Do the same river engineering works cause the same hydrosedimentary changes? A comparative approach on four bypassed reaches of the Rhône River.

Les mêmes aménagements fluviaux causent-ils les mêmes impacts hydrosédimentaires ? Une approche comparative sur quatre tronçons court-circuités du Rhône.

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ABSTRACT

Rivers in the Anthropocene have experienced significant hydromorphological changes as a result of engineering interventions (e.g., channelization, hydroelectric infrastructures) which have profoundly disrupted natural hydrosedimentary dynamics. This study examined four channelized (late 19th century) and bypassed (mid-20th century) Rhône River reaches (~60 km, ~13% of its length) to explore whether similar interventions yield comparable hydrosedimentary effects. Using GIS-based planform analysis (historical maps, aerial imagery, and satellite data), we documented channel evolution and margin terrestrialization, supplemented by hydrosedimentary data (longitudinal riverbed profiles and historical water levels). The results revealed active channel narrowing (-43% to -17% after channelization; -32% to -17% after diversion) and margin terrestrialization (27–44% after channelization; 41–66% after diversion). So, the by-passing had a more pronounced impact when post-channelization adjustments were moderate; and vice versa. In all cases, these diversions have profoundly disrupted hydrological sequences (homogenization of topo- and chrono-sequences), altering lateral connectivity patterns (less frequent but more intense), ultimately degrading the remaining elements of the alluvial mosaic, along with the socio-ecosystem functions and services it supported (e.g., habitat diversity). Additionally, gravel mining has exacerbated local bed incision, with cumulative depths reaching up to -4.1 m over the 20th century (-5 cm/year). Inter-reach variations in impact intensity reflect reach-specific factors and cumulative pressures. These findings highlight the need for a thorough assessment of the impacts of these engineering works to effectively guide management and ecological restoration strategies.

RÉSUMÉ

La trajectoire fonctionnelle et la dynamique hydrosédimentaires des cours d'eau de l'Anthropocène ont été profondément bouleversées par des phases d'aménagements successives (e.g., chenalisation, aménagement hydroélectrique). Nous avons étudié quatre tronçons corrigés (fin du 19ème siècle) et court-circuités (milieu du 20ème siècle) du Rhône (~60 km, soit 13 % de sa longueur) afin d'examiner si des aménagements similaires entrainent des impacts hydrosédimentaires comparables. À l'aide d'une analyse chronoplanimétrique (cartes historiques, photos aériennes et images satellites), nous avons analysé la rétraction de la bande active et l'atterrissement des marges alluviales à la lumière de données hydrosédimentaires historiques (profil en long du fond du lit, niveaux d'eau). Les résultats indiquent une rétraction de la bande active (-43 % à -17 % suite à la chenalisation ; -32 % à -17 % suite à la dérivation) et un atterrissement des marges endiguées (27–44 % suite à la chenalisation ; 41–66 % suite à la dérivation). Ainsi, les dérivations ont eu un impact plus marqué lorsque les ajustements post-chenalisation étaient modérés, et inversement. Dans tous les cas, ces dérivations ont profondément perturbé les séquences hydrologiques (homogénéisation des topo- et chrono-séquences) et les modalités de connectivité latérale (moins fréquentes mais plus intenses), continuant la mosaïque alluviale ainsi que les fonctions socio-écosystémiques qu'elle portait (e.g., homogénéisation des conditions d'habitat). De plus, l'extraction de granulats alluvionnaires en lit mineur a aggravé localement l'incision du fond du fleuve, atteignant jusqu'à -4,1 m cumulés sur le 20e siècle (-5 cm/an). Les variations d'intensité des impacts dépendent des caractéristiques locales et des pressions cumulées observées sur chaque site. Ces résultats soulignent l'importance d'évaluer les impacts des aménagements afin de guider les stratégies de gestion et de restauration.

Key word: River engineering, terrestrialization, groyne fields, dam diversion, floodplain

Mots-clefs : Aménagement fluvial, atterrissement, champs d'épis, barrage en dérivation, plaine alluviale

1 INTRODUCTION

Over the past two centuries, rivers in the Anthropocene have undergone significant alterations due to human interventions, modifying their hydrosedimentary dynamics and landscapes (Wohl, 2020). These changes stem from various phases of development, such as flood control infrastructures, channelization, and hydroelectric installations, all of which have disrupted natural eco-morphodynamic processes (Gregory, 2006). Notably, these modifications have hindered crucial water-mediated exchanges like sediment and nutrient movement, impacting biodiversity and habitat diversity (Geerling et al., 2006). Research on channelized rivers with bypassed sections, such as the Danube and the Rhine rivers, reveals that these rivers, once characterized by multi-thread or anabranching systems, have transitioned into single-thread configurations (Arnaud et al., 2015; Hohensinner et al., 2004). The Rhône River (France) has also undergone significant engineering interventions: channelization through hydraulic infrastructures starting in the 19th century (Phase 1), followed by the installation of hydroelectric infrastructures with by-passed reaches in the mid-20th century (Phase 2). These elements raise various questions: have the Rhône River bypassed sections that underwent both phases of development experienced similar forcings and hydrosedimentary changes? And how does this manifest at the channel and alluvial margin levels? In other words, do the same river engineering works cause the same hydrosedimentary changes?

2 MATERIAL AND METHODS

The study sites consist of four channelized and bypassed reaches, selected from a total of 17 along the Rhône River, a highly engineered French-Swiss river spanning 812 km. The reaches at Pierre-Bénite (PBN), Péage-de-Roussillon (PDR), Montélimar (MON) and Donzère-Mondragon (DZM) range from 12.5 km to over 30 km in length, collectively spanning over 60 km (approximately 13% of the river total length). Channelization works in the late 19th led to the implementation of numerous dike fields, with densities ranging from 8.4 structures per kilometer at MON to 20.8 at PBN, affecting large portions of the alluvial margins. Between 1952 and 1977, bypassing schemes drastically reduced discharge levels in these reaches, leaving residual flows as low as 10–20 m³/s at PBN and PDR, 15-60 m³/s at Mon and 60 m³/s at DZM. Restoration initiatives have raised minimum flows to 100 m³/s at PBN (since the 1990s), 50–125 m³/s at PDR, and 75 m³/s at MON and DZM (since the 2010s).

Geomorphological evolution and development contributions - We used a geo-historical GIS-based approach: aerial photographic archives were analyzed to track the terrestrialization evolution of engineered margins. Aerial photographs (1938–2009) from the National Institute of Geographic and Forest Information (IGN) were georeferenced to analyze the evolution of alluvial margins during river engineering phases. For example, at PDR: post-correction: 1938, 1949; pre-diversion: 1974; diversion: 1979; post-diversion: 1981, 1991, 2002, and the most recent state: 2009). Root-mean-square errors ranged from 4.1 ± 1.6 m (1938) to 2.2 ± 0.9 m (2002), ensuring precise rectification despite source quality variations (Arnaud et al., 2015). Using GIS protocols, active channels and terrestrial surfaces were vectorized, tracking aquatic-terrestrial changes across the four reaches (Figure 1).

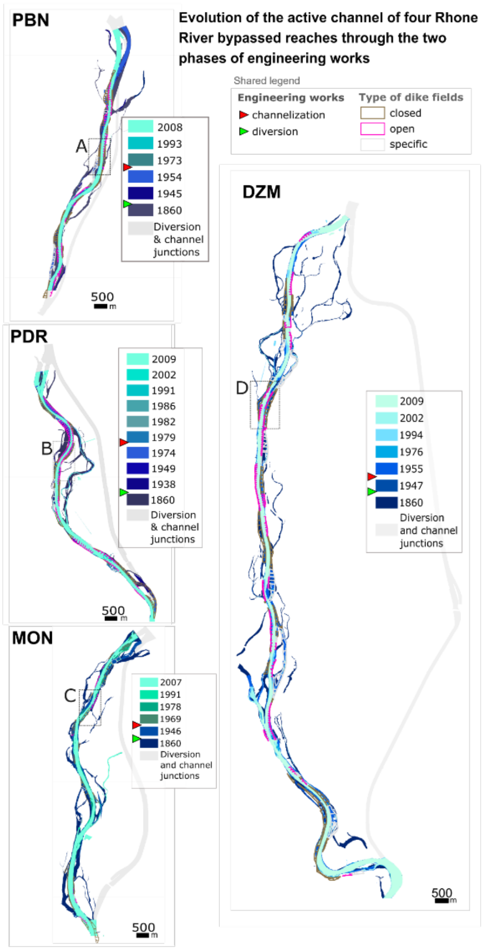

Figure 1: Rhone channel planform evolution in the four studied reaches (PBN, PDR, MON, DZM) according to two main contemporary engineering

Underlying hydrosedimentary processes - Terrestrialization along engineered river margins occurs through two main mechanisms: fine sedimentation and/or water level decline. We used historical hydrosedimentary data such as longitudinal riverbed elevation profiles and water levels (Compagnie Nationale du Rhône*, Fascicule Armand des pentes du Rhône*, Topographic Data Base) to best capture the hydrosedimentary adjustments resulting from both phases of river engineering and historical pressures (gravel mining).

3 SELECTED RESULTS AND DISCUSSION

3.1 Geomorphological evolution and development contributions

In terms of side channel retraction, the impact of channelization predominates at PBN (Phase 1: 90.4% vs. Phase 2: 9.6%) and MON (Phase 1: 99.7% vs. Phase 2: 0.3%), while it is a little more nuanced at DZM (Phase 1: 65.8% vs. Phase 2: 34.2%). At PDR, we even observe an expansion of the water surface in Phase 2 (Phase 2: +9.5% based on side channel area in 1860). In terms of main channel narrowing, channelization predominates at PBN (P1: 66% vs. P2: 34%) and PDR (P1: 63% vs. P2: 37%), while bypassing has a greater influence at MON (P1: 26% vs. P2: 74%) and DZM (P1: 39% vs. P2: 61%). Regarding terrestrialization, phases 1 and 2 have an equivalent impact on PBN (P1: 52% vs. P2: 48%). Terrestrialization is slightly more pronounced in phase 2 at PDR (P1: 47% vs. P2: 53%), while the bypassing phase has a greater influence at MON (P1: 29% vs. P2: 71%) and DZM (P1: 37% vs. P2: 63%). Focusing on the engineered margins, 87% (474 ha) of the surfaces have transitioned from aquatic to terrestrial. This terrestrialization trajectories are described by chrono-planimetric patterns that can be classified into five types (Fig. 4.B) – lateral (49%), complex (23%), concentric (9%), uniform patterns post-dam (9%), and aquatic patterns (6%) – demonstrating recurrences in sediment storage and erosion modalities.

The surveys of the riverbed altitude show that all reaches experienced incision during the 20th century: on average, around one meter for PDR, MON, and DZM, and four times as much in PBN (averaging at -4.05 m). Engineering phases marked by varied tendencies in the river bed incision across reaches – PBN and MON exhibit significant incisions in Phase 1, averaging -2.11 m and -1.28 m respectively (Table 1). PDR and DZM show low incision or even a slight aggradation (at -0.27 m and +0.08 m respectively) but substantial incisions in Phase 2, reaching -0.8 m for PDR and -0.72 m for DZM. PBN displays an even bigger magnitude in Phase 2 (-4,6 cm.y-1) than in Phase 1 (-2,8 cm.y-1), whereas the MON river bed remains stable.

3.2 Underlying hydrosedimentary processes

Phase 1 / In-dike sediment accumulation and deposit patterns - The four reaches experience in-dike sediment accumulation, leading to the progression of deposits (both lateral and vertical accretion) in dike fields protected by a longitudinal dike (closed fields), leading to fine sediment trapping. In the absence of this longitudinal dike, the phenomenon is much less pronounced in open fields which experienced low terrestrialisation in phase 1. The propensity for sediment accumulation is dependent on the capacity of dike fields to trap sediments. The density and the size of the structures (i.e., the distance between groynes and the length of the groynes) is crucial in determining the hydraulic constraints and patterns of sediment deposition (Sukhodolov et al., 2002). That is why at DZM, we hypothesize that the difference could be attributed to the larger dike fields and so greater hydraulic constraints. At MON, the lower dike field density could have initiated a less pronounced channel retraction.

Phase 1 and 2 / River bed incision trends - The four sectors show varying incision levels, affecting water levels differently. At PBN, Phase 1 causes significant riverbed incision (avg. -2.11 m), likely due to channelization and shear stress from dense dike field setting. At PDR, Phase 1 shows less incision (avg. -0.27 m) than Phase 2 (-0.8 m). This may be due to data limitations (high discharge in the "pre-diversion" reference date) or higher hydrological connectivity in Phase 2, with more breaches and concentric patterns leading to variable connections and lower terrestrialization. In Phase 2, channel retraction and dike field terrestrialization are dominant at MON and DZM, while the processes of incision and fine sediment accumulation from Phase 1 were actually less pronounced. Vázquez-Tarrío et al. (2019) showed that multiple dams can cumulatively impact sediment transfer and geomorphic interactions. In the upstream-downstream gradient, PBN is the first reach, followed by PDR, with MON and DZM further downstream. Channelization in Phase 1 increased shear stress and transport capacity, causing incision in the upstream reaches like PBN. The downstream reaches, such as PDR, benefited from the sediment load upstream, leading to moderate incision in these areas.

Phase 2 / Water level patterns induced by diversion - Significant changes in waterlines have been observed before and after dam installation, impacting both levels and slopes. Each reach exhibits a first "space-time" inflection point (IP1), where pre- and post-dam water levels cross, corresponding to

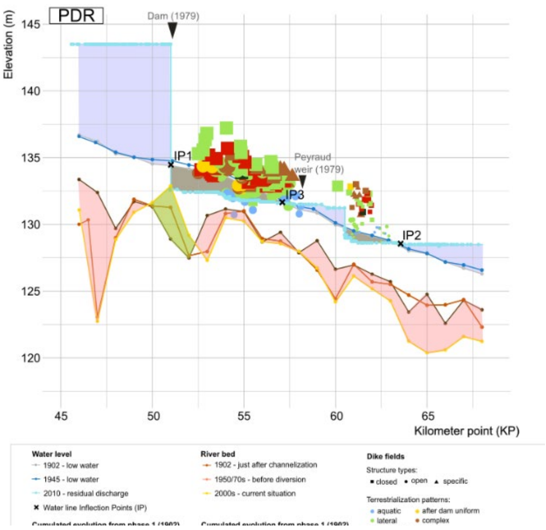

Figure 2: Upstream-downstream overview of the changes in the water level and river bed elevation during phases 1 and 2 at PDR

regulated water line upstream and downstream, with a noticeable step at the dam itself. The second "space-time" inflection point (IP2) downstream shows that the slope of the regulated water level does not recover, remaining flat due to the downstream reservoir's backwater effect. This phenomenon is characteristic of configurations with bypassed series, emphasizing that even outside of developments, their effects are observed. In summary, the longitudinal gradient of water levels within the bypassed reaches is influenced by dams themselves and the backflow effects, as well as weirs where they are present (e.g., Peyraud weir at PDR). So, the relationship between the channel and its margins varies over time and space along this upstream-downstream gradient. This differential hydrological connection modalities serve as an additional factor that may explain intra-reach/local variability in terms of chronoplanimetric and semi-aquatic patterns.

Phase 2 / Riverbed alteration after diversion works and associated gravel mining - Regarding the evolution of the riverbed consecutive to the dam installation, typical adjustments include riverbed aggradation (depositional pattern) upstream of the dam and post-dam incision (erosional pattern). The former is caused by the dam reservoir, which creates good conditions for sediment accumulation. A river bed aggradation upstream of the dam is observed at PDR and MON but not at PBN and DZM. Flood lowering in the bypassed reach typically reduces in-channel shear stress and mitigates incision, as seen in the old Rhine (Arnaud et al., 2015) and PDR (Seignemartin et al., 2023). However, despite reduced shear stresses after flow diversion, exacerbated by initial channelization, the riverbed still incises locally, particularly around gravel extraction sites, likely influenced by the specific local hydromorphological conditions.

4 CONCLUSIONS

The Rhône River, a prime example of dual engineering, illustrates the long-term effects of channelization and diversion on fluvial systems. These engineering works contribute to the terrestrialization and disconnection of its alluvial margins, with impacts varying based on initial connectivity and local hydromorphological conditions. Gravel extraction, linked to dam construction, can counter expected outcomes: despite reduced shear stress after flow diversion, the riverbed continues to incise locally, especially near extraction sites. Diversions had a more pronounced impact when post-channelization adjustments were moderate, and vice versa. In all cases, these diversions drastically affected the hydrological gradients and ultimately altered what remained of the alluvial mosaic and the socio-ecosystem functions and services it supported (e.g, semi-aquatic habitat). These findings stress the need for thorough impact assessments to guide management and restoration strategies as drivers are multiple and their effects can vary from one reach to another, limiting generalization in cause-effect relationships.

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