for delineating OCH. On the one hand, it is a logical approach because (1) bankfull discharge controls the long-term average channel morphology in many temperate floodplain rivers, within which aquatic habitat is embedded; (2)

bankfull flow is a frequent, typical flood that aquatic organisms are likely adapted to; and (3) bankfull is an easily identifiable feature (from topography, vegetation, etc.), making it a consistent and repeatable metric. As such, BFE is a convenient and relevant index of OCH extent. On the other hand, limiting delineation to the bankfull elevation could exclude additional floodplain habitat that may be available during higher flows, the extent and importance of which require further study. We speculate that results are likely basin- and species-specific, depending on hydroclimate (magnitude and duration of flooding), degree of channel confinement (floodplain geometry and hydraulics of overbank flows), type and age of riparian vegetation (roughness and floodplain complexity), and fish species/phenotype (preferred channel type and associated process domain with regard to valley geometry and flood regime, life history relative to timing of floods, and floodplain habitat requirements (depth, velocity, cover, temperature, food)). Because the OCH rules mainly apply to small and medium-sized channels with limited floodplain development, the extent of additional OCH above the BFE may be limited. Nevertheless, a certain fraction of these small channels may offer more extensive habitat that may be important in certain river systems or to certain fish species, phenotypes, and life stages. As such, further investigation is warranted, as outlined later in the report.

Finally, while the Forest Practice Rules for delineating OCH mention bankfull depth, the key issue is determining an appropriate reference elevation (bankfull or higher) that sets the datum for defining the extent of OCH.

## 5% gradient OCH Rule

The Working Group was interested in how the 5% gradient rule was determined and how 5% gradient is calculated (i.e., average, maximum, etc.). There were a few scenarios where we could conceive of a channel that was more than 5% gradient that might connect OCHs that are above the bankfull elevation. There was, however, no documentation in the FFR of the 5% gradient rule. We assume the 5% is likely based on the stream gradient limit that is considered suitable for juvenile coho or Chinook salmon rearing or passage. Providing further documentation of how the 5% rule was determined and some analysis of how often this gradient rule might, in practice, lead to exclusion of important habitats would be helpful.

## Define the flood return interval that defines 95% of OCH and related field methods

Determining the appropriate flood return interval that defines a particular percentage of OCH is no small task and is beyond the scope of what could be accomplished for this report. As noted previously, bankfull discharge typically has a flood return frequency of 1 to 2 years, though this varies considerably within and among streams and geographic provinces (Woodyear 1968; Williams 1978; Castro and Jackson 2001; Wilkerson 2008). Determining the flood return interval that will protect a specific percentage (i.e., 75%, 85%, or 95%) of floodplain habitat would require hydraulic modeling across a range of sites covered by the OCH rule. As discussed above, results will likely vary with hydroclimate (i.e., east vs. west side basins) and process domain (location within a basin, discharge regime, and degree of channel confinement; Montgomery 1999), nor are the biological consequences clear in terms of the ecological role of rare flood events relative to typical life cycles of a given species. Long-term monitoring or use of a fish population model would be needed to assess the potential biological effects.

## Examples of areas that might be excluded from the current interim rule

The OCH Work Group thought of a number of instances where the current rule could potentially exclude OCH including:

1. Wetlands, ponds, side channels or other wetted areas above BFE that do not contain fish[3] but are only connected at flood elevations higher than BFE.
2. Areas above BFE that are dry at most flows, but where fish may move into during episodic floods to rear and feed and then move back into the main channel when flows recede (i.e., Brown and Hartman 1988).
3. OCHs connected to primary channel by a channel that is steeper than 5% and does not contain fish migration barriers.
4. Areas that are currently isolated from the main channel by an obstruction, such as a logjam or natural levee (bank or berm), that may be connected in the future following natural deterioration or erosion of the obstruction (i.e., habitats that might be isolated now, but could be connected in future).

In addition, the areal extent of some habitat may change from season to season and since the RMZ would begin at the edge of the OCH, the season at which the OCH is delineated could have an impact on the starting point of the RMZ and whether the full extent of the OCH would be protected. We also note that, unlike delineation of the CMZ, temporal changes in OCH are not

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[3] If they were isolated from channel but contain fish they are Type F waters.

planned for. Rather OCH is assessed based on conditions observed at a given time. While OCH may not be as dynamic as other fluvial environments, such as the CMZ, OCH is expected to respond to large floods, such as those that occurred in 2006.

What is not clear is:

- How common are these scenarios where OCH could be excluded under the current rule (WAC 222-080-031)?
- How much OCH or what percentage of OCH would be excluded?
- What is the biological impact or importance of excluding these habitat from protection?

The Working Group felt that additional information or study was needed to determine the frequency of OCH in the streams in question and the frequency with which habitats similar to those listed above might be excluded from protection by the RMZ or used as the starting point for the RMZ.

## Suggestions for Additional Study

To address the key uncertainties above, a series of studies with two phases are recommended. Phase 1 of the study would be to examine OCHs within streams covered by the current OCH rule to determine the frequency and extent of OCH across the landscape and how often OCHs are excluded or under protected. This would likely require sampling a subset of units harvested (50 to 100) in recent years that include streams that fall in the size and gradient of streams where OCH is likely to exist. An initial office review and analysis would be conducted to determine how commonly the OCH rule is implemented. Field visits would then be conducted to 1) assess cases of omission and commission and 2) to confirm that OCHs were properly delineated and to assess the proportion of OCH within or outside the RMZ at sites where the rule was applied. Stratification and selection of sampling sites would be critical for a rigorous study and need to include geographic province (eastern vs. western Washington), ownership, channel size/stream order and other factors. The sample could potentially be drawn from unharvested units, units that will be harvested, or units that have been harvested – all of which have potential strengths and weaknesses. We recommend drawing the sample from recently harvested units (perhaps those within the last 5 years) because it would allow confirmation of how the rule is currently being applied and would likely best address the key uncertainties about the current rule. Because of the variation in conditions among sites within and between different landscapes, it is necessary to have a relatively large, well-stratified sample. Products would include an estimate of the amount of OCH present in stream types in question, the proportion of sites where OCH was accurately delineated, and an initial list of sites for more detailed sampling and modeling in Phase 2.

Phase 2 would include more detailed research to determine whether BFE is adequate or whether a higher elevation is needed to fully protect and capture important OCH functions or what elevation above BFE would be more appropriate. This would require sampling and monitoring harvested units (presumably from Phase 1) where OCH exists to:

1) Determine seasonal extent and connectivity of OCH at different flows, in different geomorphic settings, and in different hydroclimates.

2) Conduct hydraulic modeling based on field survey data and LiDAR to examine extent of OCH at various flood recurrence intervals and elevations above bankfull.

3) Monitor fish use of OCH at various flows to determine if fish are in fact using OCH that may exist above BFE.

Ideally, sites would be taken from those sampled in Phase I; however, given that OCH in the stream channels in question may not be very common, additional units with OCH may need to be identified. Geomorphic features of those sites where OCH designation has been applied could be used to help locate other likely sites. Similar to Phase 1, a relatively robust sample (>25 sites) would be needed to provide a landscape perspective of the extent and persistence of OCH and the implications to fish and fish habitat of using BFE, or some other higher elevation to delineate OCH. Sampling multiple sites would also be required to adequately address policy questions about the benefit to fish of protecting different percentages (i.e., 75%, 85%, and 95%) of OCH sampling. Products would include proportion of OCH protected or excluded by BFE under the current rule, elevation and flood return interval that protects 100% of OCH in streams in question, fish use of OCH habitats at different flows and elevations and impacts of using BFE or other elevations on fish habitat.

## Conclusions

In response to the five tasks we draw the following conclusions.

**Task 1. Collect and review current literature and protocols used to define processes for identifying OCH.**

There is extensive literature documenting the importance of OCH to fish and for regulating the productivity of streams and aquatic habitats.

**Task 2. Determine if OCH is being omitted from FPAs under the existing definition used to define OCH in the interim water typing system rule, and, if yes, describe these habitats in a manner that would facilitate coverage.**

It is likely that some OCH is being excluded by using BFE, but additional research is needed to determine the extent and how common this is across the landscape.

**Task 3. Review the existing definitions of bankfull width and bankfull depth in the forest practices rules and the FFR, and determine if using bankfull elevation in the definition would be more beneficial than bankfull depth in the determination of OCH.**

The approach for defining OCH under the current rule using BFE seems logical and is at least partially supported by existing science on use of bankfull measures to delineate channels, channel morphology, and floodplains. The critical issue is whether using BFE to delineate OCH provides adequate protection. Moreover, there are no studies that have specifically examined using BFE to delineate the extent of OCH or the flood return interval that might delineate all or a specific portion of OCH. Given the uncertainty of using BFE, amending the language of the existing rule in this regard is not recommended at this time. However, further study of the issue is encouraged.

**Task 4. Review the OCH description developed during Policy field site visits to determine if this description meets the definition of OCH and adequately covers off channel habitat as currently described in rule, WAC 222-16-031. The site visits found "*Off Channel Habitat consists of waters connected to and draining into Type S and F waters by inundation at bank full elevation of the Type S or F water and encompassed by that area of inundation at bank full width and elevation*."**

The above statement would add clarity to the current rule in terms of emphasizing the importance of bankfull elevation (as opposed to bankfull depth), but uncertainty regarding the adequacy of the bankfull datum for delineating OCH is a key issue to be addressed, as discussed above.

### Task 5: Define the flood return interval that defines 95% of OCH and the field methods delineate that flood return interval.

This question cannot be addressed without additional information and additional studies are needed to determine: (1) how commonly OCH occurs in the stream types in question, (2) whether application of the current rule excludes some OCH from protection and, if so, what elevation (bankfull or higher) would allow for protection of a given percentage of the available OCH, and (3) the biological impacts of not protecting the full extent of OCH at each site, particularly given that the tails of the areal distribution of habitat may correspond with large, rare floods (e.g., 50 or 100-year events). We outline the methods and studies that could address these and other key uncertainties.

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# Appendix A. Bios of OCH Technical Work Group

**Philip Roni (Working Group Chair)**
**Principal Scientist**
**Watershed Sciences Lab, Cramer Fish Sciences**
**Issaquah, WA**

Dr. Philip Roni is a Principal Scientist with Cramer Fish Sciences (CFS) and an Affiliate Professor at the University of Washington School of Aquatic and Fishery Sciences. He has more than 25 years of experience as a fisheries research scientist and directs the CFS Northwest science team where he focuses on designing, implementing and completing, and publishing definitive studies to address pressing questions related to protection, management and restoration of aquatic systems. Prior to joining CFS, Dr. Roni led the Watershed Program at the NOAA Northwest Fisheries Science Center where he directed more than 25 scientists conducting habitat research. His research for the last 20 years has concentrated on planning, prioritization, and evaluation of various watershed restoration techniques. He regularly teaches courses and has published numerous papers on restoration science, including the comprehensive books "Stream and Watershed Restoration: a guide to restoring riverine processes and habitat" (2013 Wiley-Blackwell) and "Monitoring Stream and Watershed Restoration" (2005 AFS). Recent ongoing large research projects include estimating salmonid egg-to-fry survival, evaluating the effectiveness of large regional restoration programs, and fish response to whole watershed restoration. He received a Presidential Early Career Award (2004) from the US President and a Certificate of Achievement (2012) from the AFS for his contributions to restoration science. He has both an M.S. and a Ph.D. from the University of Washington.

**Peter A. Bisson**
**Emeritus Scientist,**
**UDSA Forest Service, Pacific Northwest Research Station**
**Olympia, Washington**

Pete Bisson is an emeritus scientist with the USDA Forest Service Pacific Northwest Research Station in Olympia, Washington. He received a B.A. in environmental biology from the University of California at Santa Barbara, and M.S. and Ph.D. degrees in fisheries from Oregon State University. From 1974 to 1995 he was an aquatic biologist for the Weyerhaeuser Company in Tacoma, Washington. In 1995 he joined the Forest Service, where his studies included fish populations, stream habitats and food webs, riparian zones, and a variety of management issues related to aquatic ecosystems. Prior to his retirement in 2012 Pete held affiliate faculty appointments at the University of Washington, Oregon State University, and the University of Idaho, and served on two National Research Council committees: one on Pacific salmon and the other on watershed management.

**John M. Buffington**
**Research Geomorphologist**
**U.S. Forest Service**
**Rocky Mountain Research Station**
**Boise, Idaho.**

John is a Research Geomorphologist with the U.S. Forest Service, Rocky Mountain Research Station in Boise, Idaho. He graduated from the University of California Berkeley in 1988 with a BA in geology and from the University of Washington in 1995 and 1998 with MS and PhD degrees in geomorphology. He was a National Research Council Fellow from 1998 to 2000 and a professor in the Center for Ecohydraulics Research at the University of Idaho from 2000 to 2004. He currently serves on the Science Advisory Board for the Trinity River in northern California and co-edits the Journal of Geophysical Research-Earth Surface. His research focuses on fluvial geomorphology of mountain basins, biophysical interactions, and the effects of natural and anthropogenic disturbances on salmonid habitat.

**George R. Pess**
**Watershed Program Manager**
**NOAA Northwest Fisheries Science Center**
**Seattle, WA**

George has worked in the fisheries science and management field since 1989. His primary research interest during that time has been the examination of natural and land-use effects on salmon habitat and production. George has conducted research on historic and current land use impacts on salmon habitat and production, the influence of wood in forested stream channels, the development of a wood recruitment model to determine the relative influence of forestry activities, what role watershed analysis plays in ecosystem management, and how landscape characteristics and land use affect salmon abundance and distribution. George has a B.A. in Economics and Environmental Science (Bowdoin College 1987), an M.S. in Forest Science (Yale University 1992), and a Ph.D. in Aquatic and Fishery Sciences (University of Washington, 2009).

# Appendix B. Relevant Off-Channel Habitat Literature

The following provides a summary of the relevant literature we located and reviewed related to 1) importance of OCH to fish, 2) role of OCH in regulating aquatic productivity and 3) and key literature on bankfull width, depth and height. It should be noted that our focus for 1) and 2) was small streams similar to those covered by OCH rule and we excluded several references that were focused on large alluvial rivers.

**1) Importance of OCH to Fish**

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Richardson, J. S., R. J. Naiman, F. J. Swanson, and D. E. Hibbs. 2005. Riparian communities associated with Pacific Northwest Headwater streams: assemblages, processes and uniqueness. Journal of American Water Resource Association 41(4): 935-947.

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Solazzi, M. F., T. E. Nickelson, S. L. Johnson, and J. D. Rodgers. 2000. Effects of increasing winter rearing habitat on abundance of salmonids in two coastal Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 57(5):906-914.

Sommer, T. R., M. L. Nobriga, W. C. Harrell, W. Batham, and W. J. Kimmerer. 2001. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Sciences 58(2):325-333.

Sommer, T.R., W.C. Harrell, M. L. Nobriga. 2005. Habitat use and stranding risk of juvenile Chinook salmon on a seasonal floodplain. North American Journal of Fisheries Management 25: 1493-1504.

Tabacchi, E., L. Lambs, H. Guilloy, A. Planty-Tabacchi, E. Muller, and H. Decamps 2000. Impacts of riparian vegetation on hydrological processes. Hydrological Processes, Vol. 14 (n° 16-17):2959-2976.

Webster, J. R., and J. L. Meyer. 1997. Stream organic matter budgets. Journal of North American Benthological Society 16(1):3-161.

Wiplfli, M. S. and C. V. Baxter. 2010. Linking ecosystems, food webs, and fish production: subsidies in salmonid watersheds. Fisheries 35:373-387.

## 3) Key Literature on Bankfull width, depth and height including abstract

Abril, J. B., and D. W. Knight. 2004. Stage-discharge prediction for rivers in flood applying a depth-averaged model. Journal of Hydraulic Research **42**(6): 616–629.

The prediction of the stage-discharge relationship for rivers in flood is described by a finite element model of depth-averaged turbulent flow, calibrated using (three hydraulic coefficients governing local bed friction, lateral eddy viscosity and depth-averaged secondary flow. The resulting lateral distributions of depth-averaged velocity are subsequently integrated to yield the stage-discharge relationship. The calibration of the model involves the establishment of simplifying hypotheses for certain coefficients in order to give the correct depth-mean velocity and boundary shear, both across the channel and with stage. Comparisons against some experimental data from the UK Flood Channel Facility, for channels with trapezoidal and compound cross-sections, help develop the calibration philosophy for both inbank and overbank flows. Numerical experiments with the coherence method for a hypothetical river are used to extend the model calibration to rivers with homogeneous and heterogeneous roughness. Applications of the model to simulating the flow in a number of natural valley and mountain rivers serve to test hypotheses and results obtained at a real scale.

Brummer, C. J., T. B. Abbe, J. R. Sampson, and D. R. Montgomery. 2006. Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. Geomorphology 80(3): 295–309.

We combine hydraulic modeling and field investigations of logjams to evaluate linkages between wood-mediated fluctuations in channel-bed-and water-surface elevations and the potential for lateral channel migration in forest rivers of Washington state. In the eleven unconfined rivers we investigated, logjams were associated with reduced channel gradient and bank height. Detailed river gauging and hydraulic modeling document significant increases in the water-surface elevation upstream of channel-spanning wood accumulations. Logjams initiated lateral channel migration by increasing bed-or water-surface elevations above adjacent banks. Because the potential for a channel to avulse and migrate across its floodplain increases with the size and volume of instream wood, the area of the valley bottom potentially occupied by a channel over a specified timeframe - the channel migration zone (CMZ) - is dependent on the state of riparian forests. The return of riparian forests afforded by current land management practices will increase the volume and caliber of wood entering Washington rivers to a degree unprecedented since widespread clearing of wood from forests and rivers nearly 150 years ago. A greater supply of wood from maturing riparian forests will increase the frequency and spatial extent of channel migration relative to observations from wood-poor channels in the period of post-European settlement. We propose conceptual guidelines for the delineation of the CMZs that include allowances for vertical fluctuations in channel elevation caused by accumulations of large woody debris.

Buffington, J. M., B. E. Roper, E. Archer, and C. Moyer. 2009. Reply to discussion by David L. Rosgen on “The role of observer variation in determining Rosgen stream types in northeastern Oregon mountain streams”. Journal of the American Water Resources Association 45(5): 1298-1312.

We thank Rosgen (this issue) for his comments, which provide valuable insight regarding his channel classification and its correct application. However, we believe that many of his objections are based on misinterpretation of our analysis, which we hope to clarify through this reply. Because our measurement techniques differed from those advocated by Rosgen (1996), our study may not represent the range of variability in channel classification that would result from strict adherence to his methods. Nevertheless, this does not invalidate our analysis and the intended study goal of evaluating classification consistency and sources of observed differences. However, some of the identified shortcomings of the classification may stem from our use of methods different from Rosgen's and therefore deserve further analysis.

Castro, J.M., and P. L. Jackson. 2001. Bankfull discharge recurrence intervals and regional hydraulic geometry relationships: patterns in the Pacific Northwest, USA. Journal of American Water Resources Association 37:1249-1262.

The model bankfull discharge recurrence interval (annual series) (Ta) in streams has been approximated at a 1.5-year flow event. This study tests the linkage between regional factors (climate, physiography, and ecoregion) and the frequency of bank-full discharge events in the Pacific Northwest (PNW). Patterns of Ta were found to be significant when stratified by EPA Ecoregion. The mean value for Ta in the PNW is 1.4 years; however, when the data is stratified by ecoregion, the humid areas of western Oregon and Washington have a mean value of 1.2 years, while the dryer areas of Idaho and eastern Oregon and Washington have a mean value of 1.4 to 1.5 years. Among the four factors evaluated, vegetation association and average annual precipitation are the primary factors related to channel form and Ta. Based on the results of the Ta analyses, regional hydraulic geometry relationships of streams were developed for the PNW, which relate variables, such as bank-full cross-sectional area, width, depth, and velocity, to bankfull discharge and drainage area. The verification of Ta values, combined with the development of regional hydraulic geometry relationships, provides geographically relevant information that will result in more accurate estimates of hydraulic geometry variables in the PNW.

Copeland, R. R., D. S. Biedenharn, and J. C. Fischenich. 2000. Channel-forming discharge. U.S. Army Corps of Engineers Technical Note ERDC/CHL CHETN-VIII-5, Vicksburg, MS.

The purpose of this Technical Note is to provide guidance and cautions to be used in approximating channel-forming discharge with bankfull, specified recurrence interval, and effective discharge methodologies. There are limitations for each of these three methods that the user must recognize. INTRODUCTION: An alluvial river adjusts the dimensions of its channel to the wide range of flows that mobilize its boundary sediments. For many rivers and streams, it has been observed that a single representative discharge may be used to determine a stable channel geometry. The use of a single representative discharge is the foundation of regime and hydraulic geometry theories for determining morphological characteristics of alluvial channels. This representative channel-forming (dominant) discharge has been given several names by different researchers, including bankfull, specified recurrence interval, and effective discharge. This has led to confusion with both terminology and understanding of fundamental stream processes. In this Technical Note the channel-forming (dominant) discharge is defined as a theoretical discharge that if maintained indefinitely would produce the same channel geometry as the natural long-term hydrograph. Channel-forming discharge concepts are applicable to stable alluvial streams (i.e., streams that have the ability to change their shape and are neither aggrading nor degrading). For channels in arid environments where runoff is generated by localized high intensity storms and the absence of vegetation ensures that the channel will adjust to each major flood event, the channel-forming discharge concept is generally not applicable.

Faux, R., J. M. Buffington, G. Whitley, S. Lanigan, and B. Roper.2009. Use of airborne near-infrared LiDAR for determining channel cross-section characteristics and monitoring aquatic habitat in Pacific Northwest rivers: A preliminary analysis. Pages 43-60 *in* J. M. Bayer and J. L. Schei, editors. Remote Sensing Applications for Aquatic Resource Monitoring, Proceedings of the 2008 Annual Conference of the American Society of Photogrammetry and Remote Sensing, Pacific Northwest Aquatic Monitoring Partnership, Cook, WA.

Aquatic habitat monitoring is being conducted by numerous organizations in many parts of the Pacific Northwest to document physical and biological conditions of stream reaches as part of legal- and policy-mandated environmental assessments. Remote sensing using discrete-return, near-infrared, airborne LiDAR (Light Detection and Ranging) and high-resolution digital imagery may provide an alternative basis for measuring physical stream attributes that are traditionally recorded by field crews in these monitoring efforts. Here, we compare physical channel characteristics determined from airborne

LiDAR versus those measured from field surveys using a total station. Study sites representing three different channel types (plane-bed, pool-riffle, and step-pool) with bankfull widths ranging from 2.5 to 18.6 m were examined in the upper John Day River basin, Oregon. LiDAR was flown on each study reach at a native pulse density of about 4 pulses/m2, with up to four returns per pulse. Channel cross sections and stream gradient were determined from LiDAR-derived digital elevation models (DEMs) and directly compared to total station measurements. The ability to remotely sense bankfull elevations and associated channel geometry was of particular interest in this study. Because bankfull mapping from LiDAR depends on topographic indicators (breaks in streambank slope), bankfull elevation was determined objectively from plots of hydraulic depth (flow area divided by width) as a function of flow height at each cross section, with bankfull defined as the maximum value of this function, or as the first plateau in the hydraulic depth function in channels with multiple terraces. The latter definition allows a blind test of remote sensing capabilities for cases where no field observations of bankfull elevation are available.

Preliminary results show that, with the exception of one outlier, the first-terrace elevations determined from LiDAR DEMs differed from those of the total station by 0–40 cm (15 cm RMSE), corresponding channel widths differed by 0.23–5.23 m, and reach-average water-surface slopes differed by 0.0–0.0018 m/m. Furthermore, the LiDAR-derived cross-sectional profiles generally corresponded with those of the total station measurements above the water-surface elevation. However, first-terrace elevations frequently differed from field observations of bankfull stage, indicating that successful remote sensing of bankfull geometry using airborne LiDAR requires field observations to train identification of bankfull topography in LiDAR DEMs. When properly applied, remote sensing using airborne LiDAR has the potential to extend the spatial coverage, speed, consistency, and precision of physical stream measurements compared to existing field based techniques, and can be used to quantify higher-order topographic metrics (e.g., areas, volumes, curvature, and topology) beyond the point and line metrics currently measured by channel monitoring programs.

Fernández, D., J. Barquín, M. Álvarez-Cabria, and F. J. Peñas. 2012. Quantifying the performance of automated GIS-based geomorphological approaches for riparian zone delineation using digital elevation models. Hydraulic and Earth System Sciences 16(10): 3851–3862.

Riparian zone delineation is a central issue for managing rivers and adjacent areas; however, criteria used to delineate them are still under debate. The area inundated by a 50-yr flood has been indicated as an optimal hydrological descriptor for riparian areas. This detailed hydrological information is usually only available for populated areas at risk of flooding. In this work we created several floodplain surfaces by means of two different GIS-based geomorphological approaches using digital elevation models (DEMs), in an attempt to find hydrologically meaningful potential riparian zones for river networks at the river basin scale. Objective quantification of the performance of the two geomorphologic models is provided by analysing coinciding and exceeding areas with respect to the 50-yr flood surface in different river geomorphological types.

Hall, J.E., D. M. Holzer, D.M., and T. J. Beechie. 2007. Predicting river floodplain and lateral channel migration for salmon habitat conservation. Journal of Waters Resources Association 43(3):786-797.

In this article, we describe a method for predicting floodplain locations and potential lateral channel migration across 82,900 km (491 km2 by bankfull area) of streams in the Columbia River basin.

Predictions are based on channel confinement, channel slope, bankfull width, and bankfull depth derived from digital elevation and precipitation data. Half of the 367 km2 (47,900 km by length) of low-gradient channels (≤ 4% channel slope) were classified as floodplain channels with a high likelihood of lateral channel migration (182 km2, 50%). Classification agreement between modeled and field-measured floodplain confinement was 85% (κ = 0.46, p < 0.001) with the largest source of error being the misclassification of unconfined channels as confined (55% omission error). Classification agreement between predicted channel migration and lateral migration determined from aerial photographs was 76% (κ = 0.53, p < 0.001) with the largest source of error being the misclassification of laterally migrating channels as non-migrating (35% omission error). On average, more salmon populations were associated with laterally migrating channels and floodplains than with confined or nonmigrating channels. These data are useful for many river basin planning applications, including identification of land use impacts to floodplain habitats and locations with restoration potential for listed salmonids or other species of concern.

Harrelson, C.C., C. L. Rawlins, and J. P. Potyondy. 1994. Stream channel reference sites: an illustrated guide to field technique.

This document is a guide to establishing permanent reference sites for gathering data about the physical characteristics of streams and rivers. The minimum procedure consists of the following: (1) select a site, (2) map the site and location, (3) measure the channel cross-section, (4) survey a longitudinal profile of the channel, (5) measure stream flow, (6) measure bed material, and (7) permanently file the information with the Vigil network. The document includes basic surveying techniques, provides guidelines for identifying bankfull indicators and measuring other important stream characteristics. The object is to establish the baseline of existing physical conditions for the stream channel. With this foundation, changes in the character of streams can be quantified for monitoring purposes or to support other management decisions.

Hill, M.T., W. S. Platts, and R. L. Beschta. 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. Rivers 2(3): 198–210.

Healthy fish populations are dependent on streamflow regimes that protect the ecological integrity of their habitat. Fish habitats are the consequence of linkage among the stream, floodplain, riparian, and upland zones, and watershed geography. Fluvial-geomorphic processes form and control fish habitat. Because of this, multiple in-channel and out-of-channel flows are needed to maintain these processes. We present a conceptual methodology for measuring tour types of streamflow regimes: instream flows, channel maintenance flows, riparian maintenance flows, and valley maintenance flows. The combination of these four streamflow types is designed to protect fish and their habitat. Using a case study of the Salmon River near Whitebird, Idaho, we demonstrate how the methodology could be used to develop a multiple flow recommendation.

Imhof, J. G., J. Fitzgibbon, and W. K. Annable. 1996. A hierarchical evaluation system for characterizing watershed ecosystems for fish habitat.Canadian Journal of Fisheries and Aquatic Sciecnes . **53**(S1): 312–326.

We present an evaluation system and framework for determining the relations between processes that generate physical features and how these features are used by fish. This information is essential for long-term management of fish habitat within watersheds. The model is hierarchical at three scales: watershed, reach, and site. Physical characteristics at these scales are separated into attributes, features, or variables that provide information on cause-response relationships. An evaluative framework is proposed along with a logical framework to guide analysis. The framework includes a functional analysis of physical characteristics and processes that generate physical habitat and a functional analysis of habitat requirements related to life cycle of an indicator species. An example of a life stage – state analysis is presented. Concepts of “health,” “integrity,” and “fit” are used to assess the physical states and conditions of the environment to determine the potential fit for a species based on its life-cycle requirements.

Johnson, P.A., and T. M. Heil. 1996. Uncertainty in estimating bankfull conditions. Journal of American Water Resource Association 23(6):1283-1291

Bankfull depth and discharge are basic input parameters to stream planform, stream restoration, and highway crossing designs, as well as to the development of hydraulic geometry relationships and the classification of streams. Unfortunately, there are a wide variety of definitions for bankfull that provide a range of values, and the actual selection of bankfull is subjective. In this paper, the relative uncertainty in determining the bankfull depth and discharge is quantified, first by examining the variability in the estimates of bankfull and second by using fuzzy numbers to describe bankfull depth. Fuzzy numbers are used to incorporate uncertainty due to vagueness in the definition of bankfull and subjectivity in the selection of bankfull. Examples are provided that demonstrate the use of a fuzzy bankfull depth in sediment trans. port and in stream classification. Using fuzzy numbers to describe bankfull depth rather than a deterministic value allows the engineer to base designs and decisions on a range of possible values and associated degrees of belief that the bankfull depths take on each value in that range.

Lisle, T.E. 1989. Channel-dynamic control on the establishment of riparian trees after large floods in northwestern California. USDA Forest Service General Technical Report PSW-110. Berkley, CA.

Large floods in northwestern California in the past two decades have mobilized extensive areas of valley floors, removed streamside trees, and widened channels. Channel cross sections were surveyed to illustrate an hypothesis on the linkage between sediment transport, colonization of channel margins by trees, and streambank recovery. Riparian trees, e.g., white alder (*Alnus rhombifolia*), colonize the water's edge at low flow to receive adequate moisture during the dry season. Such stands can endure annual high flows only after the flood-enhanced sediment load declines and the width of the annually mobile bed contracts to the low-flow width. Streambank formation along the low-flow margin can then proceed by deposition of fine sediment and organic debris.

Myers, W. R. C., J. F. Lyness, and J. Cassells. 2001. Influence of boundary roughness on velocity and discharge in compound river channels. Journal of Hydraulic Research 39(3): 311–319.

Results are presented of an experimental compound channel research programme carried out at the UK Flood Channel Facility including fixed and mobile main channel boundaries together with two flood plain roughnesses. For comparison data from a natural compound river channel are also presented. Velocity and discharge relationships are explored illustrating the complex behaviour of compound river channels and calling attention in particular to the errors incurred in applying conventional methodologies to discharge assessment in overbank flows. Relationships are presented for velocity and discharge ratios which could form the basis of mathematical modelling of overbank flow estimation methods. The research also represents a step towards prototype conformity by the introduction of mobile boundaries.

Nagel, D. E., J. M. Buffington, S. L. Parkes, S. Wenger, and J. R. Goode. 2014. A landscape scale valley confinement algorithm: Delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-32, Fort Collins, CO., 42 p.

Valley confinement describes the degree to which bounding topographic features, such as hillslopes, alluvial fans, glacial moraines, and river terraces, limit the lateral extent of the valley floor and the floodplain along a river. Valleys can be broadly classified as confined or unconfined, with corresponding differences in their appearance, vegetation, ground water exchange rates, topographic gradient, and stream characteristics. Unconfined valleys are generally less extensive than confined valleys in montane environments, but host a diverse array of terrestrial and aquatic organisms and provide disproportionately important ecosystem functions. Consequently, identifying the location and abundance of each valley type is increasingly recognized as an important aspect of ecosystem management. In this report, we describe a GIS program called the Valley Confinement Algorithm

(VCA) that maps the extent and shape of unconfined valley bottoms using readily available spatial data as input.

The VCA is designed to operate using ESRI ArcGIS software with 1:100,000 scale stream lines from the National Hydrography Dataset (NHDPlusV1) and 10-30 m digital elevation models (DEMs). The algorithm focuses on fluvial applications and therefore only considers channeled valleys. The smallest unconfined valley that can be resolved by the VCA depends on the resolution of the DEM; the VCA is unable to resolve unconfined valleys that are narrower than about two to three times the DEM cell size (i.e., valleys that are 60-90 m in width for a 30 m DEM or 20-30 m for a 10 m DEM). In addition, as bankfull width approaches two times the DEM cell size, the VCA may misinterpret the channel as a narrow unconfined valley. Consequently, care should be exercised in interpreting results in such locations. We conducted field work in central Idaho to document channel characteristics in confined and unconfined valleys mapped by the algorithm. Results showed that channel confinement measured in the field (ratio of valley width to bankfull width) agreed with valley confinement predicted by the algorithm 79% of the time and that channel characteristics were similar to those documented in other studies of confinement. In particular, confined channels typically exhibited steep-gradient step-pool and plane-bed morphologies composed of coarse-grained bed material, with a median channel confinement of about 2 bankfull widths. In contrast, unconfined channels were primarily low-gradient pool-riffle and plane-bed streams composed of finer substrate, with a median channel confinement of about 10 bankfull widths.

We further assessed the accuracy of the algorithm by generating a stratified random sample of points equally partitioned between confined and unconfined valleys as identified by the VCA. Predicted valley types were compared with those observed from digital photos and quadrangle maps. Results showed that the algorithm could differentiate between the two valley types with 89-91% accuracy.

Navratil, O., Albert, M., Herouin, E., and Gresillon, J. 2006. Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel-bed river reaches. Earth Surface Processes and Landforms 31(11): 1345–1363.

Bankfull discharge is identified as an important parameter for studying river morphology, sediment motion, flood dynamics and their ecological impacts. In practice, the determination of this discharge and its hydrological characteristics is not easy, and a choice has to be made between several existing methods. To evaluate the impact of the choice of methods, five bankfull elevation definitions and four hydrological characterizations (determination of duration and frequency of exceedance applied to instantaneous or mean daily data) were compared on 16 gravel-bed river reaches located in France (the catchment sizes vary from 10 km2 to 1700 km2). The consistency of bankfull discharge estimated at reach scale and the hydraulic significance of the five elevation definitions were examined. The morphological definitions (Bank Inflection, Top of Bank) were found more relevant than the definitions based on a geometric criterion. The duration of exceedance was preferred to recurrence intervals (partial duration series approach) because it is not limited by the independency of flood events, especially for low discharges like those associated with the Bank Inflection definition. On average, the impacts of the choice of methods were very important for the bankfull discharge magnitude (factor of 1·6 between Bank Inflection and Top of Bank) and duration of exceedance or frequency (respectively a factor 1·8 and 1·9 between mean daily and instantaneous discharge data). The choice of one combination of methods rather than another can significantly modify the conclusions of a comparative analysis in terms of bankfull discharge magnitude and its hydrological characteristics, so that one must be cautious when comparing results from different studies that use different methods.

Radecki-Pawlik, A. 2002. Bankfull discharge in mountain streams: theory and practice. Earth Surface Processes and Landforms 27(2): 115–123.

The results are presented of an investigation of bankfull discharge in two Polish Carpathian streams: Skawica and Krzyworzeka. Existing definitions of river bankfull were reviewed and applied in tests carried out on selected cross-sections of the streams. The Woodyer method was given special attention, with a correspondingly detailed survey of plants characterizing river benches. Riley's bench index method and the methods of Williams, Wolman, Schumm and Brown, and Woloszyn were tested. The report concludes that bankfull discharge value for a mountain stream should not be reported as a single number, but rather as a range of discharges within which one could expect the bankfull value to lie.

Sullivan, S. M. P., and M. C. Watzin. 2009. Stream–floodplain connectivity and fish assemblage diversity in the Champlain Valley, Vermont, USA. Journal of Fish Biology **74**(7): 1394–1418.

To evaluate the influence of main channel–floodplain connectivity on fish assemblage diversity in floodplains associated with streams and small rivers, fish assemblages and habitat characteristics were surveyed at 24 stream reaches in the Champlain Valley of Vermont, U.S.A. Fish assemblages differed markedly between the main channel and the floodplain. Fish assemblage diversity was greatest at reaches that exhibited high floodplain connectivity. Whereas certain species inhabited only main channels or floodplains, others utilized both main channel and floodplain habitats. Both floodplain fish α-diversity and γ-diversity of the entire stream corridor were positively correlated with connectivity between the main channel and its floodplain. Consistent with these results, species turnover (as measured by β-diversity) was negatively correlated with floodplain connectivity. Floodplains with waterbodies characterized by a wide range of water depths and turbidity levels exhibited high fish diversity. The results suggest that by separating rivers from their floodplains, incision and subsequent channel widening will have detrimental effects on multiple aspects of fish assemblage diversity across the stream–floodplain ecosystem.

Verry, E.S., Dolloff, C.A., and M. E. Manning, M.E. 2004. Riparian ecotone: a functional definition and delineation for resource assessment. Water, Air & Soil Pollution: Focus 4(1): 67–94.

We propose a geomorphic basis for defining riparian areas using the term: riparian ecotone, discuss how past definitions fall short, and illustrate how a linked sequence of definition, delineation, and riparian sampling are used to accurately assess riparian resources on the ground. Our riparian ecotone is based on the width of the valley (its floodprone area width) plus 30 meters on each side to encompass the important adjacent riparian functions, and 15 meters around obvious landslides. A functionally consistent riparian definition and delineation does not derive from land adjacent to a stream, rather it derives from the valley the stream runs through.

Vondrasek, D. 2015. Delineating forested river habitats and riparian floodplain hydrology with LIDAR. Master's Thesis, University of Washington, Seattle.

Rivers and the riparian forest corridor comprise a valuable freshwater ecosystem that has been altered by human activities including timber management, road building, and other land conversions. The habitats of river dependent species in the Pacific Northwest, in particular salmon have often been degraded by these activities. Many salmon runs have become threatened with extinction and have been Endangered Species Act listed. New conservation planning and policies have developed around protecting freshwater habitats and restoring more natural river processes. In WA State, timber landowners, officials from State and Federal agencies, Native tribes, and other stakeholders developed Forest Practice rules and codified a Habitat Conservation Plan with dual goals of providing regulatory surety for timber land owners and helping to recover the threatened salmon runs in forested watersheds. Conserving critical stream ecological functions and potential fish habitats throughout watersheds while managing and regulating timber harvest across the State requires accurate and up-to-date delineation and mapping of channels, tributaries, and off-channel wetlands. Monitoring the effectiveness of protection efforts is necessary but can also be difficult. Agency staff and resources are limited for both day-to-day implementation of Forest Practice rules and adaptive management. The goal of this research has been to develop efficient and accessible methods to delineate wetlands, side-channels, tributaries, and pools and backwaters created by large log jams in forested watersheds. It was also essential to use publicly available LiDAR data and to model these waters at ecologically meaningful flows. I tested a hydraulic model at a 2-year and 50-year flows, and a relative height above river surface model and compared them. I completed two additional remote sensing investigations to correlate channel movement and the locations of off-channel wetlands: an analysis of historical aerial imagery and models of the riparian forest tree establishment using the first-return LiDAR data. The research includes two fieldwork components: an appraisal of the delineated off-channel and active channel water features, and an assessment of the accuracy of the LiDAR under the forest canopy. Both the hydraulic and the relative elevation models accurately delineated the key off channel and active channel waters. The historical imagery analysis confirmed past channel movement left many of the side channels and wetlands near to the contemporary active channel. The sequence of tree establishment tracked where channel migration had exposed new banks, colonized first by deciduous trees, then followed by cohorts of conifers, some maturing and achieving great heights. Often the lack of a closed canopy corresponded to the locations of persistent wetlands or midchannel logjams.

Williams, G.P. 1978. Bank-full discharge of rivers. Water Resoures Research 14(6): 1141–1154.

Eleven possible definitions of 'bank-full' have been used by various investigators. The active floodplain is the most meaningful bank-full level to the fluvial geomorphologist, whereas the banks of the valley flat are the most important to engineers. Comparison of 16 ways of determining bank-full discharge suggests that bank-full discharge at gaged sites should be obtained from the station's rating curve, where bank-full gage height is determined from a longitudinal profile of the floodplain along the entire reach. At ungaged sites, bank-full discharge can be estimated from the empirical equation of this study or from the Gauckler-Manning equation. In the latter case the resistance coefficient n should be estimated at the field site for bank-full flow; a measured low-flow n should not be used. Bank-full discharge does not have a common recurrence frequency among the rivers studied, and the discharge corresponding to the 1.5-year recurrence interval in most cases does not represent the bank-full discharge.

Wilkerson, G. V. (2008), Improved bankfull discharge prediction using 2-year recurrence-period discharge. Journal of the American Water Resources Association 44(1): 243-258.

Knowledge of bankfull discharge (Qbf) is essential for planners, engineers, geomorphologists, environmentalists, agricultural interests, developments situated on flood prone lands, surface mining and reclamation activities, and others interested in floods and flooding. In conjunction with estimating Qbf, regionalized bankfull hydraulic geometry relationships, which relate Qbf and associated channel dimensions (i.e., width, depth, and cross-section area) to drainage basin area (Ada), are often used. This study seeks to improve upon the common practice of predicting Qbf using Ada exclusively. Specifically, we hypothesize that predictions of Qbf can be improved by including estimates of the 2-year recurrence-period discharge (Q2) in regression models for predicting Qbf. For testing this hypothesis, we used Qbf estimates from 30 reports containing data for streams that span 34 hydrologic regions in 16 states. Corresponding values of Q2 and Ada were compiled from flood-frequency reports and other sources. By comparing statistical measures (i.e., root mean squared error, coefficient of determination, and Akaike's information criterion), we determined that predicting Qbf from Q2 rather than Ada yields consistently better estimates of Qbf. Other principal findings are (1) data are needed for at least 12 sites in a region for reliable hydraulic geometry model selection and (2) an approximate range of values for Qbf ⁄Q2 is 0.10-3.0.

Woodyer, K.D. 1968. Bankfull frequency in rivers. Journal of Hydrology **6**(2): 114–142.

The mean frequency with which streams exceed their bankfull or flood-plain level has been claimed to be remarkably constant from site to site. However, this finding is suspect because the range of bankfull frequencies quoted is considerable and it has not been shown that they could belong to one frequency distribution. Therefore, appropriate statistical methods are used here to decide if estimates of bankfull frequency for different sites might belong to one distribution.

Because of the likelihood of very recent incision of flood-plains, three channel benches are considered as well as the flood-plain. They are identified mainly by their elevation relative to the bed of the stream, and are named “high”, “middle”, and “low” benches. The “high” bench is present only at some sites believed to be recently incised and is therefore assumed to be the equivalent of the flood-plain level. It is shown that there is a reasonable probability that the grouped bankfull frequencies for the “high” bench and flood-plain levels belong to one frequency distribution. Therefore, the assumption that this grouping represents the present flood-plain level appears to be justified; moreover, the claims made for a constant bankfull frequency for the flood-plain level are substantiated in the case of streams in New South Wales. In addition the “middle” bench can be claimed to be associated with a constant bankfull frequency.

The ranges of bankfull frequencies (in terms of the annual maximum series) obtained are:

| | |
|---|---|
| “Middle” Bench | 1.02–1.21 years |
| “High” Bench – Present Flood-plain Group | 1.24–2.69 years |

Previous estimates of bankfull frequencies (for the flood-plain level only) embrace both these ranges. The recognition of stream benches is important in identifying the active flood-plain or its equivalent level and in distinguishing flood-plains from terraces.