# Side Channel Formation, Evolution, and Persistence

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## Extended Abstract

Side channels are secondary flow paths connected to the main channel at discharges less than or equal to bankfull flow. These flow paths increase the hydraulic and geomorphic complexity of river systems, which provides opportunities for aquatic habitat by increasing the shoreline length and the variability of depth and velocity. Channel margins and areas of lower velocity are important habitat features in rivers where flow and sediment alterations have created a more uniform main channel with reduced seasonal inundation of floodplains and off-channel habitats. Therefore, constructed side channels are a common habitat restoration technique to enhance the ecological function of river systems. Natural side channels provide a useful empirical reference for improving planning, resource allocation, and design methods for constructed side channels. Side channels are dynamic features that are formed and maintained by fluvial processes and evolve, senesce, and eventually may be abandoned. Our study develops a process-based classification framework for natural side channels and then analyzes their morphology and abundance between the 1930s and 2010s. Understanding the formation, evolution, and persistence of natural side channels can improve implementation and develop realistic expectations for the performance of side channel restoration projects.

We identified and classified side channels on three river systems: the Middle Rio Grande, the Sacramento River, and the Trinity River. Repeat aerial imagery between 1935 and 2012 (Middle Rio Grande), 1938 and 2009 (Sacramento River), and 1944 and 2011 (Trinity River) provided time series to assess side channel formation, evolution, and persistence. The Middle Rio Grande evolved from a wide, braided river in the early 1900s to a channelized and stabilized river during the 1950s–1980s, to a narrower river with vegetated banks and more natural maintenance practices during the 1990s–present. The early 1900s had high peak flows and high total annual flow, the mid-1900s had infrequent peak flows with low total annual flow, the 1980s and 1990s had reduced peaks from upstream dams but high annual flow, and 2000 to the present has had an ongoing drought with low peak flows and low annual flow.

The Sacramento River has been affected by irrigation and diversions throughout the study period in addition to dams and other infrastructure installed between about 1940 and 1975. The early to mid-1900s had high peaks but below average total annual flow, the 1970s through about 2010 have had lower peaks, increased base flow, and above average total annual flow, while recent years have been in a drought. The Trinity River has been subject to geomorphic alteration since the late 1800s: primarily mining through about 1950, then industrial logging through about 1990, and more recently, river restoration and more natural river management. Trinity Dam and Lewiston Dam were constructed in the 1960s and altered the downstream hydrology and sediment supply. The early to mid-1900s had high peak flows and high average annual flows, flows were dramatically reduced by upstream dams from 1960 to 1998, and then since 1998 peak flow releases occur in May with slightly elevated base flows compared to historical conditions.

We digitized side channels on the three rivers and classified them based on erosional or depositional processes. The digitization and classification process also included recording attributes such as geometry (e.g., width, angle) and location relative to the channel planform and floodplain. We analyzed these attributes for each side channel type on each river to identify relationships between morphology, evolution, and persistence while providing guidance for design. Erosional side channels form by large flow events scouring the banks, floodplain, or main channel point bars and include the following types: incised floodplains, incised bars, chutes, avulsions, anastomoses, obstructions, and sills. Depositional side channels occur when there is an increase in sediment supply or local reduction in transport capacity because of a reduction in slope or an increase in width. Depositional side channel types include medial bars, braided systems, diagonal bars, accreted bars, and backwater shoals.

Side channel abundance is calculated as number of side channels per mile to facilitate comparison between different rivers and geomorphic reaches. Comparing each river's first year of aerial imagery between 1935 and 1944, the Sacramento River has the most side channels per mile and the Trinity River has the fewest. After about the early 1960s, the Sacramento River has the lowest side channel density, and the Trinity River has the greatest side channel density. The number of side channels on the Middle Rio Grande increased significantly after about 1992. Upstream reaches of the Middle Rio Grande have the greatest abundance of incised bars and diagonal bars, while downstream reaches have the greatest abundance of incised floodplain side channels. Side channels on the Middle Rio Grande were the most dynamic of the three rivers with sediment erosion, deposition, and bar evolution creating accreted bar side channels, diagonal bars, and incised bars. Differences in side channel types are primarily linked to differences in reach characteristics from upstream to downstream.

On the Sacramento River, the upstream reach is partially confined with bedrock sections that create obstructions and sills not found in other reaches. Downstream of Red Bluff, the river is unconfined with active lateral migration and meander dynamics that form chutes and meander cutoff side channels. Flows on the Sacramento River can be roughly an order of magnitude higher than both the Middle Rio Grande and Trinity River. Historically, this created a highly dynamic river and floodplain system that has stabilized in recent years. The Sacramento River showed larger differences in side channel metrics than the Rio Grande. Chutes and cutoff meanders had the most distinct characteristics and are remnant main channel flow paths. Chutes tended to have the greatest side channel top width and the lowest side channel-to-main channel length ratio, and conversely, that ratio is highest for cutoff meanders. Cutoff meanders represent the opposite transition as a chute and tend to have opposite characteristics.

The Trinity River has a diversity of side channel types in geomorphically-complex reaches and a higher proportion of sills and obstructions in confined bedrock-dominated reaches. Incised bars and medial bars are present in all reaches, suggesting that localized sediment dynamics are important for these features. Side channel attributes exhibit many common characteristics for all three rivers, such as chutes that have small length ratios and high width ratios for the side channel relative to the main channel. Inlet and outlet angles typically vary between 35 and 55 degrees for nearly all channel types.

The three rivers have different lateral migration rates and different geomorphic characteristics between reaches. All three rivers generally have the highest migration rates during the mid-1900s between the earliest periods of aerial imagery. Migration rates increased on the Trinity

River after 2001. The number of side channels per mile increased in the four upstream Middle Rio Grande reaches, stayed consistent in the fifth and sixth reach, and decreased in the two downstream reaches. Analysis for the Sacramento River is complicated by inconsistent aerial imagery extents between years. The number of side channels decreased between 1938 and 1958 and then have remained mostly constant. Conversely, the number of Trinity River side channels increased between 1960 and 1980 and then have been consistent in recent years. The upstream three reaches were responsible for the increased abundance while the downstream reach has maintained the lowest number of side channels in nearly every year.

In addition to documenting the number of side channels by geomorphic reach and classification type, we examined channel lifespans by recording whether each side channel was newly formed, reoccupied, continued from the previous imagery year, or abandoned. The ratio of new to continued side channels was higher for earlier years of imagery. Many new side channels formed on the Middle Rio Grande in 1992 and 2002. 1992 was in the middle of a high flow period. High flows have the capacity to erode, transport, and deposit large volumes of sediment, which rearranges the channel and can create many new side channels. Starting around 2000 at the onset of the current drought for the Middle Rio Grande, a higher proportion of side channels were continued rather than newly formed. The lower flows during a drought after a long period of channel mobilization allows banks to vegetate and establishes bars that can then persist. The number of abandoned side channels is lower since 2000 and higher in the earlier years, peaking in 1962 during the channelization river maintenance period.

There is a similar trend on the Sacramento River where the number of new channels and abandoned channels is lower since about 2000 and the number of continued channels is higher. However, there is a larger ratio of new to continued side channels than the other rivers. Reaches with lower migration rates have fewer new side channels and a higher proportion of continued side channels. On the Trinity River, many new side channels formed between 1960 and 1980 when flow control from upstream dams and reduced mining impacts allowed bankline vegetation to establish and create more stable flow paths. After 1980, the quantity of newly formed side channels consistently decreased while persistent side channels that continued for multiple years became more prevalent. The total side channel abundance is consistent after 1980 because the number of abandoned channels is similar to the amount of new plus reoccupied channels. Side channel trends for the Trinity River and Middle Rio Grande indicate that wet periods create more side channels and subsequent dry periods favor continued side channels. Trends in new or continued side channels over time are likely partially influenced by the more frequent aerial images in later years, which provides greater temporal resolution.

We evaluated whether a side channel can change from one classification type to another by creating evolution diagrams to illustrate classification changes between consecutive years of aerial imagery. The results highlight that side channel type is typically stable through time, especially on the Trinity River. The Trinity River has almost no change in side channel type, which confirms the hypothesis that less mobile rivers will have more stable side channels that persist longer. A side channel that evolves between types also has a greater opportunity to become abandoned. The Middle Rio Grande is the most dynamic river system and has many side channels that alternate between types. For example, bars can become accreted and then re-incised to join the main channel multiple times throughout a side-channel's history. On both the Middle Rio Grande and Sacramento River, incised bars were relatively dynamic. Side channels are periodically reoccupied through a cycle of gradual abandonment during low flow periods and reactivation during high flows. On the Sacramento and Trinity rivers, side channels are typically more stable. For these two rivers, obstructions, sills, and medial bars are especially stable.

We quantified the longevity of side channels by going back in time for all side channels existing during the most recent year of imagery. The age of each side channel is how long it persisted between consecutive years of imagery. Many of the 2012 Middle Rio Grande side channels formed during the previous 4 years. Many side channels also persisted to the 1992 imagery but not the 1972 imagery, an age of 20 to 40 years. The largest proportion of side channels on the Sacramento River persisted to 1999 but not 1974, an age of 10 to 35 years. All reaches had side channels persisting 35 to 51 years (between 1974 and 1958) while the two upstream reaches had several side channels persisting 51 to 71 years (between 1958 and 1938). 1938 imagery was not available in the downstream reach. The Trinity River has the highest proportion of ages between 0 and 2 years, which are side channels newly formed or reoccupied between 2009 and 2011. Other age classes were broadly distributed until a decline in side channels persisting beyond 51 years (1960 or earlier).

The accreted bar has the shortest lifespan of any channel type on the Middle Rio Grande, which has almost no accreted bar channels older than 4 years. These are bars that attach to the outer bank and tend to become filled with sediment. Medial bars are short-lived features on the Sacramento and Trinity Rivers. Medial bars are also depositional features that exist where there is a local reduction in sediment transport capacity. Not all depositional side channel types have a short longevity. Diagonal bars are relatively long-lasting features on the Middle Rio Grande and Trinity River. Vegetation may help stabilize the diagonal bars and they also have a different shape with narrower channel threads and streamlines more parallel to the dominant flow direction. The side channel types with the longest persistence are the chute and sill. Sills have incised to bedrock, an inherently stable configuration, and tend to be wider because the bedrock prevents further bed erosion. On the Sacramento River, chutes have a relatively high longevity. Chutes typically have a larger relative width compared to the main channel and a shorter length on the inside of a meander bend.

The Middle Rio Grande has topographic change data available for constructed channels to further understand persistence, a dataset not available for the other rivers. Elevation comparisons for the period 2012 to 2018 showed that 14% of constructed sites had a median change above the deposition detection threshold. Quantile values corresponding to 75% and 90% non-exceedance had a larger percentage of sites above the deposition threshold, 29% and 48%, respectively. This illustrates that side channel deposition is spatially variable. An elevation change map demonstrates that most deposition occurs at the side channel inlet, with some deposition at the outlet. Therefore, suspended sediment deposition at the interface with the main river appears to be a common disconnection process for constructed side channels in some rivers or reaches.

Information from this empirical study of natural side channel classification, morphology, formation, evolution, and persistence can be applied to designing new side channels for habitat restoration. First, designers and planners should consider the geomorphic reach of the proposed project and the context of multiple geomorphic reaches within a river system. There is a balance between identifying reaches that may have a side channel deficit and understanding that certain reaches naturally do not support as many side channels. After identifying a reach for side channel implementation, the next step is to consider side channel types appropriate for that reach. The level of planning and design effort should be scaled to the expected persistence and life cycle benefit of a side channel. For example, medial bars on the Sacramento River have a short longevity while backwater shoals, chutes, obstructions, and sills may persist for much longer. Once a side channel type is selected for a general location, the geometric parameters compiled for this study can be applied to develop the design dimensions. Finally, after design and construction is complete, side channels should be monitored to track their evolution, geomorphic change, and ultimately, whether they are providing the expected habitat benefits.