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Definition of an indicator assessing the impact of a dam on the downstream river landscape

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A R T I C L E I N F O

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A B S T R A C T

The increasing number of water withdrawals in Alpine regions represents a significant threat to aquatic ecosystems and river landscape (riverscape). To assess their sustainability, the impacts on river ecological status and landscape features need to be quantified with appropriate indicators. However, assessment of landscape attributes is a complex challenge, due to the lack of standardized methods. Moreover, few metrics quantifying the impacts of water withdrawal on downstream riverscape perception are available in the scientific literature.

In this paper, a new indicator, named Landscape Protection Level (LPL), aimed at assessing the effects of water withdrawals on the river landscape, is presented. The indicator has been developed in Aosta Valley (NW Italian Alps), where the river network is heavily exploited by hundreds of withdrawals for hydropower production and irrigation, and it has been included in a multi-criteria analysis (MCA) procedure to assess the sustainability of water withdrawal licenses in relation to different flow release scenarios.

The LPL indicator is based on three parameters, Constraint Factor, Release Factor, and Visual Elements Factor, quantifying the presence of landscape protection constraints, the ratio of flow released downstream of the dam to the available river discharge, and the impact on the visual perception of the bypassed stretch, respectively.

Its application in four real case studies of existing hydropower plants is presented and discussed in the paper, demonstrating the indicator applicability to assess both specific release values and flow release scenarios varying over the year. Results are analyzed by highlighting the main strengths and weaknesses of the indicator and proposing some suggestions for future improvements. In particular, the reactiveness of the indicator, the representativeness of the stakeholders' interests, the transparency of the indicator calculation procedure, and the time required for data collection and processing are discussed. Finally, future activities aimed at further improving the indicator applicability and transferability to different river contexts are proposed.

1. Introduction

In recent decades, issues related to water resource use (e.g., ensuring residual flows downstream of hydropower and irrigation dams, managing conflicting stakes, etc.) gained increased attention, and the impacts on water availability caused by climate change will further intensify conflicts between different users, such as agriculture, hydropower, industry, and tourism (Scheurer et al., 2018). Thus, an approach balancing landscape protection and economic exploitation, analyzing conflicting aspects from multiple perspectives, is required for the implementation of future management plans (Vassoney et al., 2017; Lanz et al., 2018). Water withdrawal sites, in particular for hydropower (HP) plants, have a significant effect on mountainous areas, since they alter natural habitats and landscapes (Ferrario and Castiglioni, 2017). Given the rarity of the remaining pristine reference rivers (Hohensinner et al., 2004), strategies focusing on the conservation of ecosystems and landscapes are extremely

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important to avoid irreversible impacts (Brunke, 2002; Platform Water Management in the Alps, 2018).

However, quantifying and assessing landscape attributes, in particular aesthetic quality, is a complex challenge due to the difficulties in unambiguously assigning sensory responses to particular elements of river landscapes (i.e., riverscapes) (Pflüger et al., 2010). Riverscape assessment generally focuses on riparian vegetation and river geomorphology (e.g., Meitner, 2004; Hicks et al., 2007; Aguiar et al., 2016), river flow preferences (e.g., Brown and Daniel, 1991; Pflüger et al., 2010), as well as on river restoration measures (e.g., Rohde et al., 2005; Marttila et al., 2016). Moreover, these studies are often based on interviews or surveys involving stakeholders, like local communities or tourists (e.g., Le Lay et al., 2013; Eder and Arnberger, 2016; Verbrugge and van den Born, 2018).

However, very few metrics or indicators for riverscape assessment focusing on the effects of a water withdrawal on the stakeholders' perception of the riverscape downstream of the dam (river channel and riparian areas with reduced discharges) are available in the scientific literature. Excluding the studies focusing on riparian vegetation and river geomorphology changes, which occur over long timescales, the available metrics quantifying the impacts on the riverscape due to the watercourse flow regime alteration mainly consider some hydraulic parameters, such as water depth or water flow dynamics (e.g., Pflüger et al., 2010; Barthélémy and Armani, 2015; Eder and Arnberger, 2016; Marttila et al., 2016), or water velocity and wetted area (e.g., Brittain, 2003). Some researchers also considered visual characteristics, like the color of water and exposed gravel (e.g., Pflüger et al., 2010). Other features considered in the literature are more qualitative, including preferences and perceptions collected from watercourse users and stakeholders, like the preference for a great variety of natural conditions (e.g., Smith et al., 1995; Barthélémy and Armani, 2015), opportunities for recreation and cultural activities (e.g., Gumiero et al., 2013; Marttila et al., 2016) or the perception of appreciation and fruition of the riverscape (e.g., Sherren et al., 2016; Brummer et al., 2017; Ferrario and Castiglioni, 2017). Finally, some researchers mentioned the possible changes in downstream ecosystems (e.g., Schwarz and Bloesch, 2004; Frolova, 2010; Esselman and Opperman, 2010), aesthetic impressions about the local scenery (e.g., Brummer et al., 2017), or the need to preserve specific landscape features of the river (e.g., Bratrich et al., 2004; Hooker, 2014).

Under this framework of lack of a specific metric for the assessment of a riverscape affected by water withdrawals, this paper presents a new indicator quantifying the impacts on the river landscape due to different flow release scenarios. The indicator, named Landscape Protection Level (LPL), has been elaborated in Aosta Valley, a small Alpine region located in NW Italy. The region is strongly affected by river exploitation, with hundreds of HP plants built over the last century in a river network already altered by several agricultural withdrawals and many projects for new sites (SPARE, 2018). A procedure based on the application of multi-criteria analysis (MCA) is being used to assess the sustainability of water withdrawals, finding a sustainable balance among the different stakeholders' needs (RAVA, 2006). Landscape is among the official criteria used in the MCA assessment (together with energy, economy, environment, and fishing (Vassoney et al., 2020)), since the region has a strong tourist vocation, due to its important natural and architectural heritage which deserves a significant safeguard. Indeed, tourism is an essential resource in Aosta Valley, with over 3.6 million overnight stays in 2019 (RAVA, 2020). Tourist flows during winter, largely related to winter sports activities, are distributed over four months (from December to March), while in summer they are mainly concentrated in July and August (with almost 37% of total overnight stays in 2019) (Osservatorio Turistico Valle d'Aosta, 2020; RAVA, 2020). According to a recent survey, the main reason why tourists visit the region during summer is its "natural beauty" (TurismOK, 2016): the mountain territory is characterized by a unique natural heritage, with a system of protected areas, where tourists relax and practice sports activities. Furthermore, the inclusion of the Landscape criterion in the MCA assessment is in accordance with the principles set by the European Landscape Convention for the establishment and implementation of policies aimed at landscape protection, management and planning (Council of Europe, 2000).

Therefore, starting from a criterion of nature conservation used in Tyrol (Austria) for sustainable HP development (Landesregierung, 2011), the indicator Landscape Protection Level was developed and included in the MCA (associated with the Landscape criterion) to quantify the effects of water withdrawals on the river landscape in the bypassed watercourse stretch. The indicator takes into account the local landscape protection constraints and is correlated to the flow rate released downstream of the withdrawal site.

The purpose of this paper is to test the application of the proposed LPL indicator to four real case studies, for different watercourses and HP plants. The related results are assessed in terms of effective reactiveness of the indicator, representativeness of the stakeholders' needs, transparency of the procedure, time required for data collection and processing. The main strengths and weaknesses of the indicator and suggestions for future improvements are finally highlighted.

2. Materials and methods

2.1. Calculation of the indicator Landscape Protection Level

The first step for calculating the LPL indicator is to analyze the entire bypassed watercourse stretch downstream of the dam and to split it into different portions (hereafter named "subsections") with homogeneous visibility (high, medium, and low, see section 2.1.1). This procedure is carried out by the experts of the Regional Landscape Protection Service (RLPS) using regional cartography, orthophotos, and direct surveys. The indicator is thus defined for each selected subsection through the calculation of three different parameters: Constraint Factor (CF), Release Factor (RF), and Visual Elements Factor (VEF). These parameters, described in the next paragraphs, are subsequently summed up to obtain the LPL score for the investigated subsection (Eq. (1)).

$$LPL = CF + RF + VEF \tag{1}$$

A high LPL value (i.e., between 90 and 165, as shown in Table 3) indicates that the release scenario from the dam ensures an acceptable or high level of landscape protection for the considered watercourse subsection. On the contrary, low LPL scores are related to flow release scenarios with insufficient discharge, not ensuring an acceptable level of landscape protection. However, low LPL scores might also be due to a high landscape value of the watercourse subsection, for which even a minimal water withdrawal would likely affect the river landscape.

2.1.1. Calculation of the Constraint Factor (CF)

The RLPS experts classify the visibility of each subsection in the following three classes, according to the distance from which it is visible and to its accessibility and use: A) high visibility (subsection completely visible from a significant distance), B) medium visibility (subsection well visible from a short distance), and C) low visibility (subsection slightly visible or not visible at all). For example, a watercourse subsection flowing into a gorge is usually characterized by low visibility and accessibility: class C) will thus be assigned to this subsection. On the contrary, class A) is assigned to subsections easily accessible through roads or paths and/or highly visible from a great distance (e.g., from viewpoints frequented by tourists). If in that subsection there are no elements of the landscape or cultural heritage components safeguarded by specific national or regional laws, then the maximum score is attributed to CF, equal to 15, 30, or 45 if the visibility is high, medium, or low, respectively. Otherwise, the presence of the above elements, verified on a cartographic basis and through the RLPS experts' direct knowledge of the territory, requires the attribution of a specific score (Table 1), to be then subtracted from the maximum score. Most elements are related to specific constraints defined by landscape protection laws

Table 1
Table for calculating the CF score of a watercourse subsection according to its visibility and the presence of remarkable riverscape elements, corresponding regulatory constraints, and recreational fruition.

Remarkable riverscape elements		Subsection score		
		A High visibility	B Medium visibility	C Low visibility
Visibility		1	2	3
Origin of landscape elements – Specific landscape constraints	Buildings and areas of considerable public interest [a]	1	3	4
	Rivers, streams, watercourses [a]	1	3	4
	River system	1	2	3
Origin of landscape elements – Particular landscape constraints	Lakes [b]	1	2	3
	Areas of specific landscape interest [b]	1	2	4
	System of natural areas	1	2	3
Uniqueness of the landscape –Background landscape constraints	Lakes; Forests and areas subject to reforestation restrictions [a]	1	2	4
	Mountain areas over 1600 m a.s.l.; National or regional parks and other protected areas; Areas of archaeological interest [a]	1	2	3
	Areas of specific archeological interest [b]	1	2	3
Representativeness – Significant components of the landscape	Waterfalls, alluvial fans	1	3	5
	Ridges, peaks, important rocks	1	2	3
	Gorges, glacial terraces	1	2	3
Recreational value – Fruition of cultural and historical assets	Low	2	3	4
	Medium	3	4	5
	High	4	5	6
Maximum final score (no constraints and high recreational value of the subsection)		**15**	**30**	**45**

[a] as specified by the national Legislative Decree n. 42/2004.
[b] as specified by the Territorial Landscape Plan of Aosta Valley (PTP).

(i.e., national Legislative Decree n. 42/2004 (Repubblica Italiana, 2004) and Territorial Landscape Plan of Aosta Valley – PTP (RAVA, 1998)), based on the origin, uniqueness, and representativeness of the landscape, aimed at safeguarding different areas of specific interest (see Table 1). Additionally, the Recreational value of the considered subsection is also taken into account, classified through an expert judgment into three classes of importance (low, medium, and high), according to the presence and value of cultural and historical assets considered in the PTP (RAVA, 1998). A score from 2 to 6 is attributed (high values mean a high Recreational value) and then subtracted from the maximum CF score. As for the other landscape and cultural heritage components, if no cultural and historical assets are present in the considered subsection, no score is assigned to the Recreational value.

Furthermore, a score is usually attributed to the Visibility (equal to 1, 2, or 3 for high, medium, or low visibility, respectively): only when the subsection is not accessible and its visibility is substantially null (e.g., a very deep gorge), the score in the first row of column C is not subtracted from the maximum final score.

The resulting CF for a watercourse subsection visible from a great distance (class A of Table 1) and characterized by the presence of several remarkable landscape components and/or high recreational value will be very low. This will contribute to reducing the final LPL result for such a river subsection characterized by high landscape value because the presence of a water withdrawal would probably have a strong negative impact.

More information about the criteria used for the definition of the scores shown in Table 1, as well as for the score ranges of the following two parameters, is available in Supplementary Material (Online Resource 1).

2.1.2. Calculation of the Release Factor (RF)

The Release Factor quantifies the “naturalness” level of the watercourse discharges released downstream compared to the flow available upstream of the dam. The discharges released downstream of the dam are given by the sum of the three following water amounts:

- the ecological flows, i.e., the discharge released at the withdrawal point, according to the scheme of flow release defined in the water license to let the aquatic ecosystem continue to thrive;
- the discharges released in addition to the ecological flows, when the watercourse discharge exceeds the maximum flow rate that can be withdrawn, overflowing downstream of the dam;
- the contribution of the watershed to the bypassed subsection (e.g., small tributaries downstream of the dam).

The Release Factor is related to the “naturalness” level of the discharges flowing in the bypassed stretch, assessed as a percentage of the available flow rate of the watercourse. It is calculated through the following formula:

$$RF = \alpha \cdot \frac{Q_{e-flow}}{Q_{ref}} \tag{2}$$

where $Q_{e\text{-flow}}$ is the flow value released downstream of the dam, while Q_{ref} is the reference flow value available upstream. Also for RF, the assessment is differentiated according to the visibility of the subsection, since it is considered more important to guarantee a higher naturalness level in river reaches characterized by great visibility. Therefore, according to the visibility of the considered subsection, the term α is equal to 60 for class A (high visibility), 45 for class B (medium visibility), and 30 for class C (low visibility).

2.1.3. Calculation of the Visual Elements Factor (VEF)

For the assessment of the VEF, the entire bypassed stretch is analyzed by the RLPS experts to identify a representative viewpoint for the installation of a fixed camera (or webcam) to acquire a set of photos of the watercourse under different discharge conditions. The viewpoint must be selected at a location ensuring good visibility of a representative portion of the entire bypassed stretch, allowing the assessment of all the visual metrics that have to be related to the measured discharge of the watercourse (see Table 2). The camera shall be installed by the dam owner and synchronized with the continuous discharge monitoring system.

Table 2
Scores assigned to the alteration levels of the visual metrics of riverscape perception compared to reference conditions. The final score of VEF is the average of the scores attributed to each applicable metric.

Visual metrics of riverscape perception	Scores (expert judgment)		
	Natural	Acceptable	Altered
Natural water turbulence	90	45	9
Average water depth	90	45	9
Ratio of dry to wet riverbed	90	45	9
Presence of small waterfalls	90	45	9
Filling level of pools	90	45	9

Moreover, the same focal length and enlargement must be used for all the pictures. The orientation of the camera and the best moment during the day for the photo shooting also require a proper planning. Usually, photos are taken in the central part of the day, when sunlight is appropriate to ensure a correct evaluation of the visual metrics by the experts. For each picture, the corresponding flow rate value in l/s must be recorded. Once a consistent set of images has been collected, the evaluation is carried out by the RLPS experts selecting and comparing two images, one corresponding to the flow rate released downstream of the dam (representing the altered conditions) and the other one corresponding to the flow rate of the watercourse upstream of the dam (representing the reference conditions). The two photos are displayed on two different computer screens and carefully analyzed by the experts, considering different visual metrics of riverscape perception, such as turbulence, ratio of dry to wet riverbed, etc. A score is assigned to each of them, based on the expert judgment, quantifying the level of alteration due to the withdrawal compared to the reference conditions. To avoid the subjectivity that could result from an evaluation carried out by one single person, at least three landscape experts are involved in this assessment. Table 2 shows the list of the considered visual metrics and the corresponding scores according to the level of visual perception alteration, i.e., natural, acceptable, or altered. It has to be highlighted that the worst judgment, "altered", indicates a significant deviation from the reference conditions, but with flow release considered not completely unacceptable. For this reason, a score of 9 (and not 0) is assigned to conditions classified as altered. The VEF parameter is set equal to 0 only in the rare cases in which the flow release is extremely low compared to reference conditions. Furthermore, even in case of multiple dams, the reference conditions are referred to the watercourse conditions (and the measured flow rate) upstream of the considered dam. Therefore, the reference conditions correspond to a situation "unaltered" by the considered dam, since only the effects of a *single* withdrawal can be assessed by the indicator.

All the considered visual metrics focus on the river channel and refer to features for which a modification caused by the water withdrawal can be immediately perceived through a visual assessment. For this reason, for example, geomorphological characteristics and riparian vegetation are not taken into account, since their variations occur over long timescales.

The VEF score is given, for the entire bypassed stretch, by the average of the scores allocated to each visual metric through the expert judgment. The VEF, thus, varies between 9 (if all the metrics are considered "altered") and 90 (in the opposite case, i.e., when all the metrics are judged "natural"). Metrics not applicable for the analyzed watercourse stretch (e.g., if no pools or small waterfalls are present) are excluded from the calculation.

If the considered bypassed stretch is very long or includes an area particularly sensitive from a landscape point of view, the installation of more than one monitored viewpoint is required and the resulting VEF scores are attributed to the different subsections represented by each viewpoint.

2.1.4. Final calculation of the Landscape Protection Level indicator

The LPL value for each subsection of the bypassed stretch is calculated as the sum of the scores of CF, RF, and VEF, as shown in Eq. (1). The final value of the Landscape Protection Level for the entire bypassed stretch ($LPL_{stretch}$, dimensionless) is obtained through a weighted average of the LPL values calculated for each subsection, according to their lengths l (Eq. (3)):

$$LPL_{stretch} = \frac{\sum_{i=1}^{N}(LPL_i \cdot l_i)}{l_{tot}} \quad (3)$$

where N is the number of subsections into which the considered bypassed stretch has been split, LPL_i is the LPL value calculated for the subsection i (dimensionless) and l_i represents the length of this subsection (m). Finally, l_{tot} is the total length of the bypassed stretch (m), equal to the sum of the lengths of the N considered subsections.

The LPL indicator can be used to assess a specific release value (altered situation) against the corresponding available discharge (reference situation) or for the assessment of different release scenarios varying over the year, compared to variable reference conditions (current discharge regime). In the MCA procedure carried out in Aosta Valley, the indicator is used to assess different flow release alternatives, which usually foresee varying discharge values on a monthly basis (i.e., a fixed flow release value is set for each month). Sometimes, "real-time" scenarios are defined, for which a minimum monthly flow value has to be released, incremented by an additional release (varying on an hourly basis) calculated as a percentage of the available discharge measured upstream of the dam. Therefore, the LPL calculation is disaggregated on a monthly basis (or fortnightly, in particular when the flow regime in the watercourse is highly variable during the month or there is a large presence of tourists in a particular period of the year). In this case, monthly (or fortnightly) RF and VEF values are calculated, i.e., considering, respectively, the average monthly (or fortnightly) values of available discharge and flow releases and the images of the bypassed stretch corresponding to these flow rates. On the contrary, the CF values remain unvaried for the same subsections. The LPL value for the overall scenario is thus obtained through a weighted average of the LPL values calculated for the different months (or periods of 15 days). Higher weights are usually assigned to the months with a higher landscape interest, to increase the level of protection when the recreational and aesthetic value of the watercourse is higher (i.e., typically during summer).

Following the approach used for the other indicators considered in the MCA framework, the overall score of the LPL indicator is divided into five classes, as shown in Table 3. The thresholds defining the separation between the classes were determined after tests in 32 different regional river contexts, corresponding to the main bypassed stretches in the region, and subsequently for 29 further stretches, by assessing the correspondence of the indicator results with the experts' qualitative evaluation. Furthermore, the LPL values were normalized through a linear utility function into dimensionless values ranging between 0 and 1, allowing the comparison of the different indicators considered in the MCA framework.

2.2. Case studies

Aosta Valley is situated in the Alpine area and it is characterized by a completely mountainous territory. The Dora Baltea River, one of the main tributaries of the Po River, crosses the region (with a mean annual discharge of 110 m^3/s), supplied by several tributaries with a mean annual discharge even lower than 0.1 m^3/s. In this paper, the LPL indicator is applied in four different case studies of existing HP plants affecting three different torrents. In case study 4, due to the presence of a withdrawal for agricultural use in the bypassed stretch, the indicator is used to assess the combined effect of both water withdrawals. The location of the watercourses and HP plants is shown in Fig. 1, while the main characteristics of the case studies are listed in Table 4.

In all the considered case studies, a continuous monitoring system was installed at the dam to collect discharge data. The continuous stage

Table 3
Classes of landscape protection according to the LPL indicator.

LPL	Normalized LPL values	Class
$0 \le LPL \le 20$	$0 \le LPL \le 0.12$	Bad
$20 < LPL \le 50$	$0.12 < LPL \le 0.31$	Poor
$50 < LPL \le 90$	$0.31 < LPL \le 0.55$	Moderate
$90 < LPL \le 130$	$0.55 < LPL \le 0.79$	Good
$130 < LPL \le 165$	$0.79 < LPL \le 1$	High

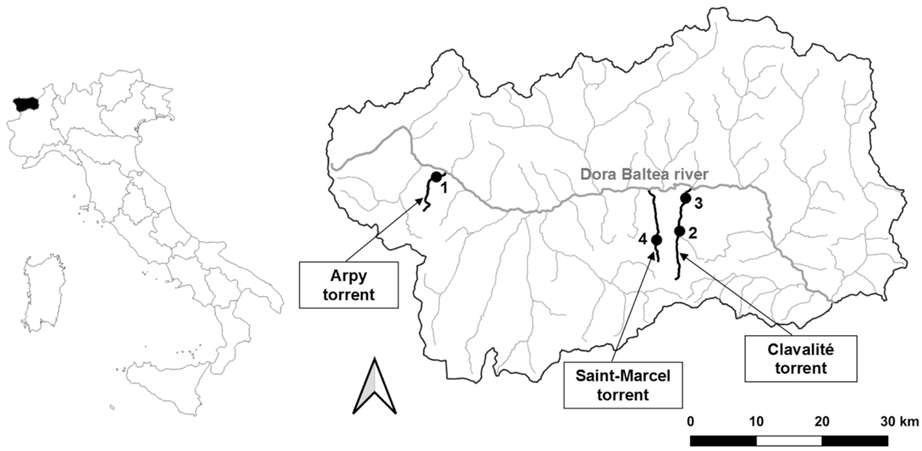

Fig. 1. Location of the watercourses of the four case studies in Aosta Valley: Arpy torrent (case study 1), Clavalité torrent (case study 2, upper watershed, and case study 3, lower watershed), and Saint-Marcel torrent (case study 4). The location of each HP plant is indicated by a black dot symbol and the number of the corresponding case study.

Table 4
Key features of the four case studies: characteristics of the HP plants and the bypassed watercourse stretches.

Characteristics	Case study 1	Case study 2	Case study 3	Case study 4
Name of the watercourse	Arpy torrent	Clavalité torrent - upper watershed	Clavalité torrent - lower watershed	Saint-Marcel torrent
Stream order (according to Strahler (1957))	1	2	2	1
Hydrological regime	Snow-pluvial	Snow-pluvial	Snow-pluvial	Snow-pluvial
Average annual discharge (m^3/s)	0.26	1.64	3.63	0.70
Length of the bypassed stretch (m)	922	1736	3931	2578
HP plant type	run-of-the-river	run-of-the-river	run-of-the-river	run-of-the-river (an agricultural withdrawal is also present in the bypassed stretch)
Altitude of the water intake point (m a.s.l.)	1378	1491	1207	1830
Altitude of the release point (m a.s.l.)	983	1144	597	1409
Average annual nominal power (kW)	697.5	2955.4	6651.3	960.8
Total head (m)	395	347	610	421
Mean annual withdrawn discharge (m^3/s)	0.18	0.87	1.28	0.23
Number of flow release alternatives (ALT) assessed through the MCA	7 (from ALT A to ALT G)	7 (from ALT A to ALT G)	6 (from ALT A to ALT F)	7 (from ALT A to ALT G)

measurements through water level sensors (submerged pressure transducer or acoustic systems) were automatically converted into discharge data through the stage-discharge relation defined for the monitored watercourse cross-section. For a provision of more reliable data series, the monitoring of flow rates was carried out on an hourly basis, subsequently aggregating the data to obtain daily discharge series.

The pictures of the bypassed stretch under different discharge conditions were collected through a webcam or scout camera installed near the dam. Photos were taken daily, during the central hours of the day to ensure an optimal vision of the bypassed stretch for a correct evaluation of the VEF parameter. A set of sample images was sent to the RLPS experts for their approval before starting the routine monitoring.

For each case study, different flow release alternatives (ALT) were proposed for the MCA assessment (see the last row of Table 4). All the considered scenarios foresaw a fixed value of flow release for each month (or 15 days), defined as a percentage of the average monthly (or fortnightly) discharge of the watercourse.

2.3. Evaluation criteria for the assessment of the indicator results

The following criteria were used to perform a critical analysis of the LPL results obtained for the four case studies presented in this paper, to identify the main strengths of the indicator and some possible weaknesses for which an improvement could be suggested:

- Effective reactiveness of the indicator, i.e., the causal relationship between the indicator and the different alternatives. This feature is essential because the use of nonreactive indicators limits the significance of MCA (Mammoliti Mochet et al., 2012). In this case, mainly the reactiveness to flow release variation has to be taken into account since the considered alternatives are different scenarios of flow release. In particular, the influence of the ratio of flow release to available discharge on the RF and VEF values and on the final LPL results is assessed for some selected examples.
- Possibility to compare the indicator results with the other indicators of the MCA framework. For example, the preference direction of the measurement unit (maximization or minimization of the stakeholders' satisfaction) (Triantaphyllou and Baig, 2005) and the possibility to normalize the final indicator result have to be considered for the MCA technique adopted in Aosta Valley, which is a linear additive method. These features are analyzed for some selected examples, looking at the final LPL results and the corresponding class of landscape protection.
- Representativeness of the corresponding stakeholders' needs and interests (Mammoliti Mochet et al., 2012). In this case, the compliance of the indicator results with the expert judgment of the Landscape Protection Service representatives is assessed, in particular by analyzing the influence of the VEF parameter on the final LPL results. The possibility of involving real landscape beneficiaries (i.e., local community and tourists) in the evaluation is also discussed in section 4.

- Objectivity of the indicator results. Essentially, the final score of the indicator should not be influenced by a subjective evaluation of the person in charge of analyzing the available data. This feature is assessed for the different phases leading to the calculation of the indicator.

The results of the evaluation of these criteria are shown and discussed in section 3.1, according to the LPL values obtained for different flow conditions for the four considered bypassed stretches.

Other general characteristics usually considered to assess the suitability of an indicator (Mammoliti Mochet et al., 2012) are discussed in

Table 5
Examples of the results of the landscape indicator (LPL) for two case studies, corresponding to different flow releases ($Q_{e\text{-}flow}$). The Constraint Factor (CF), Release Factor (RF), and Visual Elements Factor (VEF) are given for each example. The colors in the last column highlight the different classes of landscape protection (as in Table 3).

Case study 2 – Clavalité torrent (upper watershed)

Subsections		Visibility	Length (m)	CF	RF	VEF	LPL subsection	LPL stretch (normalized)	Class
ALT E – JULY: Q_{ref} = 1718 l/s, $Q_{e\text{-}flow}$ = 150 l/s, $Q_{e\text{-}flow}/Q_{ref}$ = 0.09									
1	ab	A - high	87	7	5.2	9.0	21.2	32.2 (0.20)	Poor
2	bc	C - low	1152	22	2.6		33.6		
3	cd	B - medium	497	18	3.9		30.9		
ALT B – JULY: Q_{ref} = 1718 l/s, $Q_{e\text{-}flow}$ = 805 l/s, $Q_{e\text{-}flow}/Q_{ref}$ = 0.47									
1	ab	A - high	87	7	28.1	30.6	65.7	67.5 (0.41)	Moderate
2	bc	C - low	1152	22	14.1		66.7		
3	cd	B - medium	497	18	21.1		69.7		
ALT A – JULY: Q_{ref} = 1718 l/s, $Q_{e\text{-}flow}$ = 1520 l/s, $Q_{e\text{-}flow}/Q_{ref}$ = 0.88									
1	ab	A - high	87	7	53.1	63.0	123.1	114.8 (0.70)	Good
2	bc	C - low	1152	22	26.5		111.5		
3	cd	B - medium	497	18	39.8		120.8		

Case study 3 – Clavalité torrent (lower watershed)

Subsections		Visibility	Length (m)	CF	RF	VEF	LPL subsection	LPL stretch (normalized)	Class
ALT B – DECEMBER: Q_{ref} = 500 l/s, $Q_{e\text{-}flow}$ = 100 l/s, $Q_{e\text{-}flow}/Q_{ref}$ = 0.20									
1	ab	B - medium	497	17	9.0	9.0	35.0	35.2 (0.21)	Poor
2	bc	A - high	1001	7	12.0		28.0		
3	cd	B - medium	910	18	9.0		36.0		
4	de	C - low	1412	25	6.0		40.0		
5	ef	B - medium	111	17	9.0		35.0		
ALT A – MAY 1-15: Q_{ref} = 740 l/s, $Q_{e\text{-}flow}$ = 740 l/s, $Q_{e\text{-}flow}/Q_{ref}$ = 1									
1	ab	B - medium	497	17	45.0	90.0	152.0	151.0 (0.92)	High
2	bc	A - high	1001	7	60.0		157.0		
3	cd	B - medium	910	18	45.0		153.0		
4	de	C - low	1412	25	30.0		145.0		
5	ef	B - medium	111	17	45.0		152.0		
ALT A – JUNE: Q_{ref} = 6888 l/s, $Q_{e\text{-}flow}$ = 1428 l/s, $Q_{e\text{-}flow}/Q_{ref}$ = 0.21									
1	ab	B - medium	497	17	9.3	27.0	53.3	53.6 (0.32)	Moderate
2	bc	A - high	1001	7	12.4		46.4		
3	cd	B - medium	910	18	9.3		54.3		
4	de	C - low	1412	25	6.2		58.2		
5	ef	B - medium	111	17	9.3		53.3		

section 4, such as the transparency of the elaboration procedure and the necessary dataset availability (including the difficulties linked to data collection, management, and elaboration). Moreover, the compliance with the specific context and investigation and the transferability to different river contexts (i.e., the possibility to be adapted to different locations and scales) are taken into account.

3. Results

For the calculation of the LPL indicator, each bypassed stretch was divided by the experts of the Regional Landscape Protection Service into different subsections (three subsections for case study 2, five for the other case studies) characterized by homogeneous visibility. For each of them, the related Constraint Factor (CF), Release Factor (RF), and Visual Elements Factor (VEF) were calculated. Table 5 shows some examples of LPL calculations for case studies 2 and 3.

The results of case study 2 highlight how the LPL scores vary for different release values related to the same available discharge, while for case study 3, three different flow release values ($Q_{e\text{-}flow}$) have been selected, related to periods of low, moderate, and higher flows in the watercourse. An example of the different images corresponding to the three values of $Q_{e\text{-}flow}$ considered in case study 3, used for the determination of the VEF parameter, is shown in Fig. 2. Some images for the other three case studies are shown in Supplementary Material (Online Resource 1, Figs. S1–S3). More examples of the indicator results obtained for the four case studies are also provided (Online Resource 2, Tables S1–S3, S5), with additional information about the considered constraints and the assessment of the visual metrics.

The examples shown in Table 5 refer to a calculation of the LPL indicator on a monthly basis when the alternative foresees a fixed monthly release value. In this case, the considered reference flow rate (Q_{ref}) is the average discharge of the considered month. For case study 3, in May (see MAY 1–15 in Table 5, which refers to the first 15 days of May) the indicator is calculated on a fortnightly basis: Q_{ref} and $Q_{e\text{-}flow}$ correspond to the average values calculated over the considered 15 days and the selected images of the bypassed stretch correspond to these flow rates.

The CF values assigned to the subsections remain unvaried for the same case study, since this parameter quantifies the landscape value (presence of relevant elements safeguarded by law) of the bypassed stretch, regardless of the withdrawal and, therefore, it is not influenced by the amount of water released by the HP plant. However, the CF values vary for the different case studies, since the subsections in the considered stretches are characterized by different classes of visibility and constraints (see more details in Supplementary Material – Online Resource 2, Tables S1–S3, S5). Nevertheless, if an overall CF is considered for each stretch (calculated as a weighted average of the CF values of the different subsections based on their lengths), it can be noticed that the value is similar for these four case studies (i.e., 20.4, 20.1, 17.6 and 16.9 for case studies from 1 to 4, respectively).

On the contrary, the RF and VEF values vary for the same bypassed stretch according to the flow rate released downstream of the dam compared to the available discharge of the watercourse in the same period. Fig. 3 shows the trend of the final LPL results calculated for some selected examples from the four case studies (see Online Resource 2) with the increase of the ratio $Q_{e\text{-}flow}/Q_{ref}$. It can be observed that the results for the first three stretches generally follow the same increasing trend. However, not all the values present this tendency (e.g., see the examples with $Q_{e\text{-}flow}/Q_{ref} = 0.21$ and 0.36 for case study 3 and with $Q_{e\text{-}flow}/Q_{ref} = 0.47$ and 0.49 for case study 2), because VEF does not necessarily increase with the ratio $Q_{e\text{-}flow}/Q_{ref}$. Indeed, the effect of the percentage increase in flow rate on the observer's visual perception can be different, especially during periods of low water levels or with higher flows. An example is represented by case study 3, where the slight increase of the ratio from 0.20 to 0.21 corresponds to a relatively significant increase of the VEF value (from 9 to 27, see Table 5). However, these values refer to two extremely different conditions: in February, with a reference discharge of 500 l/s, the flow release in the watercourse is only 100 l/s ($Q_{e\text{-}flow}/Q_{ref} = 0.20$, Fig. 2a), while in June, when $Q_{ref} = 6888$ l/s, the flow release is 1428 l/s ($Q_{e\text{-}flow}/Q_{ref} = 0.21$, Fig. 2c). Even if these situations correspond to a similar level of flow alteration compared to reference conditions, the impact on visual riverscape perception is quite different.

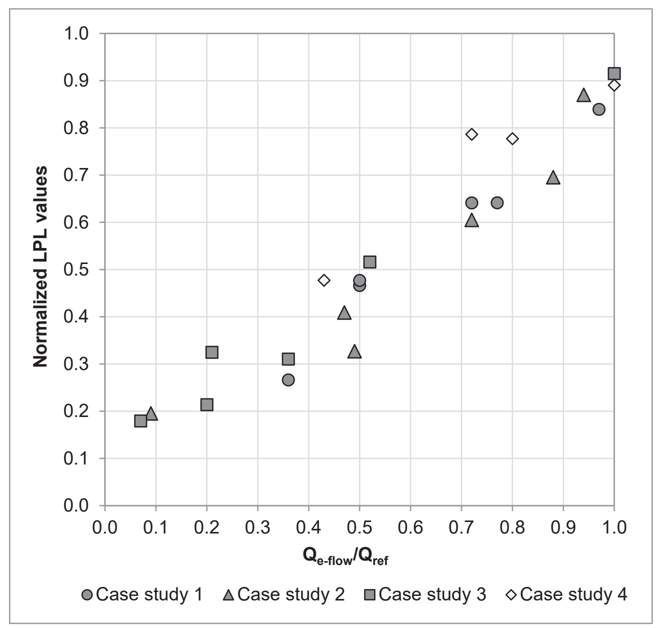

Fig. 3. Trend of the results of the landscape indicator (LPL) selected for the four case studies according to the ratio of flow release downstream of the HP plant ($Q_{e\text{-}flow}$) to the average monthly available discharge of the watercourse (Q_{ref}).

Fig. 2. Example of three images used by the landscape experts for the assessment of the Visual Elements Factor in case study 3. The images correspond to the following flow releases: (**a**) 100 l/s, (**b**) 740 l/s, (**c**) 1428 l/s (photo credit: Hydro Electrique Clavalité S.p.A.).

The first three LPL values referred to case study 4 are slightly higher: this is because, from May to the beginning of October, the HP producer has to release an additional fixed amount of water that is withdrawn by an agricultural withdrawal in the lower part of the second subsection. For this reason, the flow release (and therefore the value of $Q_{e\text{-}flow}/Q_{ref}$) in the first two subsections of this stretch is higher. Furthermore, the example with $Q_{e\text{-}flow}/Q_{ref} = 0.72$ refers to June (higher flow level), while the corresponding LPL values for case studies 1 and 2 refer to March (low water level). Hence, for the same reasons explained before, the result for case study 4 is particularly higher.

A similar graph considering the LPL values calculated for all the alternatives for the four case studies is provided in Supplementary Material (Online Resource 3, Fig. S4).

Table 6 shows the LPL indicator values calculated for the seven flow release scenarios for case study 4. As explained in section 2.1.4, the LPL values obtained for the different months are used to calculate a weighted average, which corresponds to the final LPL value for each release scenario. Each column of Table 6, from ALT A to ALT G, refers to a different alternative, for which the monthly (or fortnightly, from April to August for ALT C, D and F) LPL values are indicated, as well as the final LPL value (last row). The set of alternatives is described in Supplementary Material (Online Resource 2, Table S4).

The second column shows the weights attributed to each month by the RLPS experts, according to the data available from institutional databases about the presence of tourists in the area during the different periods of the year. The highest weight (0.22) was assigned to the summer months of July and August, but high weights were also attributed to June (0.19), May, and September (0.14), when the presence of tourists (and residents) hiking or visiting the near mining site is more frequent. On the contrary, a very low weight (0.01) has been assigned to the months from November to April, since this watercourse stretch is not accessible due to the presence of snow and the area is not even suitable for winter sports activities.

A table of this type, depicting the results of the landscape evaluation, is presented to the decision-makers and stakeholders involved in each assessment of water withdrawal sustainability in Aosta Valley. Moreover, the final LPL results of the different alternatives are used in the MCA assessment, together with the other indicators considered in the MCA framework.

3.1. LPL results assessment

A detailed analysis of the LPL results obtained for the four considered case studies was carried out based on the four criteria described in section 2.3.

With regard to the effective **reactiveness** of the indicator, the results should vary accordingly with the variation of the landscape conditions of the considered watercourse stretch. For the LPL indicator, this variation is primarily related to the different flow releases according to the considered alternatives. The difference in flow releases influences both the RF and VEF values. An example of such reactiveness can be observed in Table 5 for case study 2. The three results presented for this watercourse stretch refer to July, when the average reference discharge is 1718 l/s. According to the flow release required by the three different alternatives (i.e., 150, 805, or 1520 l/s), the ratio $Q_{e\text{-}flow}/Q_{ref}$ clearly changes, with a direct effect on the RF values (see, for example, the

Table 6
Example of the calculation of the LPL indicator for different flow release alternatives (ALT A - ALT G) for case study 4. The monthly (or fortnightly) LPL values are indicated for each alternative, while the weights assigned to the different months are shown in the second column. The final LPL results, calculated for each alternative ($LPL_{ALTERNATIVE}$) and used in the MCA assessment, are given in the last row, in bold type. The colors represent the different classes of landscape protection (i.e., blue = high, green = good, yellow = moderate, orange = poor).

<table>
<tr><th></th><th></th><th colspan="7">Normalized LPL values</th></tr>
<tr><th>Month</th><th>Weight</th><th>ALT A</th><th>ALT B</th><th>ALT C</th><th>ALT D</th><th>ALT E</th><th>ALT F</th><th>ALT G</th></tr>
<tr><td>JANUARY</td><td>0.01</td><td>0.89</td><td>0.89</td><td>0.34</td><td>0.89</td><td>0.89</td><td>0.89</td><td>0.89</td></tr>
<tr><td>FEBRUARY</td><td>0.01</td><td>0.89</td><td>0.89</td><td>0.52</td><td>0.89</td><td>0.89</td><td>0.89</td><td>0.89</td></tr>
<tr><td>MARCH</td><td>0.01</td><td>0.89</td><td>0.89</td><td>0.45</td><td>0.89</td><td>0.89</td><td>0.89</td><td>0.89</td></tr>
<tr><td>APRIL 1-15</td><td rowspan="2">0.01</td><td rowspan="2">0.89</td><td rowspan="2">0.89</td><td>0.42</td><td>0.89</td><td rowspan="2">0.89</td><td>0.89</td><td rowspan="2">0.89</td></tr>
<tr><td>APRIL 16-30</td><td>0.37</td><td>0.69</td><td>0.68</td></tr>
<tr><td>MAY 1-15</td><td rowspan="2">0.14</td><td rowspan="2">0.43</td><td rowspan="2">0.37</td><td>0.37</td><td>0.56</td><td rowspan="2">0.37</td><td>0.48</td><td rowspan="2">0.37</td></tr>
<tr><td>MAY 16-31</td><td>0.36</td><td>0.57</td><td>0.36</td></tr>
<tr><td>JUNE 1-15</td><td rowspan="2">0.19</td><td rowspan="2">0.63</td><td rowspan="2">0.52</td><td>0.54</td><td>0.79</td><td rowspan="2">0.52</td><td>0.54</td><td rowspan="2">0.52</td></tr>
<tr><td>JUNE 16-30</td><td>0.38</td><td>0.62</td><td>0.38</td></tr>
<tr><td>JULY 1-15</td><td rowspan="2">0.22</td><td rowspan="2">0.54</td><td rowspan="2">0.54</td><td>0.41</td><td>0.71</td><td rowspan="2">0.54</td><td>0.44</td><td rowspan="2">0.58</td></tr>
<tr><td>JULY 16-31</td><td>0.40</td><td>0.63</td><td>0.62</td></tr>
<tr><td>AUGUST 1-15</td><td rowspan="2">0.22</td><td rowspan="2">0.89</td><td rowspan="2">0.89</td><td>0.33</td><td>0.80</td><td rowspan="2">0.89</td><td>0.71</td><td rowspan="2">0.89</td></tr>
<tr><td>AUGUST 16-31</td><td>0.29</td><td>0.89</td><td>0.89</td></tr>
<tr><td>SEPTEMBER</td><td>0.14</td><td>0.89</td><td>0.89</td><td>0.32</td><td>0.79</td><td>0.89</td><td>0.89</td><td>0.89</td></tr>
<tr><td>OCTOBER</td><td>0.03</td><td>0.89</td><td>0.89</td><td>0.33</td><td>0.77</td><td>0.78</td><td>0.77</td><td>0.70</td></tr>
<tr><td>NOVEMBER</td><td>0.01</td><td>0.60</td><td>0.60</td><td>0.28</td><td>0.80</td><td>0.60</td><td>0.60</td><td>0.60</td></tr>
<tr><td>DECEMBER</td><td>0.01</td><td>0.65</td><td>0.65</td><td>0.31</td><td>0.89</td><td>0.65</td><td>0.65</td><td>0.65</td></tr>
<tr><td>LPL_{ALTERNATIVE}</td><td></td><td>0.69</td><td>0.67</td><td>0.37</td><td>0.73</td><td>0.66</td><td>0.63</td><td>0.67</td></tr>
</table>

variation of RF from 5.2 - ALT E - to 53.1 - ALT A - for subsection 1). At the same time, also the assessment of the "naturalness" level of perception of the visual metrics, by means of images, changes according to the flow release, leading to different VEF values (i.e., in this case, 9, 30.6, and 63, respectively). Consequently, the final LPL results vary with the required flow releases: in this example, LPL is 0.20 in the first alternative (ALT E), 0.41 in the second one (ALT B), and 0.70 in the last case (ALT A), even corresponding to different classes of landscape protection (poor, moderate, and good, respectively).

Another example demonstrating the reactiveness of the indicator is shown in Table 7. It presents some LPL results for case study 1, on the Arpy torrent, corresponding to different months but all requiring the same flow release (i.e., 58 l/s). Therefore, in this case, the ratio $Q_{e\text{-}flow}/Q_{ref}$ decreases with the increase of the average available discharge of the different months (i.e., 60 l/s in February, 81 l/s in March, and 115 l/s in December). This influences again the values of RF and VEF and the final LPL results, which decrease from 0.84 (in February) to 0.64 (in March) and 0.47 (in December), corresponding again to different classes of landscape protection (high, good, and moderate, respectively).

The second criterion for the analysis of the indicator results is the **comparability** with the other indicators considered in the MCA framework adopted in Aosta Valley. Since the methodology used for the assessment of water withdrawal sustainability is a linear additive method, the scales of all the considered indicators need to have the same preference direction and to be normalized. These two conditions are satisfied by the LPL indicator. As it can be noticed in Table 5 (second to last column), indeed, all the examples present both the final LPL result and the corresponding normalized value (in brackets) varying between 0 and 1. Moreover, since the considered decision problem is of maximization (i.e., the best alternative is the scenario with the highest score), the scales of all indicators need to have a preference direction of maximization. The LPL indicator follows this requirement: a higher LPL value corresponds to a higher satisfaction level of the related stakeholders, as previously represented in Table 3 by showing the different classes of landscape protection. The examples described above demonstrate that better riverscape conditions in the bypassed stretch (due to higher flow releases related to the available discharge) correspond to higher LPL values and, often, to a better class of landscape protection (e.g., from poor to good for case study 2 in Table 5).

Another important aspect for the assessment of the indicator results is its **representativeness** of the related stakeholders' needs and interests. This is ensured, in particular, through the VEF parameter. Based on the expert judgment, different metrics of riverscape perception are assessed using a set of photos of the bypassed stretch, quantifying the level of alteration compared to the reference conditions. Therefore, the VEF parameter allows a quantification of the visual effects of flow release amount, directly based on the knowledge and requirements of the landscape experts. Furthermore, it has to be highlighted that, among the three parameters, VEF has the greatest influence on the final result of the indicator: its score (maximum 90 points) accounts for 55% of the total range of the LPL indicator (i.e., 165). This demonstrates that also the overall indicator fully represents the satisfaction level of the landscape experts (see also Supplementary Material – Online Resource 3, Fig. S5), who in turn represent the interests of the direct riverscape users. Additionally, the CF considers the safeguard of specific landscape elements identified by national and regional laws, which by themselves represent a significant value for the community. Furthermore, it includes the point of view of the potential viewers/users considering the visibility of the analyzed river reach.

Finally, the **objectivity** of the indicator results, i.e., the limited influence of subjective evaluations by the involved experts, was assessed for each element, leading to the calculation of LPL. The CF values assigned to the subsections are unvaried in every evaluation of the indicator concerning the same bypassed stretch and are verified on a cartographic basis, thus ensuring the objectivity of this parameter, in addition to a direct normative reference. RF, which quantifies the "naturalness" level of discharge in the watercourse downstream of the dam, is not affected by personal evaluations since it directly varies with the ratio $Q_{e\text{-}flow}/Q_{ref}$. A continuous monitoring system, installed at the withdrawal point, provides a reliable flow data series, necessary for the calculation of RF. VEF, on the contrary, is the parameter that could be most affected by subjective evaluation. The landscape experts analyze different images of the bypassed stretch to quantify the level of alteration of different metrics of riverscape perception. Actually, this evaluation has a margin of subjectivity, in particular, if it is carried out by only one expert. However, for each case study, at least three RLPS experts, who have a great direct knowledge of the territory and experience in assessing the variation of these metrics, are involved in the analysis of the collected set of images, to minimize subjectivity as much as possible.

4. Discussion

The procedure for calculating the landscape indicator described in this paper is traceable and transparent. It is carried out by a group of officers of the Regional Landscape Protection Service, whose expertise is necessary (in particular for the evaluation of CF and VEF), but the entire procedure can be understood also by administrators and stakeholders without a technical background. Furthermore, the data used for the LPL calculation are transparently shared with all other actors involved in the MCA decision process.

Table 7
Different results of the landscape indicator (LPL) for case study 1, with the same flow release ($Q_{e\text{-}flow}$ = 58 l/s). The results correspond to different months and therefore the average available discharge in the watercourse (Q_{ref}) is different. This variation influences both the Release Factor (RF) and Visual Elements Factor (VEF), while the Constraint Factor (CF) is constant. The colors highlight the different classes of landscape protection (as in Table 3).

$Q_{e\text{-}flow}$ = 58 l/s		ALT A – FEBRUARY Q_{ref} = 60 l/s $Q_{e\text{-}flow}/Q_{ref}$ = 0.97			ALT A – MARCH Q_{ref} = 81 l/s $Q_{e\text{-}flow}/Q_{ref}$ = 0.72			ALT A – DECEMBER Q_{ref} = 115 l/s $Q_{e\text{-}flow}/Q_{ref}$ = 0.50		
S*	CF	RF	VEF	$LPL_{stretch}$ (Class)	RF	VEF	$LPL_{stretch}$ (Class)	RF	VEF	$LPL_{stretch}$ (Class)
ab	18	43.5			32.2			22.7		
bc	28	29.0			21.5			15.1		
cd	9	58.0	78.8	0.84 (High)	43.0	56.3	0.64 (Good)	30.3	36.0	0.47 (Moderate)
de	28	29.0			21.5			15.1		
ef	16	43.5			32.2			22.7		

*S = subsections.

The examples presented in section 3, concerning four different bypassed stretches, showed that the VEF, quantifying the alteration of riverscape visual perception, has the largest influence on the final LPL result (it accounts for 55% of the overall range of the indicator). Therefore, it can be assumed that the indicator well represents the satisfaction level of landscape users. Actually, the real beneficiaries of the river landscape, i.e., local community and tourists, are not "directly" involved in the evaluation. For example, LPL does not foresee the use of surveys or interviews adopted in several studies about the assessment of landscape attributes (e.g., Le Lay et al., 2013; Eder and Arnberger, 2016). However, for a generic landscape user, it would be difficult to carry out an accurate evaluation of how the riverscape perception changes according to even slight variations in the watercourse discharge values. Specific expertise for assessing a complex mix of different elements composing the cultural heritage is required. Additionally, the RLPS experts also have a deep direct knowledge of the regional territory and they carry out field surveys in the site in which the withdrawal is (or will be) located to ensure a more precise assessment of the different parameters. Therefore, it can be affirmed that the needs and interests of the direct landscape stakeholders are adequately represented.

Due to some characteristics of the indicator (like the preference direction of its scale, the possibility to normalize the final result - see section 3.1 – and the relation with the measured flow releases), the LPL results can be adopted in the MCA decision procedure applied in Aosta Valley to assess water withdrawal sustainability. The considered alternatives, indeed, correspond to different scenarios of monthly (or fortnightly) flow releases (an example of a set of alternatives for case study 4 is described in Supplementary Material – Online Resource 2, Table S4, while the calculation of the corresponding LPL results is shown in Table 6). Hence, through the use of the LPL indicator, the effects on the landscape can be quantified, as well as on the other affected sectors (e.g., environment, energy production, and economic aspects).

Another important feature of the indicator is represented by the RF parameter, which correlates the landscape protection level with the flow releases foreseen by the analyzed scenario. In reality, the distinction between levels of river landscape alteration corresponding to releases that differ by a few tens of l/s is not often easily perceivable, above all by a generic landscape user. However, this correlation is required because all the other indicators considered in the MCA framework are related to the discharge. Hence, the RF parameter allows the compensation of the different degrees of efficiency usually noticed in water resource use by different river beneficiaries (e.g., a decrease of flow release of 10 l/s can actually improve HP production, while it would probably not be quantified through a generic visual assessment).

Besides, this factor is based on the ratio of flow release to the watercourse reference discharge in the same period. This facilitates the identification of new scenarios for the MCA decision process, not characterized by a fixed flow release, but with flow releases varying according to the discharge available upstream of the dam. Indeed, it is currently recognized that ecosystems do not require a minimum water amount but a natural variability of the flow to maintain their ecological functioning (Arthington et al., 2006; Poff, 2018). Moreover, geomorphological aspects should be taken into account to obtain successful ecological outcomes (Yarnell et al., 2015). It has to be highlighted that, in the MCA framework, the watercourse hydro-morphological features are considered by another indicator, i.e., the Habitat Integrity Index, assessed through the MesoHABSIM (Mesohabitat Simulation Model) methodology (Vezza et al., 2017) and quantifying the effects of withdrawals on fish population and river environment. This index is also used to exclude scenarios that do not reach the class of quality identified as an environmental protection objective in regional planning. Moreover, the ecological status indexes required by the Water Framework Directive (European Commission, 2000) and the European Guidance Document about ecological flows (European Commission, 2015) are also constantly implemented during the monitoring phase, thus ensuring also the compatibility of flow releases with European regulations. However, following the example of previous researchers comparing aesthetic and eco-morphological values (e.g., Junker and Buchecker, 2008; McCormick et al., 2015), a future study could be carried out to analyze, for different case studies, the relationship between the results of the LPL indicator, assessing the effects of withdrawals on the riverscape, and the ecological responses to different flow scenarios, quantified through the Habitat Integrity Index.

Moreover, the indicator can also be applied for *ex-ante* evaluations, i.e., to assess the suitability of a new license for a dam. In this case, each alternative is a proposed scheme of flow releases to be applied downstream of the possible withdrawal point. The advantage of these evaluations is the possibility to predict the impact of a new water withdrawal on the landscape of the considered watercourse stretch before its construction. The indicator is calculated following the same phases described in section 2.1. For the assessment of the VEF parameter, the photos representing the altered conditions are selected among the images of the considered stretch with the same available discharges as the flow releases proposed in the alternative. This can be made since, during the application for a new water withdrawal license, the proponent must install a basic discharge monitoring station in the watercourse and the pictures can be related to the measured flow values. However, the process of gathering a sufficient database for *ex-ante evaluations* can usually require a longer period, since it will be related to the analysis of the different conditions of the flow regimen. For existing withdrawals, on the contrary, a significant portion of the desired flow conditions could be determined by manipulating the releases from the existing dam.

To our knowledge, this is the first landscape indicator to allow this kind of assessment for a watercourse stretch affected by a withdrawal, quantifying both the landscape asset and the impact of flow release on riverscape visual perception, and applicable *ex-ante*. Even if this approach has been developed to be specifically used in the Aosta Valley context (e.g., by considering regional and national landscape protection constraints), its transferability to other river contexts could be implemented in the future, after some revisions. First of all, for the adaptation to a different location, the CF parameter should be updated according to the local regulations in force. Furthermore, the visual metrics of riverscape perception currently considered by the VEF parameter are typical of mountain watercourses, usually small (with a mean annual discharge of a few m^3/s), with a steep slope and characterized by small waterfalls and pools. Thus, for an adaptation of the indicator to a larger scale (for example to large rivers in the floodplain), these elements should be revised as well, by identifying visual metrics corresponding to all the main hydromorphological units actually present in the different river types in the area.

However, some limitations are still present. As outlined before, the collection of representative images of the bypassed stretch covering the entire variability of the hydrologic regime, aligned with discharge data, is necessary for the VEF calculation. This can require long periods (almost one year, according to recent experience), in particular for *ex-ante* evaluations. Moreover, the time needed to obtain a reliable visual dataset is added to the time required for data processing and validation, thus increasing the time extension necessary to obtain the final LPL scores.

Furthermore, since for each alternative considered in the MCA an LPL value has to be calculated for each monthly flow release, the work carried out by the landscape experts could be particularly long and demanding. Above all, the analysis of the collected set of images and the assessment of the visual metrics of riverscape perception for the quantification of VEF is a complex procedure, which can also be characterized by a certain level of uncertainty. For this reason, at least three landscape experts are regularly involved in this task, to ensure the maximum expertise and to minimize subjectivity as much as possible. Moreover, the definition of the classes of visibility for the subsections, at the beginning of the analysis of a bypassed stretch, is not immediate. It is usually based on the distance from which the subsection is visible (e.g., from a road, a bridge) and on its riverscape accessibility and use. However, this evaluation is not always unequivocal and it often requires a discussion between landscape experts and direct surveys. The calculation of all the LPL values for the four case studies took on average about 2.5 weeks, being the duration mainly dependent on the number of considered alternatives and of the subsections to be considered.

5. Conclusions

The Landscape Protection Level (LPL) indicator allows the assessment of water withdrawal effects on the riverscape by considering the presence of landscape protection constraints, the "naturalness" level of flow releases, as well as the withdrawal impact on the visual perception of the bypassed stretch. The indicator is used to assess both the suitability of a specific release value and different release scenarios varying along the year. This is the case of the flow release alternatives assessed through the MCA procedure carried out in Aosta Valley, which also include scenarios foreseeing the release of a certain percentage of the flow arriving at the dam, monitored in real-time. At present, 30 decision-making processes are ongoing in the region, concerning both the renewal of licenses for existing water withdrawals and the release of new licenses. The examples of the LPL indicator use demonstrate its fitness to real case studies, even in more complex situations involving different withdrawals (see case study 4 in Supplementary Material – Online Resource 2).

Compared to previous studies, the LPL indicator allows quantifying both the landscape value of the watercourse stretch and the impact of different flow releases on the visual riverscape perception, thus enabling a correlation of the landscape protection level with a precise value of the discharge flowing in the bypassed watercourse. However, since some limitations of this indicator are still present, future work will be carried out to further improve its applicability. In particular, to ensure a more scientific basis to the VEF (Visual Elements Factor) parameter, the visual metrics of riverscape perception should be aligned with the classification of hydromorphological units according to Rinaldi et al. (2016), already used in the MCA framework for the indicator Habitat Integrity Index. This would allow including in the landscape assessment the possible variations of the watercourse morphology downstream of the withdrawal dam, which can influence the users' visual perception. This revision could also be the starting point to allow the transferability of the LPL indicator to other river contexts.

Moreover, future research could be carried out to test the indicator applicability, after a possible adaptation, for individual landscape assessments as well (i.e., not included in the MCA framework). In this way, the LPL indicator could be used to compare different watercourse stretches in the same area of the watershed, by quantifying their landscape asset (through the Constraint Factor) in addition to the flow release effects, to identify locations where a new withdrawal could be less impacting.

Furthermore, some activities could be directed to involve also the river landscape users in the procedure of water withdrawal suitability assessment, in particular for a final evaluation of the selected flow release alternative. For some case studies, the impressions of river users/viewers about the aesthetic pleasantness and naturalness of the affected watercourse stretch, after the implementation of the selected release scenario, could be collected. This analysis can be carried out through surveys or interviews with a representative sample of the main river users (e.g., tourists, fishermen, canoeists) to get also their ex-post assessment of the actual withdrawal effect on riverscape perception.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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