WATER RESOURCES RESEARCH, VOL. ???, XXXX, DOI:10.1002/,

Multi–decadal dynamics of alternate bars in the Alpine Rhine River

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Abstract. We report on a multi-decadal analysis of alternate bar dynamics in a 41.7 km reach of the Alpine Rhine River, which represents an almost unique example of a regulated river with fixed levees, straight reaches and regular bends in which alternate gravel bars spontaneously formed and migrated for more than a century. The analysis is based on freely available Landsat imagery, which provided an accurate and frequent survey of the dynamics of the alternate bar configuration since 1984. Bars were characterized in terms of wavelength, migration, and height. Longitudinal and temporal patterns are investigated as a function of flood occurrence and magnitude and in relation to the presence of local planform discontinuities (bends and ramps) that may affect their dynamics. Bars in the upper part of the reach are mostly steady and relatively long (about 13 channel widths); bars in the lower part of the reach are migrating and shorter (about 9 channel widths). Bar height is rather uniform along the reach, ranging between 3 to 4 m. The temporally long hydrological dataset allowed the investigation of bar migration during flood events, showing that bars migrate faster for intermediate floods. The observed relationship between bar migration and wavelength was consistent with linear theories for free migrating and steady forced bars in straight channels. The comparison of theories with observations highlights the key role of theories to support interpretation of observations, for a better understanding of the morphodynamic processes controlling bar formation and dynamics.

1. Introduction

Alternate bars have been documented in channelized river reaches for nearly 3 centuries (e.g *Engels* [1914], *Werth* [2014]). They emerged as a morphological response of river beds to levee construction and channel straightening. Their widespread occurrence in wide, morphologically regulated streams attracted the attention of hydraulic engineers because of their undesired effects on bridges, embankments, intake structures and river navigation (*Jäggi* [1984]). Moreover, regular periodic oscillations that alternate bars impose to the flow in a straight channel initially provided an intriguing (though lately questioned) possible explanation for the origin of river meandering, (*Lewin* [1976], *Parker* [1976]), thus stimulating the interest of fluvial geomorphologists.

In the 1960s, a consistent research effort to understand causes and controls onar formation, their geometrical properties (length, magnitude of scours and deposits), and migration was undertaken, through complementary approaches, mainly including mathematical and physical scale modeling. A remarkable bias towards modeling approaches is evident in the alternate bars literature, with limited availability of field observations until recently. This was mainly because of the relatively long temporal and spatial scales needed to properly describe their dynamics (e.g., *Eekhout et al.* [2013]). Such bias limits our present understanding and ability to predict the morpho-dynamic response of regulated rivers to hydromorphological pressures, for instance those related to changes in the flow and sediment supply regime, in levee alignment, and with other river management or restoration measures.

A consistent theoretical framework on alternate bar dynamics, strongly supported by laboratory observations, has been developed in the past four to five decades (e.g., *Engelund and Hansen* [1967], *Struiksma et al.* [1985], *Colombini et al.* [1987], *Tubino et al.* [1999], *Lanzoni* [2000a], *Lanzoni* [2000b], *Crosato et al.* [2011]). However, most of its outcomes were derived and verified using assumptions such as constant flow discharge, channel width, and slope; homogeneous sediment size; and indefinitely or semi-indefinitely long straight channels. The relevance of other neglected factors has not been thoroughly investigated so far, given the scarcity of observations documenting the morphological properties of alternate bars in complex (though regulated) rivers. More robust field observations are therefore of fundamental importance, to assess the possibility of using mathematical theories as predictors (e.g., *Parker* [1976], *Fredsøe* [1978], *Crosato and Mosselman* [2009]) as well as tools to interpret (e.g., *Rodrigues et al.* [2015]) the expected or observed bar morphodynamics. Some indications of the potential of bar theories to predict observed behaviors emerged from recent works (*Eekhout et al.* [2013], *Rodrigues et al.* [2015], *Jaballah et al.* [2015]), though these same studies stress the need for continued research that integrates modeling and field approaches.

The observation gap has been increasingly addressed only very recently, thanks to the development of in-situ monitoring technologies (e.g., flow and bathimetric survey), (*Rodrigues et al.* [2015]), as well as through remote sensing and the use of satellite imagery (*Henshaw et al.* [2013]). Table 1 summarizes the main existing field studies with a focus on alternate bar dynamics. Three studies out of eight (*Welford* [1994]; *Eekhout et al.* [2013]; *Jaballah et al.* [2015]) focused on a reach length of nearly 100 channel widths or more, allowing the observation of a considerable number of alternate bar units. However, only one of these three (*Jaballah et al.* [2015]) covers a multi-decadal time scale, with the other two multi-decadal studies referring to reaches with a more limited number of bars (*Church and Rice* [2009], *Ferguson et al.* [2011]). Furthermore, the three multi-decadal analyses have a relatively poor temporal resolution of surveys, with an average of 1 available survey every 3 to 5 years.

The present paper focuses on a quantitative understanding of long-term dynamics of alternate bars in the Alpine Rhine River. This is a renowned example of a channelized stream where an impressively long and regular sequence of alternate bars has been observed for decades (*Jäggi* [1984]). Moreover, it is believed to be one of the few examples of rivers where migrating alternate bars can be observed (*Crosato and Mosselman* [2009]).

The goals of this study were: i) to quantify the morphodynamics of alternate bars in the Alpine Rhine River, with a particular emphasis on bar migration; ii) to assess to what extent the predictions of analytical bar theories are consistent with field observations; and iii) to further explore how theories may help interpret observed alternate bar dynamics. These goals are achieved by developing and analyzing a dataset of freely available multitemporal Landsat imagery, which combine unprecedented temporal length (3 decades); spatial length (> 400 channel widths); and temporal resolution (~ 2 images per year).

2. Study site and methods

2.1. The Alpine Rhine River

The Rhine river is one of the largest rivers in Europe, with a basin of $1.85 \times 10^6\,\mathrm{km}^2$ and a length of 1326 km. The upper part of the basin, between the confluence of Vorderrhein and Hinterrhein and the lake of Constance, is called Alpine Rhine. This sub-basin is located in the eastern part of Switzerland, western Austria (the tributary Ill) and the whole territory of Liechtenstein (Figure 1). The Alpine Rhine is 93 km long and its catchment area is 6123 km^2.

We focused the analysis on a reach that is 41.7 km long and is located between the Landquart's confluence (km 23.3 of the Alpine Rhine, Landquart's drainage area: 618 km^2) and the confluence with the Ill river (km 65.0, Ill's drainage area: 1281 km^2). No other relevant tributaries are present along the study reach. The whole reach was heavily channelized in the 19th and 20th centuries, with the last levees built in the 1930s and 1940s. These engineering works aimed at increased flood protection and drastically simplified the originally dynamic multi-channel morphology. Nowadays, the reach is characterized by a continuous sequence of alternate bars, which makes the Alpine Rhine the perfect site to study this morphological pattern.

The hydrological regime is pluvio-nival, characterized by snow-melt in spring and summer and by larger floods most probable in autumn. The river is strongly affected by hydro-power production, with water release fluctuations superimposed throughout the year. Hydropeaking increases discharge on average by 70-80 m^{3}s^{-1}, exhibiting a regular daily (and weekly) pattern. After 2010, the pattern became more irregular, due to new rules of the energy production management.

There are several available hydrometric stations in this reach. We used the daily data of the Austrian gauging stations in Bangs, Feldrik, and Lustenau for the period 1951 - 2010, and of the Swiss station in Diepoldsau for the period 1919 - 2012. For this last station, 10-min data were also available for the period 1984-2013. The average discharge upstream of the Ill's confluence was 150 m^{3}s^{-1} (dataset 1996-2010). Minimum flow was 40.3 m^{3}s^{-1} and maximum recorded flood peak (1988) was 2650 m^{3}s^{-1} (Figure 2).

The cross-section of the channelized reach was designed with a classical trapezoidal shape, with a base width (W) that increases from 85 m in the upstream part up to 106 m downstream. No floodplain is present and the levees (with a transverse slope of approximately 35°) are composed of boulders that prevent any planform changes. Bed material is primarily composed by gravel, with a median grain size ranging between 60 mm upstream and 20 mm downstream [*Hunziker et al.*, 2001], with local variability caused by the alternate bars grain sorting. Longitudinal bed slope decreases along the reach, from 2.9 ‰ upstream, to 1.3 ‰ downstream. Though there are no sharp discontinuities in the streamwise variability of slope and grain size, it is possible to identify three sub-reaches, each having rather homogeneous values of width, slope and median grain size (Table 2). Furthermore, we identified the presence of planform and bed elevation discontinuities, in the form of bends and two unstructured ramps, these latter formed by boulders with a diameter much larger than the representative diameter of the bed. These ramps artificially impose a local increase of the longitudinal slope, respectively imposing a change in the bed elevation of 2.60 m (r_1) and 1.40 m (r_2). Their location was marked in the vector map (Figure 1 and Figure 3d), in order to assess their potential impact on bar morphodynamics.

2.2. Image database

For this study, we used the images acquired by Landsat 4-5 TM (30 m resolution), Landsat 7 ETM+ and Landsat 8 OLI (15 m resolution of the panchromatic band). The dataset covers a period of around 30 years, starting from 1984, with a partial interruption of acquisition between 1991 and 1998. A total number of 58 images out of 78 available were downloaded and used for this study. Cloud cover and high discharge are the two main causes of removal of images from the study.

Figure 2 shows the temporal sequence of the available images, superimposed to the discharge record. Emerged gravel bars are visible on the Landsat images only for discharge values lower than $350\,\mathrm{m^3 s^{-1}}$. The full dataset of 78 images covers a discharge range from $64\,\mathrm{m^3 s^{-1}}$ to $540\,\mathrm{m^3 s^{-1}}$. Figure 3a)-c) shows three examples of Landsat images, taken at different discharges. The mirror alignment problem that affected the Landsat 7 ETM+ sensor after 2003 (and produced the black strips visible in Figure 3b) did not affect our analysis in a significant way, as it was generally possible to locate the front and tail of most of the bar units. Furthermore, a more detailed aerial image (Google Maps ©) was used to accurately define the embankment line and the low flow channel width (W).

2.3. Bed topography database

We used a complete cross-section dataset of the Alpine Rhine surveyed in 2005 by the International Rhine Regulation (IRR) to determine hydraulic variables of the study reach. The survey includes more than 200 cross sections with a longitudinal spacing of approximately 200 m. Mean hydraulic conditions were determined for each of the three sub-reaches (Table 2).

Uniform flow conditions were computed in each cross section, using a log-like formula for roughness, corresponding to the average sediment size in every sub-reach and the sub-reach averaged longitudinal slope. The analysis identified: i) the value of discharge that submerged all the bar deposits (fully wet discharge, Q_{FW}, equal to an average of $300\,\mathrm{m^3 s^{-1}}$); and ii) the discharge at which the full cross section was expected to actively transport bed material as bed load (fully transport discharge, Q_{FT}, equal to an average of $650\,\mathrm{m^3 s^{-1}}$). Transport conditions were evaluated considering a threshold on the dimensionless bed shear stress equal to 0.03 [*Parker et al.*, 2007]. This choice is independent from the computations of the thresholds values of the bar theory described in the following paragraphs.

2.4. Monitoring of bar properties

The 41.7 km long reach included a series of approximately 40 bar units. Here we define a bar unit as extending between two consecutive fronts (or tails) on the same side of the river. Satellite images were imported into Quantum GIS software (*QGIS Development Team* [2009]) and the location of bar fronts and tails was measured in each of the 58 available images, as the most downstream and upstream point of the emerged deposits. Figure 3d) reports an example of the resulting vector map of the alternate bars. From this dataset of geographical coordinates, bar wavelength (L) and bar migration were computed. Bar wavelength is defined as the distance between two consecutive fronts (or tails) on the left (or right) bank (length of the bar unit). Bar migration is the temporal difference between the location of the front (or tail) of the same bar unit. The high temporal resolution of the Landsat imagery ensured an easy recognition of the same bars on the images. A parameter called bar elongation was also computed as the wavelength difference of the same bar unit between two different Landsat images. Reference Landsat data for the difference in time are October 22, 1999 ($Q=149\,\mathrm{m^3s^{-1}}$) and July 16, 2010 ($Q=154\,\mathrm{m^3s^{-1}}$).

In the case of images acquired with largely different discharge conditions, location of bar fronts and tails are affected by changes in the exposed area. This implies that the front (or tail) of the bar may appear to move upstream (or downstream) only because of a different water level. In order to minimize this effect, we performed a spatial average, combining fronts and tails results.

Free bar theory provides an estimation of the bar amplitude, which is defined for each bar unit as the difference between the highest and the lowest bed elevation values over the entire unit. The relatively coarse longitudinal spacing between consecutive cross-sections in the available topographic survey (200 m) didn't allow an exact computation of bar amplitude. For this reason, a parameter called "bar height" was computed in the cross-section dataset as the difference between the lowest and the highest values of bed elevation in each cross-section. This probably underestimates the actual bar amplitude, as the highest and lowest bed elevation values over one entire bar unit may not occur at the same cross-section.

2.5. Overview of bar theories

Since the late 1960s, several mathematical theories have been proposed to investigate and predict morphodynamics of alternate bars in straight river reaches [*Callander*, 1969] (an accessible introduction to the topic can be found in *Nelson* [1990]). These are mostly analytical theories, i.e. mathematical models based on analytical (or semi-analytical) solutions of the governing physical system, typically the two dimensional Saint Venant - Exner shallow water model [*Tubino et al.*, 1999]. The mathematical model is kept at the lowest meaningful level of complexity through a series of simplifying assumptions such as considering small bar amplitude, hence small deviations from the plane bed solution. This ensures the possibility to obtain mathematical solutions in close analytical form.

It is useful here to briefly recall the main features and outcomes of analytical bar theories that will be compared with the field observations on the Alpine Rhine River. The planform of the study reach can be viewed as a sequence of 16 straight longitudinal sections, connected by 14 short bends of constant curvature, and two ramps (left panel of Figure 1). The most relevant bar theories for this case are therefore those for straight river reaches, which account for 83% of the whole reach length. As with many other analytical models for river bars and meandering, most of these theories predict properties of alternate bars for given constant values of flow discharge, channel width, reach slope, and sediment grain size. Quantitative results depend also on the choice of the roughness formula and of the bedload predictor. In the calculations we used a log-like formula for the former and the Meyer-Peter and Müller one for the latter. Moreover, the model assumes flow conditions where the entire cross section is actively transporting sediments. This means that the channel width corresponds to the active width (*Ashmore et al.* [2011]; *Zolezzi et al.* [2012]).

According to analytical theories, alternate bars in straight, equiwidth reaches can develop because of a free instability mechanism of the riverbed ("free bars": *Colombini et al.* [1987]; *Schielen et al.* [1993]). Alternate bars in straight channels can also be forced by local persistent perturbations of the straight channel planform, as for example by the abrupt transitions from bends to straight reaches or by localized narrowing ("forced bars": *Struiksma et al.* [1985], *Johannesson and Parker* [2013], *Struiksma and Crosato* [2013]).

Linear theories consider bars as small-amplitude perturbations of the bed topography, i.e., much smaller compared to the reach-averaged flow depth. They allow computation of how deformation of an initially planar bed affects near-bed flow direction and strength, and the direction and rate of bedload. Thus, they predict formation, wavelength, and migration of bars. Non-linear theories (*Colombini et al.* [1987]; *Schielen et al.* [1993]) are needed to predict the amplitude of bars. In straight channels, linear theories predict free alternate bars to be downstream migrating and forced alternate bars to be non-migrating. In the same setting, forced steady bars are predicted to be about twice as long ($L/W \sim 15-20$) as free migrating bars ($L/W \sim 6-10$). Comparable length scales are predicted by non-linear theories, while migration speed is largely overestimated by linear theories, in comparison with data and non-linear theories [*Colombini et al.*, 1987].

In addition to the above simplifying assumptions, free bar theories assume an indefinitely long straight river reach, while theories for forced bars refer to a reach of finite length. The above assumptions strongly simplify the actual heterogeneity that characterizes natural rivers, where discharge is unsteady, grain size is heterogeneous, and channel width and slope may vary in the streamwise direction. *Tubino* [1991] proposed an analytical non-linear theory to investigate the role of discharge unsteadiness on alternate bar formation, amplitude, and wavelength. This mathematical analysis provides a suitable framework to evaluate the ratio between the temporal scales of floods and that of bar development, defined as U by *Tubino* [1991]. When $U \gg 1$ floods do not last long enough to ensure bars reach a morphological equilibrium, whereas when $U \ll 1$ it is possible to have instantaneous equilibrium of bar morphology with the flow conditions (see also *Eekhout et al.* [2013] for a recent application). Moreover, the assumption of constant grain size has been removed by *Lanzoni and Tubino* [1999] who developed a linear theory for free bars with bimodal sediments.

3. Results

Results of the Landsat imagery analysis are presented here in terms of bar wavelength, migration, and amplitude with focus on the longitudinal and temporal variations. The observed bar properties are then compared and interpreted by the available bar theories.

3.1. Bar wavelength

Bar wavelengths along the whole 41.7 km reach of the Alpine Rhine river are shown in Figure 4 for the period 1984-2013. Here, each point represents the wavelength of a single bar unit, as measured on one of the Landsat images. A total of 39 bar units are included.

Overall bar wavelengths range in the interval 750 - 1700 m, which corresponds roughly to 7 - 17 average channel widths. Based on bar wavelength values, the study reach can be divided into two main sectors. In the upstream sector, which extends down to km 16 (bend 4), bars tend to be longer, with wavelengths in the interval 1200 - 1700 m ($L/W =$ 14 - 20). Large fluctuations of the locally averaged wavelength are present along this first sector, with minimum values occurring close to the localized persistent planform discontinuities, such as bend b_1 and b_2, and the first ramp r_1.

A sudden shortening is visible starting from bend 4, and shorter bars occur throughout the sector, with wavelengths generally in the interval 700 - 1200 m ($L/W =$ 7 - 12). The local bar wavelength shows a more uniform spatial trend on average, but with a higher number of outliers, with bars as short as 500 m and longer than 1700 m. Overall, the mean behavior of the data cloud in Figure 4 appears to vary rather smoothly within the straight reaches, while the presence of ramps, individual sharp bends, or sequences of nearly consecutive bends, is often associated with discontinuities in the spatial trend, inducing local elongation/shortening of bars. Wavelength values in the three sub-reaches were compared through a Kruskal-Wallis test. The outcome confirmed that the upstream sub-reaches is characterized by longer values (p <0.05). Bar wavelength shows a much higher local variability in the three longer straight reaches located in the upstream sector compared both to the shorter reaches located in the same upstream sector and to the three longer reaches located in the downstream sector. The opposite behavior occurs in the downstream sector, where the highest variability in local bar wavelength is observed in the short straight reaches located in between bends. Local wavelength variability in straight reaches 2, 9, and 15 is the largest, with wavelengths that may differ by up to 500 m.

Cumulative values of bar elongation are reported in Figure 5, where the change from 1999 to 2010 is shown. We chose to limit the analysis to this period, to avoid the long gap between 1990 and 1999, which hinders an accurate reconstruction of bar dynamics. During this time interval, maximum elongation as well as maximum shortening range around 200 - 250 m (approximately 2.5 - 3 times the river width). Upstream of bend 4, bar wavelengths tend to remain fairly constant in time, with total variations shorter than one river width. The larger variations are observed in the reach between bend 4 and bend 7, with bars experiencing an elongation of more than 200 m just downstream of bend 4, followed by an almost linear transition to a shortening of more than 200 m before bend 7. Close to bend 8, bars suddenly shifted to elongation (up to 150 m). Downstream of this, in the long straight sub-reach between bend 10 and 11, bars showed little variations, with a tendency to shorten towards the end of the reach. Also the longitudinal mean trend of bar elongation shows abrupt shifts near some bends, as it has been observed in Figure 4 for bar wavelength.

3.2. Bar migration

The second parameter considered in the characterization of bar dynamics is their migration. In Figure 6, the spatial trend of the cumulative bar migration over the period 1999-2010 is presented. Maximum downstream migration was approximately 1000 m (about 9

- 10 river widths or one average bar wavelength in the case of the downstream part of the reach). Many bars, mainly located in the upstream sub-reach and near planform obstacles, showed very low values of migration, with only 3 bars from a total of 77 denoting a slight upstream migration (negative values). In analogy with bar wavelength (Section 3.1), two rather different bar migration patterns characterize the same upstream and downstream sectors of the study reach, with the Kruskal-Wallis test resulting in a statistically diffferent behaviour for the upstream sub-reach (lower migration) compared to the central and downstream sub-reaches ($p < 0.05$). Upstream of bend 4 bars are generally non-migrating (or "steady"), with total migration values lower than one river width in both straight and curved reaches. A few km downstream of bend 4 migration reaches its maximum, with values around 1000 m. Along this second sector, bars tend to migrate downstream consistently, with several bar units moving downstream by 700 - 1000 m in most of the long straight subreaches 7, 8 and 13. The slowing effect of bends and ramps on alternate bars in the downstream sector is clearly visible. Close to bends 7, 8, 9 and 12, 13, 14, bars migrated less than half of the distance migrated by bars in the long straight sub-reaches. A few steady bars can be observed at the inner bank of bends 5, 12, and 13, and also close to the second ramp. Similarly to Figure 5, where from km 15 to km 24 and from km 24 to km 35 the proximal bars elongated and the distal bars shortened, in Figure 6 the proximal bars migrate at a faster than average rate, while distal bars migrate at a slower than average rate.

Bar migration is analyzed also at the time scale of the single flood event, by computing bar movement between each consecutive Landsat image. Bars migrated no more than a few hundred meters (i.e. a few channel widths) even during the largest floods and we never observed a complete rearrangement of the bed topography, with disappearance of the bar structure and formation of a new sequence. Two different sets of bars are presented in Figure 7, as representative of the different behavior of steady and migrating bars. The first set of bars (bar 36 and bar 30, located at km 5 and 12, respectively) was chosen to represent non-migrating bars (closed symbols in Figure 7). The second set of bars (bar 23 and bar 09, located at km 22 and 35, respectively) includes bars that are located sufficiently far from bends and ramps, so that they freely migrate downstream (open symbols). The step-by-step migration of these 4 bars shows that they move mainly during larger floods (see Figure 2 for a comparison). Periods without significant events (e.g., in 2006-2007) are characterized by hardly any migration, even in the case of the migrating bars. Figure 7 shows also that steady bars (closed symbols) moved slightly upstream and downstream in a narrow range of about 2 river widths, and are not influenced by flood occurrence. These fluctuations around a fixed position may also be due to changes in the exposed area, as a consequence of the different discharge at which the Landsat images were acquired. Overall, the analysis of bar migration suggests that a migration threshold of 2 channel widths (i.e., 180 m) can be used to discriminate between migrating and steady bars by comparing it with the decennial (1999 - 2010) cumulative migration of each bar unit.

The effect of different floods on bar migration has been further analyzed for the entire period 1984-2012 by focussing on the bars in sub-reaches 7 and 13, which migrated the longest distance. Several floods were singled out by consecutive Landsat images, covering a range from $780\,\mathrm{m^3s^{-1}}$ to $2650\,\mathrm{m^3s^{-1}}$. The value of $780\,\mathrm{m^3s^{-1}}$ was chosen as a morphologically relevant threshold, because it corresponds to conditions of fully transporting cross sections, and because no significant migration of bars was observed for floods with a lower peak discharge. The effect of different floods is reported in Figure 8 as a function of three potentially controlling factors on bar migration. Overall, none of these considered flow parameters provide clear explanatory trends for bar migration. There is a tendency of bar migration to increase for higher flood duration (Figure 8b) and flood volume (Figure 8c), but the scatter of the data is high. A maximum migration value was observed at a peak discharge up to roughly 1800 $\mathrm{m^3s^{-1}}$, and then decreases again, reaching values close to 0 m for the largest flood on record (Figure 8a).

3.3. Bar height

Bar height ranged between 2.5 m and 4 m and, in contrast to bar wavelength and migration, did not show any particular spatial trend (Figure 10). These values of bar height correspond to approximately 1 - 1.5 times the reach averaged water depth calculated with Q_2 =780 $\mathrm{m^3s^{-1}}$. Bar height presents longitudinal fluctuations, often characterized by a minimum value near bends and ramps. In particular, the second ramp has a strong effect, reducing bar height to 2 m.

3.4. Application of bar theories

The following bar theories were applied to predict bar properties and to support interpretation of the field observations: the linear theories for free migrating bars, and for forced steady bars, in the versions proposed by *Colombini et al.* [1987] and by *Zolezzi and Seminara* [2001]; the non-linear theories for free migrating bars of *Colombini et al.* [1987] and of *Tubino* [1991].

First of all, the reach-averaged lower discharge limit for fully transporting cross-sections was computed to establish the meaningful discharge range for theory application. The fully transporting discharge Q_{FT} ranges between $500\,\mathrm{m^3s^{-1}}$ and $800\,\mathrm{m^3s^{-1}}$ in the different sub-reaches (Table 2). These values are sensitive to the choice of the bed roughness and on the critical threshold for the incipient motion θ_C.

The linear theory for free migrating bars was applied to predict the conditions of free bar occurrence and their wavelength. This theory predicts free bar instability whenever the width to depth ratio β is higher than a critical threshold β_{cr}, which depends on the shear stress and the average grain size roughness, and which generally ranges between 10 and 20. We computed the discharge value Q_{cr} that determines critical conditions ($\beta = \beta_{cr}$), for each of the three reaches. According to the theory, discharge values below this threshold are likely to induce bar formation. Values range between $1850\,\mathrm{m^3s^{-1}}$ and $1950\,\mathrm{m^3s^{-1}}$ (Table 2). This is the second relevant discharge threshold that sets the flow conditions under which alternate bar formation is expected. These two thresholds (Q_{FT} and Q_{cr}) are depicted in Figure 2, considering the values for the center reach. The figure shows that almost every flood is characterized by a peak value that falls in the area where alternate bars should form, according to *Colombini et al.* [1987]. During the considered time interval of 30 years, only two floods peaked above the critical threshold Q_{cr}. Overall, for 99.9% of the time when discharge exceeded the fully transporting threshold, the study reach was in a condition of free bars instability ($\beta > \beta_{cr}$).

Results from the linear theory show that the most unstable wavelength for free migrating bars is approximately 750 m and remains almost constant along the study reach, because the decline in grain size is almost counterbalanced by the decline in longitudinal slope. The intrinsic uncertainty in the choice of representative reach-average slope and grain size values due to their local variability, does not affect the theoretical prediction of bar wavelength significantly. More precisely, from a sensitivity analysis performed on the values of the reach-averaged sediment size used as model inputs (Table 2), and within a range of formative discharges between $400\,\mathrm{m^3s^{-1}}$ and $1000\,\mathrm{m^3s^{-1}}$, the value of the most unstable migrating bar wavelength changes by only 5% when grain size and slope are varied by 20% around their reach-average values. This also accounts for the influence of the grain size value on the roughness coefficient. From a sensitivity analysis performed on the critical shear stress, we saw that bar wavelength changes by only 5% using values of the critical shear stress in the range 0.03-0.05. Using a different bed-load formula (e.g. *Parker* [1990]), bar wavelength variability remains below 5%. The predicted value of the most unstable wavelength is slightly shorter than the measured wavelengths of the alternate bars that were observed to migrate, which range from 750 to 1000 m. On the other hand, the computed wavelength of forced steady bars ranges between 2000 and 3200 m, i.e. almost twice as much as the observed wavelength (1200 to 1500 m) of the bars classified as non-migrating in our analysis, which mostly occurred in the straight reaches of the upstream sector.

Values of bar height presented in Figure 10 were compared to the values of the free migrating bars equilibrium amplitude predicted by *Colombini et al.* [1987] and also by the empirical formulation proposed by *Ikeda* [1984], which estimates bar height as a function of sediment diameter and the width to depth ratio. In the *Colombini et al.* [1987] weakly non-linear theory with steady flow conditions, bar height is a function of flow and sediment characteristics, and of the distance from the critical conditions for free bar instability ($\beta - \beta_{cr}$). The two formulations give similar results, with bar height decreasing from upstream to downstream (ranging from 6.2 m to 4.8 m for $Q = Q_2$), and decreasing for higher discharges until disappearing when Q approaches Q_{cr}. Therefore, bar height computed with $Q = Q_2$ can be considered an upper limit, as larger floods are likely to reduce bar height. The observed bar height is on average smaller than the predicted values. This could be the result of a series of larger floods occurred in the five years before the topographic survey (2005, see Figure 2).

Finally, an application of Tubino's (1991) theory for free bar evolution under unsteady flow conditions was attempted. The analytical non-linear model of *Tubino* [1991] allows the comparison of the relevant time scales of the morphological evolution and of the flood duration, through the dimensionless parameter U (see Section 2.5). The value of U computed for several floods that occurred in the last 30 years in the Alpine Rhine is approximately 20, therefore falling in the case $U \gg 1$. This means that floods are short with respect to the time needed by free bars to grow to their equilibrium height.

4. Discussion

The availability of a spatially and temporally long dataset of the Alpine Rhine proved useful to better understand the morphological properties and dynamics of alternate bars in channelized rivers. Although the observations are specific to the investigated reach, the comparison with the outcomes of existing analytical theories of free and forced alternate bars can help interpret other field studies (see Table 1). In the following, we discuss the results obtained in this study focussing on (i) the relevance of the developed dataset in comparison with existing ones; (ii) the comparison of the observed alternate bar properties with previous field observations; and (iii) the ability of analytical bar theories to predict and interpret field observations.

4.1. The Alpine Rhine alternate bar dataset

The availability of a remotely sensed dataset of a 41.7 m long reach of the Alpine Rhine covering about 30 years allowed a thorough investigation of the morphology and dynamics of 40 bar units. This is a valuable source of information to understand the controls on alternate bar formation and migration, which may greatly increase the possibility to evaluate and predict the evolution of these bed forms. Landsat imagery proved to be an excellent source of freely available data, in terms of number of images per year and pixel resolution, confirming the findings reported by *Henshaw et al.* [2013]; *Constantine et al.* [2014]. The possibility to choose among several images allowed for combining a multi-decadal analysis, with details on the effect of single floods. Such an approach can be replicated to study the dynamics of bars (not only alternate bars) on river reaches of the same or of larger size worldwide.

The relevance of the developed dataset emerges in comparison to previous field studies, which generally considered a much smaller number of bars and/or a much shorter time period. The present study is the only multi-decadal study on alternate bar dynamics in a river reach that includes about 40 bar wavelengths and based on an average of nearly 2 available surveys (i.e., Landsat images) per year. The reported results on the Alpine Rhine show that bar morphology and dynamics are variable in time and space. The effect of spatial discontinuities like bends, or temporal events like floods (or the absence of) can have an impact on bar wavelength and migration in relatively long reaches. This has to be taken into account to improve our general understanding of these bedforms. Spatially and temporally long observations are even more relevant when the aim is to quantify bar migration. Very few field data on bar migration are available in the literature and this data set provides a valuable source of information for testing physical, numerical, and mathematical models.

Table 1 lists the main field observations reported in the literature in the last decades. Most previous field studies are limited to short artificial channels (e.g., *Lewin* [1976]; *Welford* [1994]; *Ferguson et al.* [2011]; *Eekhout et al.* [2013]) or analyzed a relatively short time-scale (e.g., *Rodrigues et al.* [2012]; *Zolezzi et al.* [2012]; *Rodrigues et al.* [2015]). Our observations on the Alpine Rhine showed large variations in bar morphology both in space and in time. This suggests that local effects, as well as the occurrence of specific floods may affect bar morphodynamics. The only comparable cases in terms of space and time scale are the studies presented by *Church and Rice* [2009], *Ferguson et al.* [2011] and by *Jaballah et al.* [2015]. Though all these studies refer to alternate bars, their setting may slightly differ, suggesting that some care is required when comparing observations. For example, in the Fraser River [*Church and Rice*, 2009], channel width shows more pronounced spatial oscillations, which likely provide an additional forcing effect, enhancing the formation of steady bars [*Repetto et al.*, 2002]. This occurs also in the Arc River [*Jaballah et al.*, 2015], though to a much smaller extent and only before the engineering works that flattened the channel bed towards the middle of the observation period. In other cases, as in *Rodrigues et al.* [2012] and *Rodrigues et al.* [2015], the relatively short reach length may produce significant local effects, imposed by the upstream and downstream morphological conditions. Moreover, in both the Fraser and Arc rivers, vegetation is reported as a relevant factor that tends to affect bar dynamics by stabilizing them, stopping their migration, as well as by changing their wavelength and amplitude (*Bertoldi et al.* [2014]). Furthermore, some of the existing field studies (e.g. *Eekhout et al.* [2013]; *Jaballah et al.*

[2015]) studied the initial development of alternate bars, while others (e.g. *Welford* [1994]; *Rodrigues et al.* [2012, 2015]) as well as the present case have already completed this initial development and are nowadays presumably nearer a condition of quasi-equilibrium.

4.2. Observed bar morphodynamics: wavelength and migration

In terms of observed bar wavelength (as a function of channel width), the freely migrating bars of the downstream part of the Alpine Rhine show comparable results to those reported in previous field studies, ranging between the shorter bars monitored by *Church and Rice* [2009] (4 to 5 times the width) and the longer (9 to 10 widths) reported by *Ferguson et al.* [2011]. This range is comparable also to laboratory findings (*Ikeda* [1984], *Jäggi* [1984], *Tubino et al.* [1999]).

Few other studies report on data about bar migration. The Alpine Rhine shows an average migration of the free bars located in the downstream reach that is of the order of 0.8 - 0.9 times the average channel width per year. Previous studies on the same river reach, though based on a different methodology, indicate migration rates in the 1960s and 1970s ranged between 1.5 and 3 times the average channel width per year (*Zeller* [1967] cited in *Jäggi* [1983], *Jäggi* [1983]). A close comparison between our estimate and previous estimates on the same river reach is barely possible because previous estimates were based on different observation time periods, and thus the discrepancy is likely due to the effect of a few relevant flood events. Moreover, the two ramps were built in the early 1980s, possibly adding a further effect that may have forced (some) of the bars in more stable locations.

An analogous result, with a bar migration equal to 0.7 times the channel width per year, can be inferred from data presented by *Rodrigues et al.* [2012] on the Loire river, which has sandy bed material. Bar migration is a complex function of discharge (or sediment transport rate), bar morphology, and is also strongly affected by grain sorting (*Lanzoni* [2000b]) and presence of obstacles. Therefore, it is difficult to compare bar migration among different rivers, and between field observations and flume experiments, where the discharge is generally constant and the channel is perfectly regular and straight. *Crosato et al.* [2012] reported on long-term experiments on alternate bar dynamics, showing that there is a strong decreasing relationship between bar migration speed and bar wavelength, with bar migration reducing to half when the wavelength increases from 5 to 7.5 times the channel width. Our observations on the Alpine Rhine show a similar relationship, although with a few differences. The relationship between cumulative bar migration in the period 1999 - 2010 and bar wavelength is explicitly plotted in Figure 9. Differently from Figure 4, the wavelength value for each point in the plot is obtained as the average wavelength of the bar unit for which the cumulative (1999 to 2010) migration has been computed. The migration threshold of 180 m (two channel widths) used to discriminate between steady and migrating bars is represented through a horizontal dashed line. Average bar wavelengths fall into two markedly different clusters, resulting in a bar wavelength gap in the range 1090 m - 1190 m, where no bars plot. This allows to distinguish between "long" (i.e., > 1190 m) and "short" (i.e., < 1090 m) alternate bars. Long bars can be found only in the upstream sector (open symbols of Figure 9), while short bars are found only in the downstream sector (closed symbols of Figure 9). A rather close relation between bar wavelength and cumulative migration appears: short bars are mostly migrating, whereas long bars are mainly steady. More precisely, 75% of long bars are steady and 90% of short bars migrate. Maximum migration of the shorter bars occurs within a wavelength range of 900 - 1000 m, though smaller migration values are possible in the same range. Only a few short bars show a different behavior, with much lower values of migration (10% of the short bars). These are generally bars close to bends or ramps, and their wavelength is strongly affected by these obstacles. In most cases, ramps determine the occurrence of a steady bar front immediately upstream, with bar wavelength adjusting accordingly. This could be caused by the forced flat bed cross section imposed by the fixed ramp and by the high sediment transport flux induced by the larger local longitudinal slope. The presence of bends is invariably associated with a reduction of bar migration rate (Figure 6), and presents a twofold effect on bar wavelength (Figure 4): in the upstream reach, bends trigger sharp changes in the spatial variability of bar lengths, while in the downstream reach they are associated with a large local variability of bar lengths.

Crosato et al. [2012] also reported on the formation of steady longer bars (particularly in the upstream part of the flume), which are likely to suppress the migrating bars. It is not clear whether the systematic occurrence of steady bars in the upper reach of the Alpine Rhine may be explained in these terms, or whether they are caused by the occurrence of sharp bends which may induce the formation of forced bed forms (see *Zolezzi and Seminara* [2001]; *Zolezzi et al.* [2005]). The recent extensive study of *Jaballah et al.* [2015] on alternate bar dynamics in the Arc River, France, showed the existence of migrating bars, along with steady, longer bars affected by spatial constraints such as a bend or a bridge. Similarly, *Ferguson et al.* [2011] reported the coexistence of steady and migrating bars in the Vedder Canal. *Jaballah et al.* [2015] pointed out the relevance of including flow unsteadiness, to better understand and predict river bar evolution. In particular, flow conditions falling under the fully transport discharge may be responsible for the creation of shorter mid-channel bars that contribute to a more complex pattern.

4.3. A theoretical perspective on the observed bar dynamics

The results presented in the present work show that several bar properties (e.g. wavelength, migration) occurring over a 3-decade period in a long ($>$ 400 channel widths) reach of the Alpine Rhine are qualitatively consistent with analytical bar theories.

At the same time, discrepancies between observations and predictions can be highlighted. According to linear theories, both free migrating and forced steady bars can occur in the upstream and in the downstream sectors of the study reach, while observations suggest a spatially selective behavior, whereby long steady bars occur upstream and short migrating bars occur downstream. Moreover, the observed length of steady bars in the upstream straight reaches is shorter compared to the predictions of the linear theory for forced steady bars. We suggest that this discrepancy may be related to the effects of some of the assumptions on which the theories are built, which simplify the actual complexity of the real systems and allow focusing on "key" physical factors thought to act as major controls on bar morphodynamics. Clarifying what theories can and what they cannot predict is important to better illustrate how they can be used effectively to interpret field observations. In the following we focus on: (i) the unsteadiness of the flow; (ii) the finite length of straight reaches and (iii) the heterogeneity of the grain size.

4.3.1. Flow unsteadiness

Application of *Tubino* [1991] non-linear theory for free migrating bars in straight channels indicates that the time scale of flow unsteadiness is much shorter than the morphological time scale needed for free bars to reach their equilibrium amplitude. This underpins the possibility to use the assumption of steady flow. Under this hypothesis, the linear free bar theory predicts the wavelength of migrating bars, which is also known to be almost unaffected by non-linear effects (*Colombini et al.* [1987]), and does not show significant changes during the 30 years of observation. Therefore, despite the fact that the observed alternate bar configuration was generated by the action of a long lasting ($>$ 150 years) sequence of unsteady flows, the present analysis strongly suggests the validity of assuming a constant, bar-forming value of discharge to predict the condition of occurrence and the wavelength of migrating bars. On the other side, floods with the same intensity and duration can determine different migration properties of the same bar units: flow unsteadiness might then be relevant at shorter time scales (i.e. flood event), in locally reshaping and moving individual bars. Moreover, the analysis of the U parameter proposed by *Tubino* [1991] suggests that the two floods (in 1987 and 2005) that peaked at a discharge larger than Q_{cr} did not have enough time to flatten the riverbed, resetting the bar configuration. This confirms our observations, which exclude the possibility that the alternate bars were flattened during the 2005 flood, as the bar configuration before and after the flood was remarkably similar, with most bars only moving slightly downstream (Figure 8a).

4.3.2. Finite reach length

The linear theory for free migrating bars is obtained referring to an infinite channel length, where a periodical analytical solution is derived in the streamwise direction. An analogous assumption characterizes the linear theory for forced steady bars, where the channel length is assumed infinite only in one direction, with an upstream (or downstream) boundary where a local persistent perturbation of the straight, equiwidth channel geometry is present. The reported observations may help define a minimum reach length that can satisfy the (semi) infinite length condition. Our study site included a total of six straight reaches (three in each main sector) longer than approximately 2 km, i.e. 3 times the predicted free bar wavelength. Every straight reach is bounded upstream and downstream by local planform perturbations consisting of bends, ramps, confluences, which force steady bars in the nearby straight reaches. Only in some of the straight reaches, namely the three located in the downstream sector, migrating bars are observed. *Jaballah et al.* [2015] observed migrating bars in a 2.3 km long (~ 45 channel widths, or ~ 4 times the longest bar wavelength) straight reach of the Arc River in France, bounded by an upstream bend and by a downstream asymmetrical bridge pier. In their study, the number of migrating bars decreased with time. The migrating bars observed by *Eekhout et al.* [2013] occurred in a longer straight reach (in terms of bar wavelengths), while the secondary channel of the Loire River where alternate bar migration was observed by *Rodrigues et al.* [2015] is not longer than 2 bar wavelengths. The above observations suggest that a straight reach length of several times the free migrating bar wavelength might be a necessary though not a sufficient condition for migrating bars to occur.

4.3.3. Sediment size heterogeneity

Another simplifying assumption in the examined theories is the uniformity of grain size. The mathematical modeling and experimental works by *Lanzoni and Tubino* [1999] and *Lanzoni* [2000a] showed that graded sediments cause elongation of migrating bars, as well as a decrease of the migration speed. Indeed, we observed also a much slower migration rate than that predicted by linear theories. In addition to the previous points, bar migration is affected also by non linear effects caused by bar amplitude. As a result, bar migration cannot be accurately predicted by linear theories, and weakly non-linear theories or numerical models are needed.

The awareness of how much the theoretical assumptions may limit their applicability allows a more critical use of theories to interpret field observations. All of the observed bar wavelengths fall within the two limits set by linear theories for free migrating and forced steady bars in straight reaches. The range of variability of these limits is relatively narrow, when considering meaningful ranges for discharge, grain size, and channel slope (*Adami et al.* [2014]). Such analytically derived limits may therefore be viewed as the lower and upper boundaries of what can be actually observed in the corresponding real setting of straight river reaches. The alternate bars observed in the Alpine Rhine are likely to be the result of a non-linear interaction between the two types of bars (free and forced) predicted by the theories. This is in agreement with the experimental and numerical results of *Crosato and Mosselman* [2009] and *Crosato et al.* [2011] and with the analytical studies referring to weakly meandering channels with constant width (*Kinoshita and Miwa* [1967], *Tubino and Seminara* [1990]) and to straight channels with spatially oscillating width *Repetto and Tubino* [2001]. We argue that the result of such non-linear interaction would eventually result in bars with wavelengths falling within the limits predicted by linear theories. Interestingly, in the Alpine Rhine the observed migrating and steady bar lengths are closer to the computed limits for free and forced bars, respectively, which further supports this hypothesis. While the broad tendency can be therefore attributed to the physical processes already retained in the linear theories, further developments on the non-linear free-forced bars interaction in straight channels are needed to provide a complete picture of the controlling parameters and of the dominant effects. Furthermore, an analytical theory that addresses the role of bed discontinuities, such as ramps, on alternate bars in straight channels is also still missing.

5. Conclusions

This paper reports on the morphological dynamics of alternate bars in the Alpine Rhine. The analysis resulted in the longest spatial and temporal field case study of river bars in channelized rivers with a temporal survey resolution allowing to investigate the effect of individual floods. This quantitative dataset on bar wavelength and migration proved valuable to better interpret bar dynamics at the reach scale and to demonstrate the applicability and limits of analytical theories. Bars show a spatially selective behavior, with short, migrating bars occurring in distinct straight reaches with respect to longer, steady bars. A full range of bar wavelengths and more complex patterns occur in reaches with bends and ramps. Bar height obtained from cross section monitoring was found to be much more uniform. The temporally long dataset, including approximately 30 floods with different magnitude and duration, allowed the investigation of bar migration as a function of discharge, showing that bars migrate faster during intermediate floods, as larger discharges are probably responsible for a slight flattening of the bed forms.

The dataset also provided useful information to assess the applicability of analytical bar theories, so far mainly tested against flume experiments, and following recent attempts in French and Dutch streams. Values predicted by linear theories for free and forced bars in straight channels are in good general agreement with field observations, when considering conditions of bar formation and bar wavelength. Comparing theories and observations suggests that theoretical outcomes may represent the boundaries of the actual, intermediate behavior of bars, which likely reflects non-linear interactions, flow unsteadiness, sediment size heterogeneity and finite length of straight reaches, which are not retained in linear theories. The comparison demonstrates the value of theories for the interpretation of field observations. For instance, the difference in the migration-wavelength relation may suggest the long, steady bars to be forced by local planform discontinuities and the short migrating bars to result from a free instability of the riverbed. Flow unsteadiness seems to have a minor role here while grain size sorting might affect bar wavelength and migration. Together with analytical theories set up to separately investigate both effects, a numerical analysis might also help to study bar dynamics subject to real flood sequences.

Despite the above limits, the work shows that bar theories not only provide information on bar geometry and dynamics, but they can also help interpret the physical processes at the basis of their occurrence, i.e., set a suitable framework to differentiate between free migrating or forced steady bars.

Acknowledgments. Landsat data are freely available from the U.S. Geological Survey at http://landsat.usgs.gov. The authors wish to thank Lukas Indermaur (Lukas.Indermaur@wwf.ch) for providing the hydrological data from three gauging stations along the Rhine and David Vetsch (vetsch@vaw.baug.ethz.ch) for providing the cross sections of the Alpine Rhine. Codes for the analytical theories are available upon request to the corresponding author (luca.adami@unitn.it). The authors thank Rob Ferguson, David Dominic and an anonymous referee for their constructive comments and remarks.

References

Adami, L., W. Bertoldi, and G. Zolezzi (2014), Morphodynamics of alternate bars in the alpine rhine river: Methods for the applicability of mathematical models using felds observations, *Proceedings of the International Conference on Fluvial Hydraulics, RIVER FLOW 2014*, pp. 1213–1220.

Ashmore, P., W. Bertoldi, and J. Tobias Gardner (2011), Active width of gravel-bed braided rivers, *Earth Surface Processes and Landforms*, *36*(11), 1510–1521, doi:10.1002/esp.2182.

Bertoldi, W., A. Siviglia, S. Tettamanti, M. Toffolon, D. Vetsch, and S. Francalanci (2014), Modeling vegetation controls on fluvial morphological trajectories, *Geophysical Research Letters*, *41*(20), 7167–7175, doi:10.1002/2014GL061666.

Callander, R. A. (1969), Instability and river channels, *Journal of Fluid Mechanics*, *36*, 465–480.

Church, M., and S. P. Rice (2009), Form and growth of bars in a wandering gravel-bed river, *Earth Surface Processes and Landforms*, *34*(10), 1422–1432, doi:10.1002/esp.1831.

Colombini, M., G. Seminara, and M. Tubino (1987), Finite-amplitude alternate bars, *Journal of Fluid Mechanics*, *181*, 213–232, doi:10.1017/S0022112087002064.

Constantine, J. A., T. Dunne, J. Ahmed, C. Legleiter, and E. D. Lazarus (2014), Sediment supply as a driver of river meandering and floodplain evolution in the Amazon Basin, *Nature Geoscience*, *7*(12), 899–903, doi:10.1038/ngeo2282.

Crosato, A., and E. Mosselman (2009), Simple physics-based predictor for the number of river bars and the transition between meandering and braiding, *Water Resources Research*, *45*(3), n/a–n/a, doi:10.1029/2008WR007242, w03424.

Crosato, A., E. Mosselman, F. Beidmariam Desta, and W. S. J. Uijttewaal (2011), Experimental and numerical evidence for intrinsic nonmigrating bars in alluvial channels, *Water Resources Research*, *47*(3), n/a–n/a, doi:10.1029/2010WR009714.

Crosato, A., F. B. Desta, J. Cornelisse, F. Schuurman, and W. S. J. Uijttewaal (2012), Experimental and numerical findings on the long-term evolution of migrating alternate bars in alluvial channels, *Water Resources Research*, *48*(6), doi:10.1029/2011WR011320.

Eekhout, J. P. C., A. J. F. Hoitink, and E. Mosselman (2013), Field experiment on alternate bar development in a straight sand-bed stream, *Water Resources Research*, *49*(12), 8357–8369, doi:10.1002/2013WR014259.

Engels, H. (1914), *Handbuch des Wasserbaues: fur das Studium und die Praxis*, Engelmann.

Engelund, F. A., and E. Hansen (1967), *Monograph on sediment transport in alluvial streams. / By Frank Engelund and Eggert Hansen*, Copenhagen: Teknisk forlag.

Ferguson, R. I., D. J. Bloomer, and M. Church (2011), Evolution of an advancing gravel front: observations from Vedder Canal, British Columbia, *Earth Surface Processes and Landforms*, *36*(9), 1172–1182, doi:10.1002/esp.2142.

Fredsøe, J. (1978), Meandering and braiding of rivers, *Journal of Fluid Mechanics*, *84*(pt 4), 609–624, cited By 73.

Henshaw, A. J., A. M. Gurnell, W. Bertoldi, and N. A. Drake (2013), An assessment of the degree to which Landsat TM data can support the assessment of fluvial dynamics, as revealed by changes in vegetation extent and channel position, along a large river, *Geomorphology*, *202*(0), 74 – 85, doi:http://dx.doi.org/10.1016/j.geomorph.2013.01.011.

Hunziker, Zarn, and Partners (2001), Morphologie und geschiebehaushalt alpenrhein (morphology and sediment budget of alpine rhine), *Project A-108*, Internationale Regierungskommission Alpenrhein (International Government Commission of Alpine Rhine).

Ikeda, S. (1984), Prediction of alternate bar wavelength and height, *Journal of Hydraulic Engineering*, *110*(4), 371–386, doi:10.1061/(ASCE)0733-9429(1984)110:4(371).

Jaballah, M., B. Camenen, L. Pnard, and A. Paquier (2015), Alternate bar development in an alpine river following engineering works, *Advances in Water Resources*, *81*(available on-line), 103–113, doi:http://dx.doi.org/10.1016/j.advwatres.2015.03.003.

Jäggi, M. (1983), Alternierende kiesbanke (Alternate bars), Ph.D. thesis, Swiss Federal Institute of Technology Zürich Laboratory of Hydraulics, Hydrology and Glaciology, Switzerland.

Jäggi, M. (1984), Formation and effects of alternate bars, *Journal of Hydraulic Engineering*, *110*(2), 142–156, doi:10.1061/(ASCE)0733-9429(1984)110:2(142).

Johannesson, H., and G. Parker (2013), *Linear Theory of River Meanders*, pp. 181–213, American Geophysical Union, doi:10.1029/WM012p0181.

Kinoshita, R., and H. Miwa (1967), River channel formation which prevents downstream translation of transverse bar (in japanese), *Shinsabo*, *94*, 12–17.

Lanzoni, S. (2000a), Experiments on bar formation in a straight flume: 1. uniform sediment, *Water Resources Research*, *36*(11), 3337–3349, doi:10.1029/2000WR900160.

Lanzoni, S. (2000b), Experiments on bar formation in a straight flume: 2. graded sediment, *Water Resources Research*, *36*(11), 3351–3363, doi:10.1029/2000WR900161.

Lanzoni, S., and M. Tubino (1999), Grain sorting and bar instability, *Journal of Fluid Mechanics*, *393*, 149–174, doi:10.1017/S0022112099005583.

Lewin, J. (1976), Initiation of bedforms and meanders in coarse grained sediment, *Bulletin of the Geological Society of America*, *87*(2), 281–285.

Nelson, J. (1990), The initial instability and finite-amplitude stability of alternate bars in straight channels, *Earth Science Reviews*, *29*(1-4), 97–115, doi:10.1016/0012-8252(0) 90030-Y.

Parker, G. (1976), On the cause and characteristic scales of meandering and braiding in rivers, *Journal of Fluid Mechanics*, *76*(3), 457–480, doi:10.1017/S0022112076000748.

Parker, G. (1990), Surface-based bedload transport relation for gravel rivers, *Journal of Hydraulic Research*, *28*(4), 417–436, doi:10.1080/00221689009499058.

Parker, G., P. R. Wilcock, C. Paola, W. E. Dietrich, and J. Pitlick (2007), Physical basis for quasi-universal relations describing bankfull hydraulic geometry of single-thread gravel bed rivers, *Journal of Geophysical Research: Earth Surface*, *112*(F4), doi:10.1029/2006JF000549.

QGIS Development Team (2009), *QGIS Geographic Information System*, Open Source Geospatial Foundation.

Repetto, R., and M. Tubino (2001), Topographic expressions of bars in channels with variable width, *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, *26*(1), 71–76, doi:10.1016/S1464-1909(01)85017-6, cited By 4.

Repetto, R., M. Tubino, and C. Paola (2002), Planimetric instability of channels with variable width, *Journal of Fluid Mechanics*, *457*, 79–109, doi:10.1017/S0022112001007595.

Rodrigues, S., N. Claude, P. Juge, and J.-G. Breheret (2012), An opportunity to connect the morphodynamics of alternate bars with their sedimentary products, *Earth Surface Processes and Landforms*, *37*(2), 240–248, doi:10.1002/esp.2255.

Rodrigues, S., E. Mosselman, N. Claude, C. L. Wintenberger, and P. Juge (2015), Alternate bars in a sandy gravel bed river: generation, migration and interactions with superimposed dunes, *Earth Surface Processes and Landforms*, *40*(5), 610–628, doi: 10.1002/esp.3657.

Schielen, R., A. Doelman, and H. de Swart (1993), On the nonlinear dynamics of free bars in straight channels, *Journal of Fluid Mechanics*, *252*, 325–356.

Struiksma, N., and A. Crosato (2013), *Analysis of a 2-D Bed Topography Model for Rivers*, pp. 153–180, American Geophysical Union, doi:10.1029/WM012p0153.

Struiksma, N., K. Olesen, C. Flokstra, and H. De Vriend (1985), Bed deformation in curved alluvial channels, *Journal of Hydraulic Research*, *23*(1), 57–59, doi:10.1080/00221688509499377.

Tubino, M. (1991), Growth of alternate bars in unsteady flow, *Water Resources Research*, *27*(1), 37–52, doi:10.1029/90WR01699.

Tubino, M., and G. Seminara (1990), Free-forced interactions in developing meanders and suppression of free bars, *Journal of Fluid Mechanics*, *214*, 131–159, cited By 57.

Tubino, M., R. Repetto, and G. Zolezzi (1999), Free bars in rivers, *Journal of Hydraulic Research*, *37*(6), 759–775, doi:10.1080/00221689909498510.

Welford, M. R. (1994), A field test of Tubino's (1991) model of alternate bar formation, *Earth Surface Processes and Landforms*, *19*(4), 287–297, doi:10.1002/esp.3290190402.

Werth, K. (2014), *Geschichte der Etsch zwischen Meran und San Michele Flussregulierung, Trockenlegung der Mser, Hochwasserschutz.*, Athesia.

Zeller, J. (1967), Flussmorphologische studie zum mäanderproblem / meandering channels in switzerland, *Project 74*, ETH Zürich.

Zolezzi, G., and G. Seminara (2001), Downstream and upstream influence in river meandering. part 2. planimetric development, *Journal of Fluid Mechanics*, *438*, 183–211, doi:10.1017/S002211200100427X.

Zolezzi, G., M. Guala, D. Termini, and G. Seminara (2005), Experimental observations of upstream overdeepening, *Journal of Fluid Mechanics*, *531*, 191–219.

Zolezzi, G., W. Bertoldi, and M. Tubino (2012), *Morphodynamics of Bars in Gravel-Bed Rivers: Bridging Analytical Models and Field Observations*, pp. 69–89, John Wiley & Sons, Ltd, doi:10.1002/9781119952497.ch6.

Figure 1. Overview of the study area with the catchment of the Rhine River in light gray and the catchment of the Alpine Rhine highlighted in dark gray. Within the left panel, locations of bends and ramps in the study reach are identified.

Figure 2. Discharge record for the period 1984-2012. Circles represent acquisition date and corresponding discharge value of the analyzed Landsat imagery. Horizontal lines indicate the fully wet discharge Q_{FW} (continuous line); the fully transporting discharge Q_{FT} (dashed line) and the critical discharge for alternate bar formation following *Colombini et al.* [1987], Q_{cr} (dotted line). See Table 2 for further details.

Figure 3. Three examples of Landsat images acquired at different flow stages: a) March 04, 2002, Q = $53.5\,\mathrm{m^3s^{-1}}$; b) July 21, 2006, Q = $152.5\,\mathrm{m^3s^{-1}}$; c) May 01, 2000, Q = $313.0\,\mathrm{m^3s^{-1}}$. d) Example of digitized bars of a short reach, pointing out location and definition of bar fronts, bar tails, and bar wavelength. Dotted lines represent digitized bars of LANDSAT L4-5 TM, March 28, 1984, Q =$127\,\mathrm{m^3s^{-1}}$; solid lines represent LANDSAT L7 ETM+, July 16, 2010, Q = $154\,\mathrm{m^3s^{-1}}$

Figure 4. Bar wavelength of each monitored bar unit on the complete Landsat imagery dataset (1984-2013). Vertical lines represent bends (dashed) and ramps (continuous). Light grey area represents the theoretical wavenumber range of free bars, while dark grey area represents the theoretical range of forced bars.

Figure 5. Bar elongation in the period 1999-2010. Length along river centerline refers to bar fronts in 1999. Vertical lines represent bends (dashed) and ramps (continuous).

Figure 6. Cumulative bar migration in the period 1999-2010. Each point represents the total migration of single bars. Vertical lines represent bends (dashed) and ramps (continuous).

Figure 7. Four examples of bar migration as a function of time in the period 1999-2010. Open symbols refer to migrating bars, closed symbols refer to steady bars. Vertical lines refer to the discharge record of the same period, where the discharge (Q) is scaled with the fully transporting discharge (Q_{FT}).

Figure 8. Bar migration during single floods as function of: i) peak flood discharge; ii) flood duration, considering a threshold equal to Q_2; iii) flood flow volume above the threshold discharge Q_2. Two migrating bars are considered over several flood events: bar 09 (km 35, squared symbols) and bar 23 (km 22, circled symbols) of Figure 7.

Figure 9. Cumulative bar migration in the period 1999-2010 as a function of bar wavelength.

Figure 10. Bar height for each surveyed cross section as a function of the length along river centerline. Vertical lines represent bends (dashed) and ramps (continuous).

Table 1. References, geometric and hydraulic data of the field studies reported in the literature.

Authors	River	d_{50} $[mm]$	s $[m/km]$	W $[m]$	Q_{mean} $[m^3 s^{-1}]$	L_R $[km]$	n_{bars} $[-]$	ΔT $[year]$
Lewin [1976]	Ystwyth (UK)	0.7 – 42	3.7	36	5.5	0.5	4	2
Welford [1994]	Embarras, Illinois (US)	0.53	0.6	12	0.1	4	-	0.25
Church and Rice [2009]	Lower Fraser, British Columbia (Canada)	17 – 53	0.48	1000 – 2000	3410	50	20	51
Ferguson et al. [2011]	Vedder Canal, British Columbia (Canada)	12 – 35	2 – 5	100 – 240	67	4.7	9	57
Rodrigues et al. [2012]	Loire (France)	0.83	0.25	145 – 200	850	3	2	2
Zolezzi et al. [2012]	Tagliamento (Italy)	40	3.6	840	1400	3	braided	5
Eekhout et al. [2013]	Hooge Raam (The Netherlands)	0.218	0.18	7.5	0.22	0.6	6	3
Jaballah et al. [2015]	Arc (France)	80	6 – 11	35 – 50	12	8	10	30
Rodrigues et al. [2015]	Loire (France)	0.83	0.25	145 – 200	850	3	2	2
present paper	Alpine Rhine (Switzerland-Austria)	20 – 60	1.3 – 2.9	86 – 106	230	41.7	80	30

Table 2. Geometrical and hydraulic properties of the three sub-reaches of the Alpine Rhine. W is channel width, d_s a representative sediment diameter, s longitudinal slope, Q_{FW} is the fully wet discharge, Q_{FT} the fully transporting discharge, Q_{cr} the critical discharge for bar formation. Discharge parameters were calculated following *Colombini et al.* [1987].

	Position	Geometry			Discharge		
Sub-reach	from - to $[km]$	W $[m]$	d_s $[mm]$	s [‰]	Q_{FW} $[m^3s^{-1}]$	Q_{FT}	Q_{cr}
Upstream	0.00 - 12.27	85	60 - 50	2.9	381	829	1845
Center	12.27 - 30.94	95	50 - 30	2.0	270	628	1942
Downstream	30.94 - 41.70	106	30 - 20	1.3	230	511	1880