PERSPECTIVES ON SUSTAINABLE HYDRO-POWER

Long-term effects and cost-benefit analysis of eight spawning gravel augmentations for Atlantic salmon and Brown trout in Norway

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Abstract River regulation alters flow and sediment regime, habitat availability, and ultimately the ecological functioning of rivers. Various restoration and mitigation measures have been developed to improve ecological function, and among them is the addition of gravel to enhance the reproduction of gravel bed spawning fishes. However, information on long-term efficiency, costs, and maintenance needs of gravel additions are scarce. Here, we study the functioning of gravel additions at eight sites in three rivers in western Norway for up to 18 years. Gravel was added between 2002 and 2010 to enhance spawning of Atlantic salmon and anadromous Brown trout. We monitored changes in the size of the gravel-covered areas, sediment composition, interstitial oxygen, egg survival, and juvenile fish densities. Additionally, we report monetary costs, identify potential maintenance needs, and calculate a cost-benefit ratio. Juvenile densities of Atlantic salmon and Brown trout increased significantly after the gravel augmentations. After 10–18 years, the median egg survival was still high (> 90%) and sediment conditions were still suitable for salmonid fish reproduction. The areas were, however, shrinking across time (median area reduction 26%), mostly caused by scouring of gravel in the steep, supply-limited, and partly regulated rivers. The average construction costs of spawning gravel augmentations were 11.2 NOK (1.12 €) m^{-2} year^{-1}. Compared to similar measures elsewhere, the measures have had a long life span (up to 18 years) at relatively low costs. Gravel augmentation was concluded to be a successful management measure that contributed to significantly increased Atlantic salmon and Brown trout reproduction.

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Introduction

Brown trout (*Salmo trutta* Linnaeus, 1758) and Atlantic salmon (*Salmo salar,* Linnaeus, 1758) are gravel bed spawners, similar to many other rheophilic fishes of the northern Hemisphere (Jungwirth et al., 2000; Klemetsen et al., 2003). The species are nest builders that dig spawning redds into gravel substrate where eggs are fertilized and then buried by the fish. Characteristic spawning habitats are found in glides, often between runs or pools, and riffles on gravel sediments (grain size range 5–100 mm). Water depth at these sites during median discharge is usually 0.1–1 m and water velocity 0.1 to 0.6 m s^{-1} for both Atlantic salmon and Brown trout (Klemetsen et al., 2003; Barlaup et al., 2008; Louhi et al., 2008). As interstitial spawners (Pulg, 2009), the species depend on loose and clean gravel to provide sufficient interstitial water supply. The eggs usually need 2 to 5 months to develop in the interstitial spaces, depending on temperature (Barlaup et al., 2008; Louhi et al., 2008; Pulg, 2009). Eggs require average interstitial O_2 concentrations (IO_2) larger than 6.7 mg l^{-1}, average grain size diameters (Dg) larger than 5.7 mm, and percentage fine sediment (PF, < 1 mm grain size) lower than 18.5%. High egg-to-fry survival (50–100%) is correlated with IO_2 of at least 10.4 mg l^{-1}, Dg of at least 12.9 mm and PF of maximum 10.3% (Pulg et al., 2013).

Lack of spawning habitats in regulated rivers is considered a main driver of the decline of gravel bed spawning fishes (Sear & DeVries, 2008a; Hauer et al., 2018a, b). River regulation may cause reduced gravel supply by blocking gravel transport from upstream reaches with physical barriers, but also by increasing transport capacity (scouring) or in the opposite, by reducing flood dynamics (reduced turnover and lacking renewal of substrate, Barlaup et al., 2008; Pulg et al., 2013). Bank stabilization, riprap, development of infrastructure in the floodplain, and other measures will reduce lateral gravel input that replaces sediments transported downstream by floods (Hauer et al., 2018a), resulting in net losses of spawning habitat and shrinking of the area suitable for gravel bed spawning. Surplus of fine sediments (grain size < 1 mm) infiltrating the gravel and clogging pore space often cause a degradation of spawning habitats. Water and oxygen supply of eggs and alevins are interrupted, leading to high mortality (Soulsby et al., 2001; Greig et al., 2007; Pulg et al., 2013). Increased fine sediment accumulation can be caused by river regulation, e.g. dams and impoundments. It is accelerated by erosive land use and input of fines (Opperman et al., 2005; Pulg, 2009; Pulg et al., 2013; Hauer et al., 2018a). In western Norway, however, the supply of fine sediments in non-glacial river catchments is comparatively limited with typically < 15 t km^{-2} per year (Bogen, 2015) compared to e.g. 250–1000 t km^{-2} annually in the Alps or the Rocky Mountains (Walling & Webb, 1996; Hauer & Pulg, 2018). Due to thin soil cover and low percentage of agricultural land use (< 3%) the deposition of fine sediments in rivers is often considered of minor importance for spawning success, even at low flow velocities (Barlaup et al., 2008). The occurrence and distribution of salmonid spawning habitat is rather dependent on gravel supply, gravel stability, and scouring rate (Hauer et al., 2020).

Negative impacts of river regulation on spawning gravel supply and dynamics can be offset by gravel augmentation. Spawning gravel augmentation has become widely spread in Europe and North America as a mitigation measure in regulated rivers (Wheaton et al., 2004; Sear & DeVries, 2008a; Barlaup et al., 2008; Pulg et al., 2019; Hauer et al., 2020; Staentzel et al., 2020). However, gravel augmentations often do not address the mechanisms underlying the decline and the availability of high-quality spawning habitats, such as dams and input of fines. Augmentations therefore have a limited life span depending on fine sediment load (Pulg et al., 2013), flood frequency, and magnitude (Merz et al., 2006). Strategies for resupplying gravel are not well developed because case studies on the effects of such gravel augmentations are usually limited to short periods of 1 to 5 years, if conducted at all, or ignore sediment monitoring (Sear & DeVries, 2008a; Pedersen et al., 2009; Harrison et al., 2019). In a study on restored spawning sites in the USA, Chinook salmon (*Oncorhynchus tshawytscha*, Walbaum 1792) used the sites for spawning after 14 years, which to our knowledge is the only study that evaluates spawning habitats for longer than 10 years (Harrison et al., 2019). Hauer et al. (2020) documented a life span of spawning gravel addition of

at least 5 years in Aurlandselva in Western Norway. Pulg et al. (2013) estimated that Brown trout spawning gravel was operational for 4 to 6 years in a German lowland stream (energy slope river 0.001; energy slope spawning ground 0.003–0.006). Pander et al. (2015) documented that their gravel augmentations were only operational as potential spawning habitat for 1 year in impounded German lowland streams.

River restoration should be based on natural fluvial processes because habitat enhancement methods have limited lifespans and need to be repeated (Hendry et al., 2003; Beechie et al., 2010). Thus, most gravel augmentation are rather management than restoration measures. Though not process based restoration, habitat enhancement techniques may contribute to attainment of environmental goals, such as an increase in total fish abundance or fish migration (Hauer et al., 2013; Roni, 2019). If applied properly, enhancement measures can function as intended and the limited life span can be handled by maintenance when necessary (e.g. repetition of gravel addition after some years)— as is the case for many other man-made structures in regulated rivers (Hauer et al., 2013). While literature on long-term effects of restoration and habitat enhancement is scarce (Louhi et al., 2016; Staentzel et al., 2020), published data on costs of the projects are nearly non-existent. Only exceptionally costs are reported but then usually summed up for a variety of measures belonging to larger projects (Pedersen et al., 2007). There is a substantial knowledge gap on the link between costs and long-term effects of river restoration measures, even though such cost–benefit analyses should be essential to ecological policy. Ecological restoration is now included in policies worldwide, as underlined by the United Nations Decade On Ecosystem Restoration 2021–2030 (https://www.decadeonrestoration.org/, accessed February 19, 2020). In Europe, the Water Framework Directive has initiated habitat enhancements and billions of dollars are assumed to be spent on river restoration and habitat enhancement worldwide (Roni, 2019). There is a need for studies on the long-term effects of habitat enhancement measures, including their monetary costs and life span, to inform future efforts.

This study summarizes the extent to which eight gravel augmentations have functioned to restore salmonid spawning habitat in Norwegian rivers. It was hypothesized that they would improve sedimentologic spawning conditions and increase both salmonid egg survival and fry densities. It was predicted that the effect would decrease across time and it was aimed to measure the life span as well as the costs to estimate the maintenance needed to provide ongoing spawning possibilities. The analysis provides long-term data on the ecological effects and costs of such measures.

Materials and methods

Eight of the oldest known spawning gravel augmentation sites were studied in three Norwegian rivers. We measured the effect on the target fish species, anadromous Brown trout and Atlantic salmon, by sampling sediment quality, egg survival, and juvenile abundance (Barlaup et al., 2008; Pedersen et al., 2009; Pulg et al., 2013). Six sites were in River Aurlandselva, (Fig. 1, built in 2010), one in River Flekkeelva (built in 2005), and one in River Matreelva (built in 2002). Sampling was conducted at all six sites in Aurlandselva from 2010 to 2020; in Matreelva in 2002, 2003, 2006–2017 and 2020, in Flekkeekva 2006–2010 and 2018. The sampling and its timing are presented in detail in Table 2.
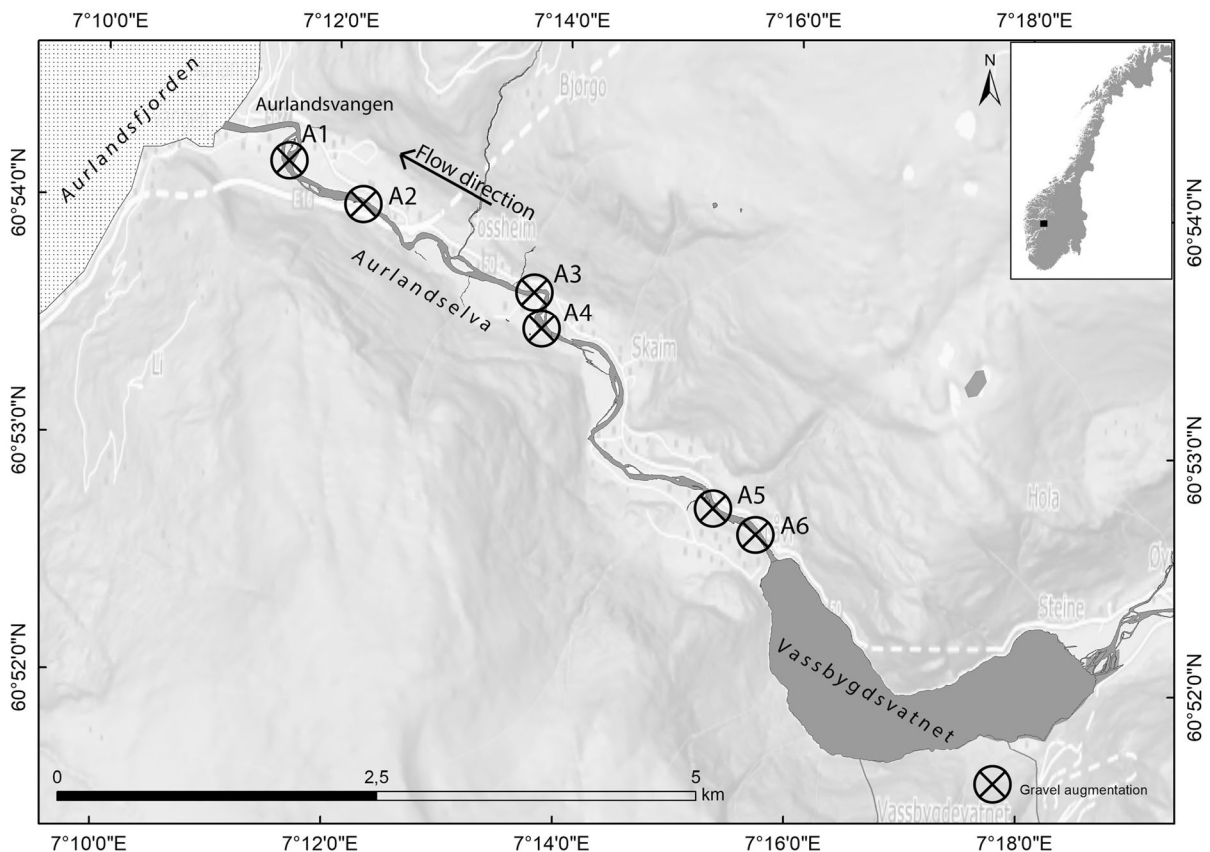
Study area

Western Norway's coastal streams and lakes are inhabited by mainly five fish species, Brown trout (*Salmo trutta* Linnaeus, 1758), Atlantic salmon (*Salmo salar* Linnaeus, 1758), Arctic char (*Salvelinus alpinus* Linnaeus, 1758), three-spined stickleback (*Gasterosteus aculeatus* Linnaeus, 1758), and European eel (*Anguilla anguilla* Linnaeus, 1758). Bedrock consists mainly of Caledonian gneisses, partly also phyllite, amphibolite, anorthosite, and Proterozoic granites. Recent tectonic dynamics are lacking. The post-glacial landscape has scoured bedrock valleys with low sediment supply and fluvial, semi-fluvial and non-fluvial river reaches (Hauer & Pulg, 2018). Lakes occur in most watersheds, and there is a high morphological variation between river reaches, in contrast to fluvial rivers which typically have decreasing slope from source to sea (Kinghton, 1998; Vannote et al., 1980). Land use in the drainages of the rivers is characterized by small percentages of agriculture (< 1.7%) and little human settlement (< 0.1%). The

drainages are dominated by forest (7–44%), mountain tundra and exposed rock (36–77%), as well as lakes (8–15%) (www.nevina.nve.no, accessed September 29th 2020). The rivers are clear and likely to have low suspended loads (only data from Aurland-selva < 2 mg l^{-1}, Ugedal et al., 2019).

The river Aurlandselva (Fig. 1) has a catchment area of 802 km^2. The average energy slope of the study reach, the lowest 7.8 km between the river mouth and lake Vassbygvatnet is 0.0069 (53.82 m drop at 7.8 km length). The discharge regime is heavily modified by hydropower regulation, with 75% of the annual precipitation being temporarily stored in reservoirs and directed through hydroplants (Væring-stad, 2019). There is a minimum flow requirement in winter and summer of 3 m^{3}s^{-1} and 20 to 30 m^{3}s^{-1}, respectively (Ugedal et al., 2019). Average flow (2010–2020) was 14.6 m^{3}s^{-1}, while the average yearly flood estimate is 51 m^{3}s^{-1} (Table 1). During low flow conditions, the average water depth is 0.66 m

and the mean channel width is 23.4 m. The river exhibits morphological alterations, such as bank protection, groins, and a weir with fish pass at the outlet of lake Vassbygdvatnet. Sediment transport is not possible through lake Vassbygvatnet, thus the sediment continuum is naturally interrupted. More-over, lateral gravel supply from glaciofluvial deposits is considered significantly reduced in the lower stretch due to reduced flood dynamics and bank protection measures along the lower river. Reduced spawning habitat was therefore identified as a bottleneck for reproduction of anadromous Brown trout and Atlantic salmon (Ugedal et al., 2019; Hauer et al., 2020).

Matreelva has a catchment area of 159 km^2, an average flow after regulation (2002–2020) of 3.5 m^{3}s^{-1}, and an average yearly flood estimate of 23 m^{3}s^{-1} (Fig. 2, Table 1). The average energy slope in the lower stretch (4.7 km) accessible for anadromous salmonids is 0.016. A small lake of 0.5 km length is situated halfway between the mouth and the natural

Fig. 1 Study area: River Aurlandselva and spawning gravel augmentation sites

Table 1 Hydrological parameters for the three case rivers

	Aurlandselva 2010–2020		Matreelva 2002–2020		Flekkeelva 2005–2020	
	Discharge (m^3s^{-1})	Nr. of flood events	Discharge (m^3s^{-1})	Nr. of flood events	Discharge (m^3s^{-1})	Nr. of flood events
Q50	4.1		1.9		12.6	
QA	14.6		3.5		22.5	
range	2.0–143.6		0.04–119.41		0.5–325.3	
HQm	51	33	23	47	223	11
HQ5	92	3	70	2	278	4
HQ10	109	2	90	2	314	1
HQ20	127	1	110	1	360*	0
HQ50	149	0	137	0	383	0

Median, average, and range of discharge and annual to 50-year flood events

Q50 median discharge, *QA* average discharge, *interpolated

migration barrier. The flow regime is heavily modified by hydropower in the lowest 4.7 km, with a 75% reduction of annual average flow which is paralleled through a hydroplant with a maximum discharge of 30 m^3s^{-1} (Gabrielsen et al. 2011). The power company discharges a voluntary residual flow of 0.2 m^3s^{-1} in the lower stretch of the river. During errors, discharge can drop lower (range 0.04 - 119.41 m^3s^{-1}, Table 1). Parts of the riverbanks are stabilized by riprap enforcement and the upper quarter below the migration barrier lacks spawning areas (Gabrielsen et al. 2011).

Flekkeelva has a catchment area of 262 km^2, an average flow (2005–2020) of 22.5 m^3s^{-1} and an average yearly flood estimate of 223 m^3s^{-1} (Fig. 3, Table 1). The flow regime is not modified by hydropower regulation, but there are minor bank enforcements in parts of the river. The average energy slope in the lower stretch (8.2 km) accessible for anadromous salmonids is 0.0024. Three lakes dominate this stretch, with 6 km of 8.2 km in lakes. The hydrograph of the rivers is shown in Figs. 15, 16, and 17 and discharge parameters for the catchment are shown in Table 1.

Flood indices and hydrology

Flow data and the recurring intervals of floods are used to evaluate the life span of the gravel augmentations. Annual flood (HQm) is defined as the average yearly maximum discharge, and e.g. HQx is a flood event with x years recurring interval. In order to reflect flow

conditions after regulation in Aurlandselva and Matreelva we used Gumbel-distributions of the maximum annual discharge to calculate flood recurrence intervals after regulation, with discharge data provided by the hydropower companies for the last 30 years in Aurlandselva and the last 11 years in Matreelva. The discharge for the remaining time in Matreelva (2002–2009 and data gaps) was correlated to the nearest water gauge (Svartavatn, NVE nr. 62.18.0, approximately 30 km distance, linear regression $y = 0.999 + 0.288x$, $R2 = 0.561$). The gauges are correlated by 0.749 (Pearson correlation, Sig. 0.000).

In Flekkeelva, which is not regulated by hydropower we used the official flood calculations provided by the national water authority (https://www2.nve.no/h/hd/plotreal/Q/0082.00004.000/, accessed September 28th, 2020), Only HQ20 was calculated by a Gumbel distribution. Flow charts are presented in Figs. 15, 16, and 17.

Fish and egg sampling

Electrofishing surveys were conducted in autumn (September–October) along the shore at the spawning gravel addition sites. They started at least the year before fry could hatch from the added gravel (Table 2). In Aurlandselva, the sites were sampled annually from 2010 to 2020. In Matreelva, the gravel augmentation site was fished annually from 2002 to 2005 and from 2008 to 2017. At Flekkeelva, fish sampling was conducted annually between 2004 and
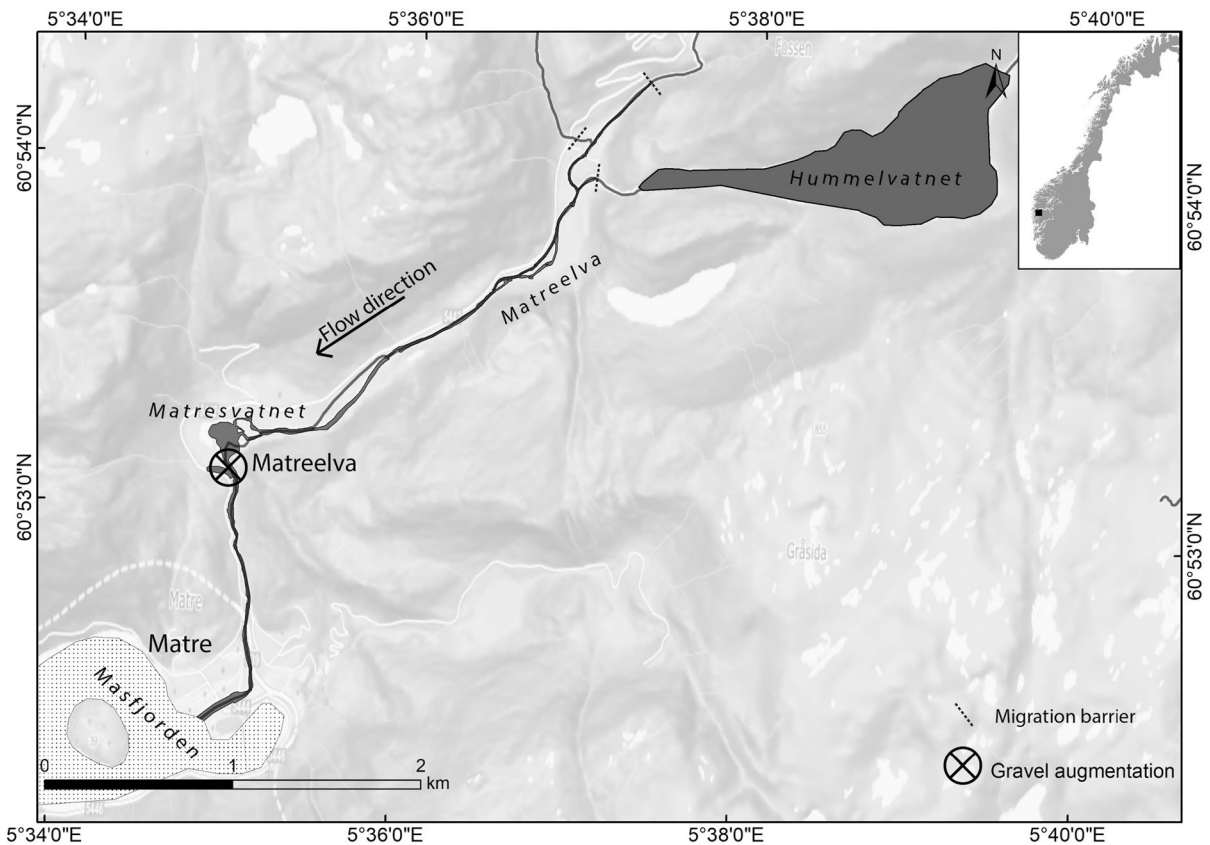
Fig. 2 Study area: River Matreelva and spawning gravel augmentation site

2010 and in 2018. The electrofishing was conducted with backpack electrofishing equipment on a single-pass longitudinal transect up to 4 m width and 50 m length and a total area of 100 m^2(Hedger et al., 2018, 1400 V, DC, pulsed current, GeOmega A/S). The single-pass data were used for our data analysis. This protocol underestimates the true density, but provides a standard index to test for changes in juvenile density over time (Bohlin et al., 1989, 2006; Foldvik et al., 2017; Hedger et al., 2018).

Captured fish were identified to species, measured, and released alive. Age class was estimated from the length of the fish, allowing distinction of the age groups fry (< 7 cm), considered to be 0+ young of the year fish, and parr (8–16 cm), which could be 1 to 3 years old (Pulg et al., 2019). Fry densities were used to evaluate effects of the gravel augmentations because fry are relatively immobile and considered as good indicators for spawning (Teichert et al., 2011; Foldvik et al., 2017; Pulg et al., 2019). Juvenile anadromous Brown trout and Atlantic salmon in the

region usually reach smolt age at 12–16 cm after 3 years in the rivers, and outmigrate in spring to feed on marine resources (Jonsson & Jonsson, 2011; Jonsson et al., 2011). Egg survival was measured following Barlaup et al. (2008). Snorkelers searched the gravel for spawning redds in March when eggs were just before hatching or had hatched. Egg pockets were opened by carefully removing gravel and counting the visible subsample of living and dead eggs or alevins, before covering the pockets with gravel. Egg survival was measured in Matreelva 2002–2011 and 2018, in Flekkeelva 2018 and in Aurlandselva 2011–2019.

Sediment quality and coverage

IO$_2$, Dg and PF were chosen as indicators of spawning sediment quality (Barlaup et al., 2008; Pulg et al., 2013). IO$_2$ was measured in situ by applying a Terhune standpipe at a sediment depth of 0.15 m in the spawning gravel and a WTW 3440i multimeter
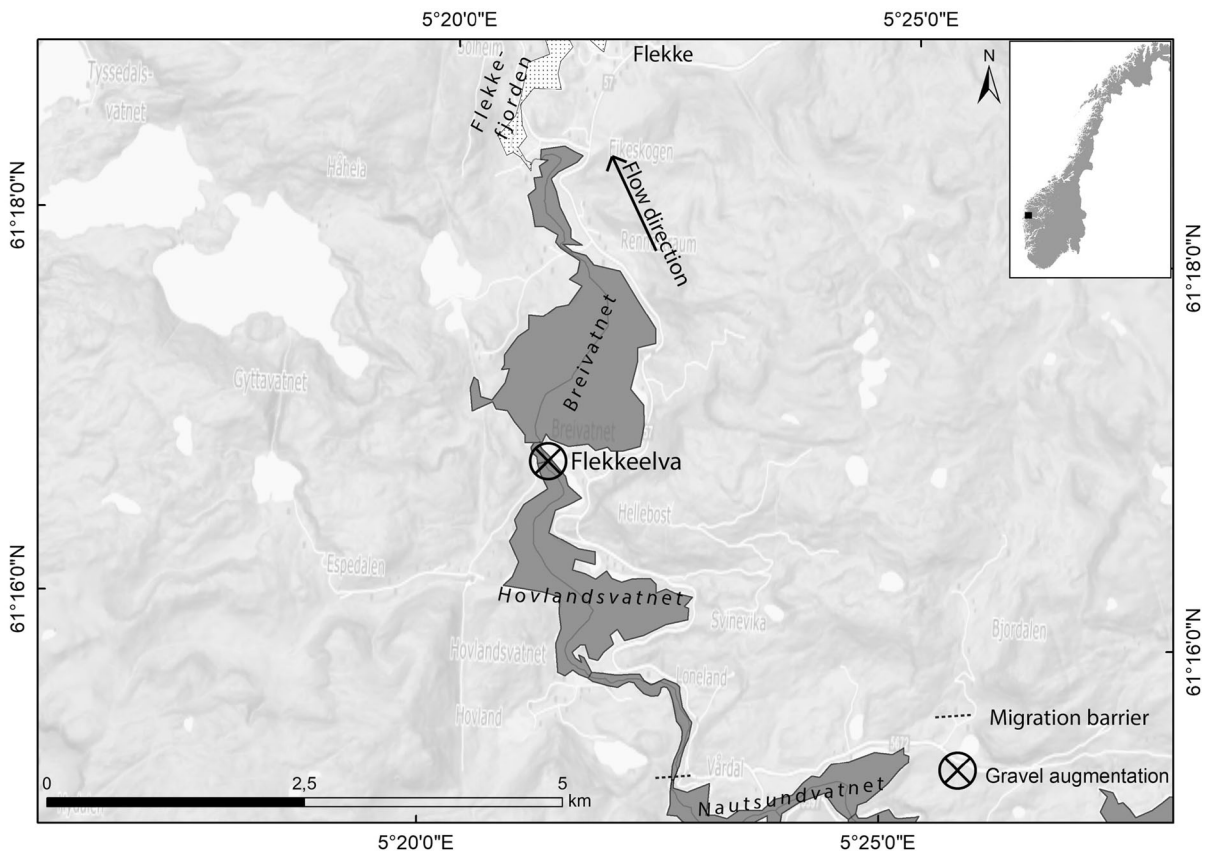
Fig. 3 Study area: River Flekkelva and spawning gravel augmentation site

(Terhune, 1958; Barlaup et al., 2008). For sediment sampling, the upper 15 cm of the sediment was shoveled into a submersed bag made of 150 µm nylon netting, and sieved using mesh sizes 1, 2, 4, 8, 16, 32, 64 and 128 mm (Barlaup et al., 2008). About 33 kg of dry sediments were sampled on each occasion in Matre- and Flekkeelva. Dg was calculated following Rubin & Glimsaeter (1996). The grain size distribution curve in Matreelva 2002 and Flekkeelva 2005 were provided by the gravel mining operators delivering the applied sediments. In Aurlandselva, 10.1 kg of the original gravel was sieved in 2010 and one sediment sample was taken on each spawning site 2018 (6.9 to 12.3 kg).

The area covered by the added gravel was measured with a handheld differential RTK GPS (Trimble T3; horizontal precision 2 cm/vertical precision 5 cm). After 2015, area was measured from orthophotos provided by Statens kartverk (norgeibilder.no, accessed 25.2.2020, 10 cm accuracy) and digitized

georeferenced UAV aerial pictures (DJI Mavic 2 Pro, Esri ArcGIS 10.5, Agisoft Metashape Pro, 4 cm accuracy).

Gravel addition design

All sites with gravel augmentations were carefully chosen after mapping the river for sufficient morphologic and hydraulic conditions. In all cases, the gravel was placed in glides with lower energy slope (reach drop devided by reach length, see Fig.4) than the average slope of the river (Figs. 1, 2, 3). In Matre- and Flekkeelva, the glides were situated at lake outlets, whereas in Aurlandselva the sites were situated in the river. The design followed recommendations of Barlaup et al. (2008) and Pulg et al. (2013) using sieved gravel between 16 and 128 mm, placed by an excavator and a dump truck (Fig. 4).

In Aurlandselva, 150 m³ of gravel were introduced in 2010. The gravel had a Dg of 37 mm and 0.01%

Table 2 Biotic and abiotic data of the gravel augmentation sites in chronological order

Year site	Salmon fry [ind.m^{-1}]	Salmon parr [ind.m^{-1}]	Trout fry [ind.m^{-1}]	Trout parr [ind.m^{-1}]	Egg survival [average %]	Spawning area [m^2]	IO$_2$ [mg l^{-1}]	DG [mm]	PF [%]
2002 Flekke	26.8	4	21	1					
2003 Flekke	17.6	8.1	7	0					
2002 Matre	1	0	5	32.2		271	12.2	32.2	0
2003 Matre	0	1	30	22.7	93.2				
2004 Flekke	7.6	2.2	3	6.1					
2005 Flekke	58.2	7	0	3		500		37	0
2005 Matre					93.5				
2006 Flekke	30	15.7	0	0					
2006 Matre					91.3				
2007 Flekke	22	11	4	1					
2007 Matre					86.9				
2008 Flekke	17	25.2	5.2	5					
2008 Matre	0	7	5	45.6	90.9				
2009 Flekke	56	22.7	5.2	2					
2009 Matre	0	3	9.1	43.3	94.4				
2010 A1	2	0	30	16		120		37	0.01
2010 A2	0	0	48	8		42		37	0.01
2010 A3	0	0	46	14		336		37	0.01
2010 A4	0	2	42	18		196		37	0.01
2010 A5	8	8	14	2		261		37	0.01
2010 A6	20	6	16	0		68		37	0.01
2010 Matre	0	4	40	58	89.8				
2010 Flekke	26.9	7.4	3.1	7.1					
2011 A1	6	0	36	10	63.0	122	13		
2011 A2	2	0	44	2	100.0	40	13.5		
2011 A3	2	0	62	4	100.0	340	13.2		
2011 A4	4	4	40	16	73.1	175	12.9		
2011 A5	18	10	34	6	83.0	285	113.1		
2011 A6	0	34	20	0	61.0	68	13.1		
2011 Matre	1	6	14.8	72.7	89.6				
2012 A1	0	0	130	18	91.1	110	14		
2012 A2	4	0	50	20	92.5	39	14.1		
2012 A3	6	4	34	32	95.1	334	13.9		
2012 A4	0	5	66	28	93.6	177	13.9		
2012 A5	26	42	58	14	94.8	278	13.7		
2012 A6	9	12	27	12	70.7	65	13.3		
2012 Matre	5	0	14	20					
2013 A1	6	4	118	30	79.5	98	14.4		
2013 A2	7	5	50	23	78.8	38	15.5		
2013 A3	10	10	64	23	96.0	339	14.4		
2013 A4	0	3	105	53	94.8	174	14.3		
2013 A5	0	20	68	24	96.3	274	14		
2013 A6	4	10	52	10	63.3	64	14.1		
2013 Matre	6.2	8	24	76					

Table 2 continued

Year site	Salmon fry [ind.m^{-1}]	Salmon parr [ind.m^{-1}]	Trout fry [ind.m^{-1}]	Trout parr [ind.m^{-1}]	Egg survival [average %]	Spawning area [m^2]	IO$_2$ [mg l^{-1}]	DG [mm]	PF [%]
2014 A1	19	8	120	35	69.9	98	13.9		
2014 A2	14	9	55	24	92.6	24	13.8		
2014 A3	0	13	45	33	94.4	291	13.6		
2014 A4	0	4	70	62	95.8	115	13.2		
2014 A5	0	20	50	35	96.7	210	13.7		
2014 A6	4	10	40	30	84.4	45	12.9		
2014 Matre	2	14	20	56					
2015 A1	32	6	73	35	84.4	100	14.8		
2015 A2	25	2	45	32	96.9	20	14.9		
2015 A3	18	6	25	75	98.5	291	14.8		
2015 A4	9	4	65	69	100.0	114	14.6		
2015 A5	33	8	61	35	96.4	203	14.4		
2015 A6	37	5	65	27	91.7	45	14.6		
2015 Matre	0	26	22	44					
2016 A1	0	0	106	22	76.5	95	14.4		
2016 A2	20	22	46	76	94.0	1	14.4		
2016 A3	14	12	62	44	95.7	286	14		
2016 A4	2	0	31	71	80.6	94	13.9		
2016 A5	31	12	41	29	78.0	195	13.9		
2016 A6	19	21	36	43	95.2	43	13.1		
2016 Matre	2	2	34	38					
2017 A1	0	1	183	59	97.8	93	14.2		
2017 A2	2	11	79	48	98.8	1	14.4		
2017 A3	0	18	41	29	93.4	259	14.4		
2017 A4	0	11	25	78	88.9	92	14		
2017 A5	4	20	70	38	97.3	195	13.9		
2017 A6	0	20	18	32	83.9	43	13.5		
2017 Matre	24	37.4	28.2	112.8					
2018 A1	0	26	40	32	94.7	93	14.33		
2018 A2	16	21	56	43	88.1	1	14.43		
2018 A3	0	11	53	15	81.1	259	14.43		
2018 A4	6	14	64	54	86.8	92	14.16		
2018 A5	0	12	90	32	95.5	195	13.99		
2018 A6	0	0	184	22	92.8	43	13.1		
2018 Matre					83.0	195	10.8		
2018 Flekke	20	14	1	4	93.9	485	12.8	29.6	0.02
2019 A1	1	3	120	58	98.0		14.1	25.2	4.5
2019 A2	0	4	78	59	100.0		14.2	26.2	3.2
2019 A3	1	4	64	62	87.6		14.1	27.7	0.1
2019 A4	1	11	57	71	80.0		14	40	0.03
2019 A5	6	16	83	44	100.0		13.9	37.2	0.07
2019 A6	40	10	16	14	98.1		14	32.4	0.04
2019 Matre								12.8	10.4
2020 A1	0	30	36	22	93.4		14.4	32.9	3.2

Table 2 continued

Year site	Salmon fry [ind.m^{-1}]	Salmon parr [ind.m^{-1}]	Trout fry [ind.m^{-1}]	Trout parr [ind.m^{-1}]	Egg survival [average %]	Spawning area [m^2]	IO$_2$ [mg l^{-1}]	DG [mm]	PF [%]
2020 A2	4	16	83	29	98.0		14.3	28.5	2.8
2020 A3	0	5	68	44	94.6		13.9	33.7	0.2
2020 A4	0	22	40	90	88.1		14.3	41.4	0.04
2020 A5	0	10	60	48	86.4		14	32.6	0.04
2020 A6	0	0	133	56	95.3		14	41.9	0.05
2020 Matre					69.7		11.2	15.6	6.8

fines. The gravel was spread on six sites ranging from 42 to 336 m^2, average area was 171 m^2. The energy slopes at the sites were between 0.002 and 0.005.

In Matreelva, 80 m^3 of spawning gravel with a Dg of 32 mm no fines were added in 2002 using an excavator and a dumper. The area covered was initially 271 m^2. Energy slope of the reach measured over 100 m in length was 0.002. The hydraulic profile was narrowed from approximately 41 m to 29 m at median flow by constructing a groin to increase flow velocities to at least 0.3 m s^{-1} on the spawning gravel.

In Flekkeelva, 70 m^3 of spawning gravel with a Dg of 37 mm and no fines were added in 2005 using an excavator and a dumper. The area covered was initially 500 m^2. Energy slope of the reach measured over 100 m length was 0.001 (lake outlet).

Costs

The information about costs for measures in Flekkeelva was documented by Gabrielsen et al. (2007), while the information was provided by the hydropower companies E-Co Energy in Aurlandselva and BKK in Matreelva. The costs include the material and the construction work to conduct the gravel introduction. They do not include costs for planning and monitoring. The costs were adjusted for inflation using the Norwegian Banks online tool (https://www.norges-bank.no/Statistikk/Priskalkulator/) and are presented in 2017 Norwegian krone (NOK, 1 € = 10 NOK April 27th, 2020).

Data analysis

Changes in sediment characteristics are analyzed by linear regressions (*lm*) in R (R Core Team, 2018) on IO$_2$, Dg, spawning area, and fish densities. Juvenile Atlantic salmon and Brown trout densities vary in the three rivers with trout dominating in Aurlandselva and Matreelva and salmon dominating in Flekkeelva. The species have high niche-, habitat-, and behavioral overlap (Jonsson & Jonsson, 2011), especially in their spawning habitat (Louhi et al., 2008). Thus, the sum of the juvenile densities of both species was chosen to evaluate the development, and the densities of both species were pooled in the regression analysis, called "Atlantic salmonids" (Foldvik et al., 2017, Pulg et al., 2019). Egg survival was modeled by logistic regression with the *glm* function in R using the proportion of surviving eggs as the dependent variable. Fixed effects
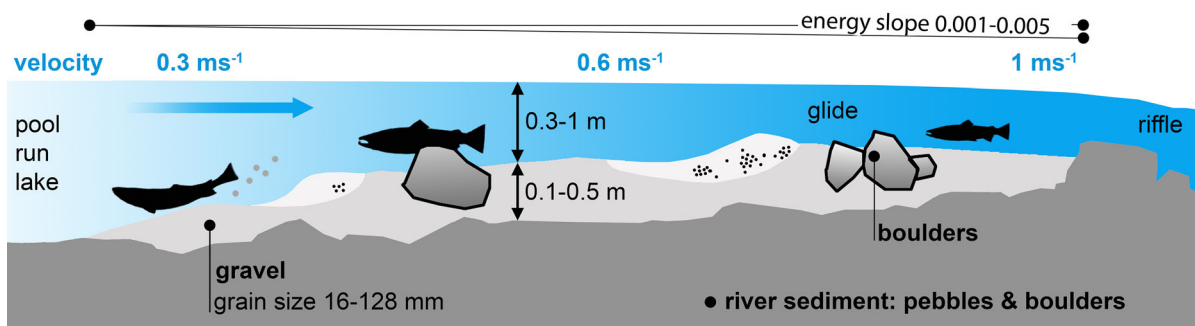
Fig. 4 Design of the spawning gravel augmentations shown as principal longitudinal section at median discharge

were years since intervention and river. Flekke was excluded because only one egg measurement was made. Density of Atlantic salmonids was modeled by simple linear regression with one model for parr and one for fry using the lm function in R. Fixed effects were the river (all sites in Aurland were pooled, so this had three levels, Aurland, Flekke, and Matre), life stage (parr or fry), and years since treatment. Years since treatment was preferred to year as a raw numeric to reduce heteroskedasticity.

The regression analysis was conducted for all datasets including more than two sample years. The life span of the gravel additions is evaluated by hydraulics and the flood events that have occurred after gravel augmentation, instead of only relying on simplified models and p-values (Amrhein et al. 2019, Hauer et al. 2020).

Results

Sediment quality and coverage

IO_2 on the gravel sites in Aurlandselva, Matreelva, and Flekkeelva are shown in Figs. 5, 6, and 7 and Table 2. The concentrations were 12.9 to 15.5 mg l^{-1} (average 14 mg l^{-1}), 7.53 to 13.9 (average 11.2) and 9.4 to 14.6 (average 12.8), respectively. The IO_2 did not change significantly over time in Aurlandselva ($R^2 = 0.08$, $P = 0.2$ for IO_2, DF = 51). There were not enough data points to conduct linear regressions over time in Matreelva and Flekkeelva. At the Matreelva test site, median IO_2 (13.2 mg l^{-1}) was approximately the same as in 2002 (13.1 mg l^{-1}) but reached the lowest individual data point (5.1 mg l^{-1}). At the Flekkeelva test site IO_2 was 13.7 mg l^{-1} in 2018. Both in Aurlands-, Matre- and Flekkeelva median IO_2 indicated good incubation conditions after Pulg et al. (2013).

The sediment composition in the areas with gravel augmentation was relatively stable between 2010 and 2020 in Aurlandselva (Dg 2020 = 37 mm, PF = 0.1, 2020: Dg = 35.2 mm, PF = 1.1, Table 2, Fig. 11). In Matreelva, the gravel composition became more fine-grained over time (Dg 2020 = 15.6 mm, PF = 6,8, Table 2, Fig. 11). In Flekkeelva, the grain size composition changed very slightly from 2005 to 2018 (Dg 2020 = 29.6 mm, PF = 0.02, Fig. 11).

The size of the spawning area at the test sites changed over time (Fig. 12, Table 2). In Aurlandselva, the total area of the six sites was reduced significantly ($R^2 = 0.88$, $P < 0.01$, $y = -0.044x + 1.0781$) from 1012 m^2 in 2010 to 683 m^2 in 2018. This corresponds to an average reduction of 32.5%, ranging from 2 to 77% on the 6 different sites (1–259 m^2). In Matreelva, 72% (195 m^2) of the original gravel area was left in 2018. In Flekkeelva, the gravel area was reduced by 3% from 500 m^2 2005 to 485 m^2 in 2018. In total, the median spawning area was reduced by 26% on the eight sites. The digging and searching for eggs (see below) revealed that the thickness of the gravel layers still was sufficient for spawning (> 14 cm) at all sites.

Egg survival and juvenile fish densities

All six test sites in Aurlandselva were used by spawning salmonids annually from 2010 to 2020. At least five redds and egg pockets were found and analyzed at each site, except for site five, which was reduced to only 1 m^2 in 2015 (Fig. 12). At this site, only one redd was found per year after. Median egg survival in Aurlandselva was 93%, on average 85% (Fig. 8). At the site in Matreelva, more than ten redds were found in each sampling year. Average survival was 91%, median survival 100% (Fig. 9). The range of survival rates broadened in the last years including lower values, but there was no significant negative trend. The site in Flekkeelva was only sampled in 2018 and seven redds were found. The egg survival values ranged from 80 to 100%, with a median of 100% and an average of 94% (Fig. 10). Local anglers had observed spawning and redds on the site every autumn from 2005 to 2007 (Gabrielsen et al., 2007). In total, the eight sites in the three rivers had an average egg survival of 90.2% after gravel augmentation in all monitored years. There was no temporal change in egg survival ($t = 0.715$, $P = 0.47$), which did not differ between Matre and Aurland ($t = 0.17$, $P = 0.87$).

Juvenile fish densities increased after the spawning habitats were established (Table 2, Figs. 13 and 14). Average fry densities of Atlantic salmonids on the six sites in Aurlandselva were 38 ind.m^{-2} in 2010. After the gravel augmentation (2011–2020), average fry densities were 72 ind.m^{-2}. Brown trout dominated the total catch (fry 55%, parr 30%), with a smaller abundance of Atlantic salmon (fry 8%, parr 8%,
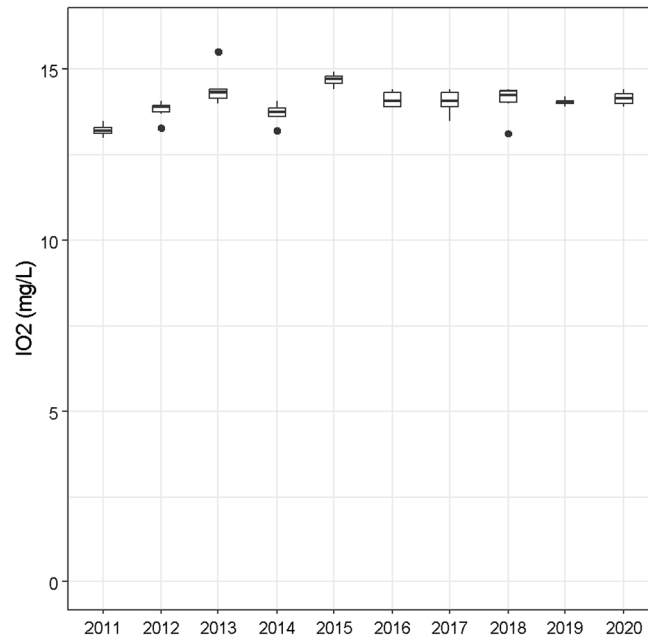
**Fig. 5** Interstitial oxygen concentrations in mg l^{-1} (IO$_2$) at the test sites in Aurlandselva
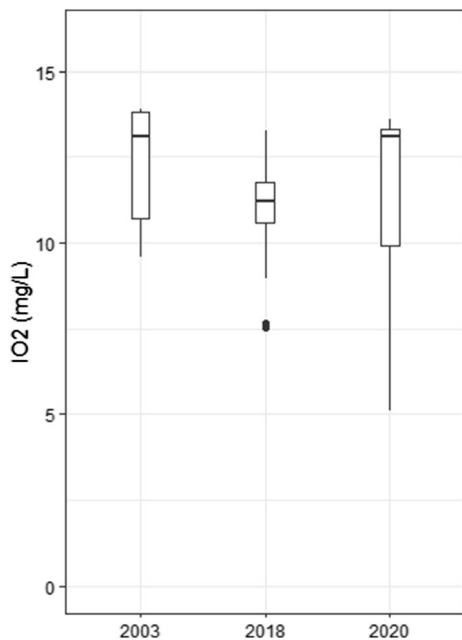
Fig. 6 IO$_2$ at the test site in Matreelva
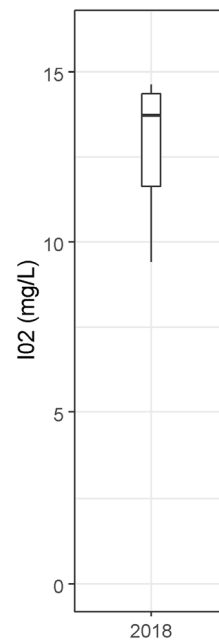
Fig. 7 IO$_2$ at the test site in Flekkelva

Table 2). At the gravel augmentation site in Matreelva, fry densities of Atlantic salmonids were 6 ind.m^{-2} in 2002 and 20 ind.m^{-2} (average) in the years after gravel augmentation. There was a high year to

year variation ranging from 5 to 52 ind.m^{-2} (Table 2). Brown trout dominated the total catch (trout fry 28%, trout parr 59%). Salmon fry had a percentage of 4%, salmon parr 9%. At the test site in Flekkeelva, average
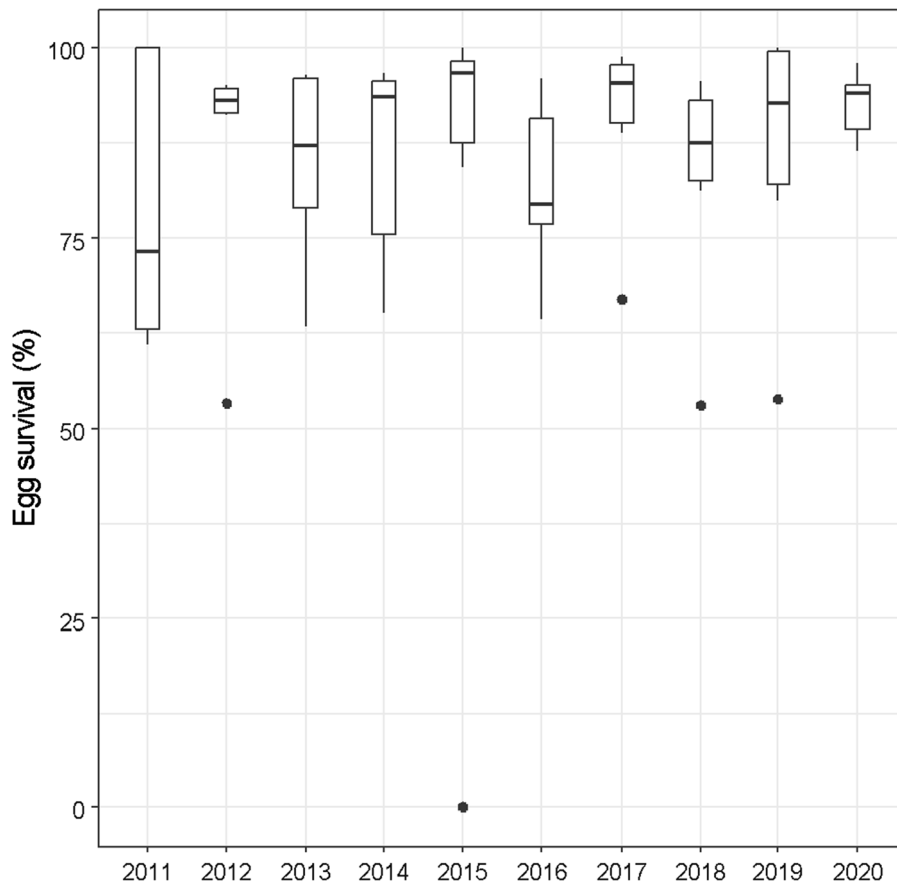
Fig. 8 Egg survival at six test sites in river Aurlandselva

fry densities of Atlantic salmonids were 23.8 ind.m^{-2} before and 25 ind.m^{-2} in the years after gravel augmentation. Atlantic salmon dominated the total catch (salmon fry 60%, parr 27%) and with a smaller abundance of Brown trout (fry 6%, parr 7%). The average total juvenile densities were lower in Flekkeelva (48 ind.m^{-2}) than in the other rivers (Aurland 110 ind.m^{-2}, Matre 89 ind.m^{-2}). Juvenile densities increased with time after gravel augmentation (fry: $t = 2.21$, $P = 0.03$; parr: $t = 6.97$, $P < 0.01$). Model slopes indicate that fry increased by about 2.04 individuals per 100 m^2 per year after gravel augmentation, whereas parr increased by about 4.1 individuals per 100 m^2 per year after gravel augmentation. Aurlandselva had higher parr ($t = -2.56$, $P = 0.01$) and fry ($t = -5.07$, $P < 0.01$) densities than Matreelva and higher fry densities than Flekkeelva ($t = -2.78$, $P = 0.01$).

Hydrology

The average and median discharge in Aurlandselva from 2010 to 2020 were 14.6 m^{3}s^{-1} and 4.1 m^{3}s^{-1}, respectively (Table 1). The maximum discharge during the period was 141 m^{3}s^{-1} exceeding HQ20. There were three exceeding HQ5, two of these in the year after gravel augmentation. In Matreelva, the average and median discharge between 2002 and 2018 were 3.5 m^{3}s^{-1} and 1.9 m^{3}s^{-1}, respectively. Flood events exceeded HQ20 in 2014 and HQ10 in 2018. The average and mean discharge in Flekkeelva between 2005 and 2020 were 22.5 m^{3}s^{-1} and 12.6 m^{3}s^{-1}, respectively. The maximum discharge during the period was 325.3 m^{3}s^{-1} exceeding HQ10 (Table 1).
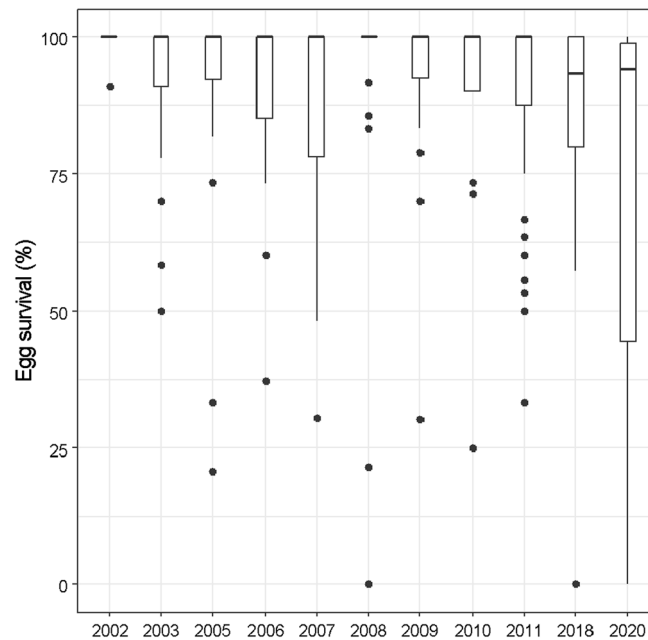
Fig. 9 Egg survival at the test site in Matreelva
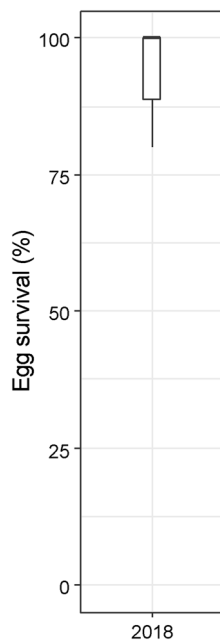
Fig. 10 Egg survival in Flekkelva

Costs

The total construction cost for the six gravel augmentation sites in Aurland was 183,327 NOK (in 2017-NOK, 18,333 €). The costs consisted of gravel transport from the nearby (1–6 km) gravel pit to the test sites with a dump truck and distributing the gravel by a 22 t excavator in the river. No morphological modifications of the river channel were necessary. Local boulders were placed near- or within the gravel augmentations to increase shelter for spawners.

The total construction cost for the gravel augmentation site in Matreelva was 671,763 NOK (in 2017-NOK, 67,176 €). The work consisted of gravel transport from a gravel pit (50 km) to the chosen sites with a dump truck and distributing the gravel by a 20-t excavator. Extensive morphological modifications (terrain adaptation and groins) were implemented to constrict the water current on the spawning glide.

The total construction cost for the gravel augmentation site in Flekkeelva was 64,107 NOK (in 2017-NOK, 6,411 €). The work consisted of gravel transport from a nearby (3 km) gravel pit to the augmentation site with a dump truck and distributing

the gravel by a 20-t excavator. No morphological modifications of the river channel were necessary.

Discussion

Sediment development

The monitored spawning gravel in Aurlandselva did not degrade by accumulation of fines during the monitoring period. Sediment samples taken after 10 years indicate minor changes of Dg (from 37 to 35.2 mm) and minimal accumulation of fines (0 to 1.1%, Fig. 11). The sediment composition is nearly identical over the period, despite a few individual stones > 64 mm that most likely originate from the natural riverbed and were mixed with the gravel by digging activity of spawning fish. The grain size distributions indicate good reproduction conditions for salmonids (Pulg et al., 2013), which was validated by high egg survival (85% on average) and no declining trend in egg survival (Fig. 8). The size of the augmentation area, however, was reduced significantly, in particular for the site A3 (Fig. 12). This can be explained by scouring during floods. Scouring already occurred during the first 5 years after the gravel augmentation, as described and hydraulically characterized by Hauer et al. (2020). Our data indicate that this process has continued since 2015—but rather linearly than suddenly. The variation in area reduction among the test sites is large, with the site A3 being nearly eroded in 2018 (2% left after 8 years) and site A3 with 78% of the original area left (value for all sites is 69%, after 8 years Table 2). However, it is

important to note that the sedimentological boundaries and morphological framework have an impact on the stability characteristics. Structural features may create favorable flow conditions, like boulders or groins, or shelter against gravel erosion. On the other hand, structural features or rough surface by large grains may increase local turbulence with the consequence of increased scouring (Hauer et al., 2020). Thus, not only are the flood magnitude and forces directly influential, but they also exert secondary influence with respect to how they affect the small-scale flow conditions at the river bottom.

In Matreelva, the accumulation of fines caused a change in the sediment composition during the 15-year period. Nevertheless, the sediment composition remained within threshold values for good reproduction (Pulg et al., 2013, Dg > 12.9 mm, PF < 10.3%), and the average egg survival remained high at the end of the study (Fig. 8, Table 2). If the accumulation of fines continues, however, the spawning conditions will deteriorate. Fines may originate from the drainage or from autochthonous sediments in the lake outlet, which were observed there before (Gabrielsen et al., 2011). These sediments may have been mobilized and mixed with the added gravel by floods and spawning fishes at the low gradient site (energy slope = 0.002). Similar to Aurlandselva, the size of the spawning area in Matreelva was reduced over time (72% left after 16 years). The reduction was caused by scouring of gravel from the lower area and growth of the macrophyte *Juncus bulbosus* L. in the upper area (Velle et al., 2021). The vegetation is likely to baffle the water velocity and contribute to settlement of fine sediments that would otherwise continue
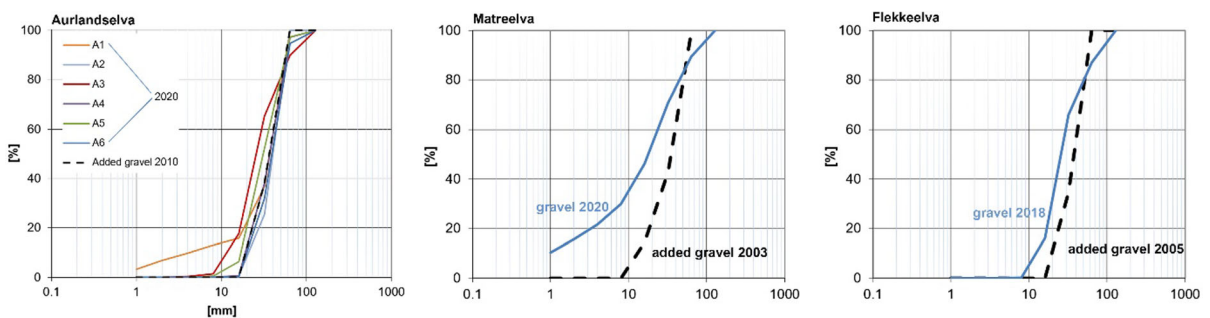
Fig. 11 Grain size distribution curves for the gravel augmentation in Aurlandselva in 2010 and 2020 (left). The average Dg was 35.2 mm and PF 1.1% in 2020. Middle: Grain size distribution curves for the gravel augmentation in Matreelva 2002 (dashed) and 2020 (blue). Dg was 12 mm and PF 10.4% in 2018. Right: Grain size distribution for the gravel augmentation in Flekkeelva in 2005 (dashed) and 2018. Dg was 29.6 mm and PF 0.02% in 2018
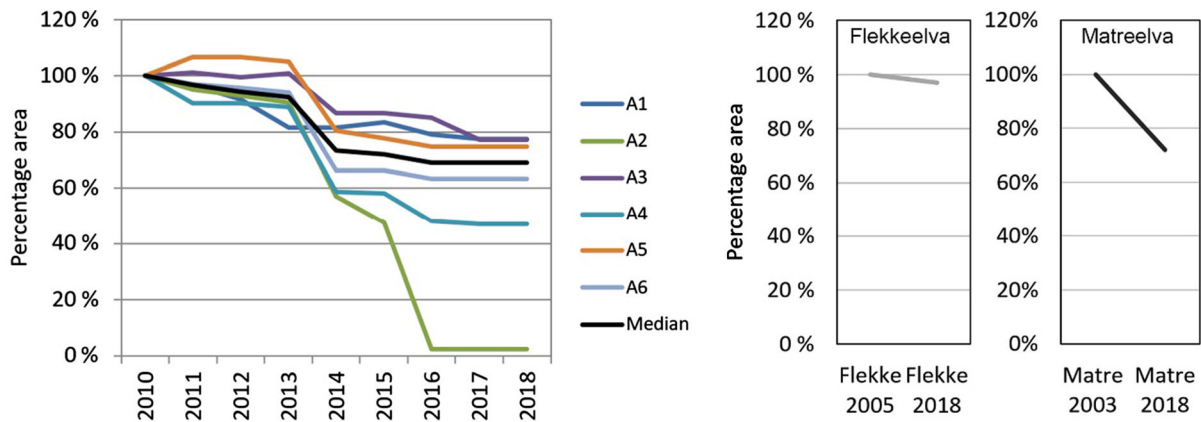
Fig. 12 Percentage of the gravel areas from augmentation to 2018 in Aurlandselva (left), Flekkeelva (middle), and Matreelva (right)

downstream. The limited decrease in the size of the spawning area in Matreelva indicates that the morphological adaptations in the riverbed were well dimensioned and that the placing of the gravel at an energy slope of 0.002 was sufficient.

In Flekkeelva, there were no relevant changes in sediment composition and only minor changes in the size of the augmentation area (97% of the original site left after 13 years). The large lake directly upstream of the gravel augmentation area functioned as sediment trap for fine sediments. Land use in the drainage area with very limited agriculture, pasture, and foresting is not likely to cause discharge of fine sediments (Opperman et al., 2005; Pulg, 2009). The ratio between HQm and the average discharge is 14 in Flekkeelva, which is lower than in the other study rivers and may partly explain that the gravel augmentation was intact after 11 annual floods up to HQ10.

Generally, the sediment composition on the eight sites indicates good reproduction conditions for fish in the rivers after 10, 13 and 18 monitoring years. Only site A3 in Aurland was nearly scoured after 5 years (8 m^3 gravel added, 2% remaining, energy slope = 0.004). The site was directly downstream a bridge that probably has functioned as a hydraulic constriction during high flows increasing scouring forces. The gravel area at the other test sites were fairly intact (Aurland 69%, Matre 72%, Flekke 97%) and at sufficient thickness (at spawning redds > 14 cm). It can be questioned if the results are biased by sampling methods or yearly variation, especially in Flekkeelva with few sampling years. However, because we linked several independent monitoring methods (abiota and biota, sediment, egg survival, juveniles) that all indicate high reproduction success, we conclude that the results reflect good spawning and reproduction conditions throughout. The test sites were not chosen randomly, but with an expectation to still find some gravel left from the oldest augmentations that we are familiar with. Thus, they do not represent a mean of all gravel augmentations measures existing in the region. Hauer et al. (2020) showed that some gravel augmentations sites in Aurlandselva are scoured after only 1 to 2 years. It is therefore concluded that augmentation sites must be chosen carefully after hydraulic- and hydromorphologic suitability under given discharge dynamics, preferably by combining underwater field mapping with hydraulic models. Two dimensional hydraulic models are helpful in fluvial river stretches but are not sufficient to evaluate these criteria on diamictic riverbeds in semi- and non-fluvial reaches, which are typical for post-glacial Western Norwegian rivers (Hauer & Pulg, 2018; Hauer et al., 2020).

Egg survival and juvenile fish densities

Spawning activity, high egg survival and the significant increase in fry densities after gravel addition, indicate that the measures functioned as intended (Figs. 5, 6, 7, 13, 14). Parr densities increased also significantly, though electrofishing sampling was not primarily designed for parr habitat. The results can be explained by high shelter availability at the shore and partly patchy submersed vegetation at the sites, which is an attractive parr habitat (Foldvik et al., 2017; Pulg et al., 2019; Velle et al., 2021). In Aurlandselva, parr
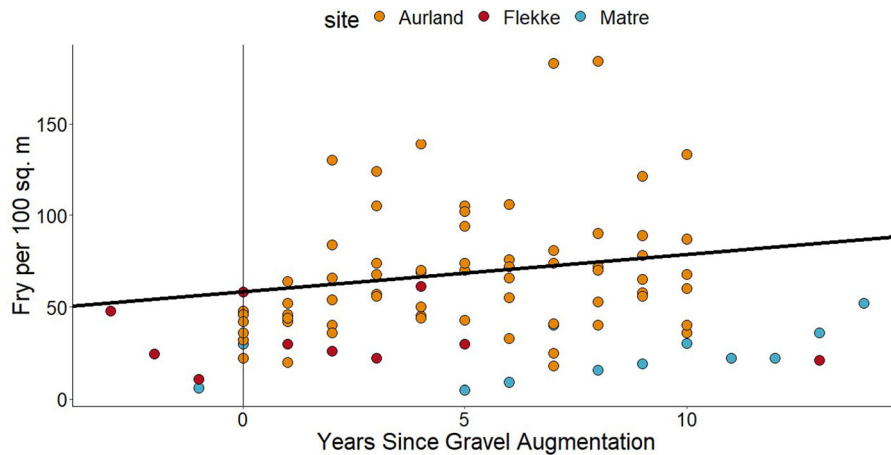
Fig. 13 Atlantic salmon and Brown trout fry densities at the test sites
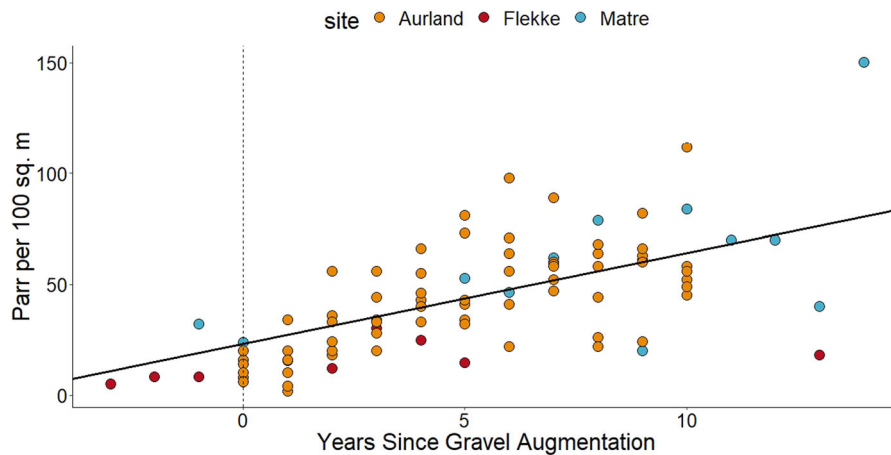

Fig. 14 Atlantic salmon and Brown trout parr densities at the test sites

densities are correlated to fry densities the year before ($R^2 = 0.66$, $P < 0.01$) suggesting that the positive effect on fry densities also affects parr densities the year after; a 1-year time dependency indicating temporal autocorrelation. However, autocorrelation functions did not indicate violation of independence so temporal autocorrelation structures were not included. Thus, the results may indicate not only a positive effect on fry but also on parr and thus total juvenile production. Uncertainty and among-year variation in the electrofishing results can be a result of fishing at different conditions (discharge, timing, water temperature, conductivity, substrate type, species and fish length; Scholten, 2003; Hedger et al., 2018) especially in the atypical fry habitat at the lake sites, but it can also reflect natural year to year variation. In regulated

Aurlandselva, the fishing was conducted at approximately the same time, temperature, conductivity, discharge and personnel each year fulfilling the requirements for a robust dataset.

Life span and cost–benefit analysis

Sediment characteristics, egg survival, and fish density indicate functioning of the gravel augmentation measures after 10 years in Aurlandselva, 13 years in Flekkeelva, and 18 years in Matreelva. Average egg survival in Matre was lower in 2020 (70%) than before, but there wasn't a significant negative trend. The results contrast results on gravel augmentation in other parts of the world where similar measures have had shorter life spans, e.g. ranging from 1 to 6 years
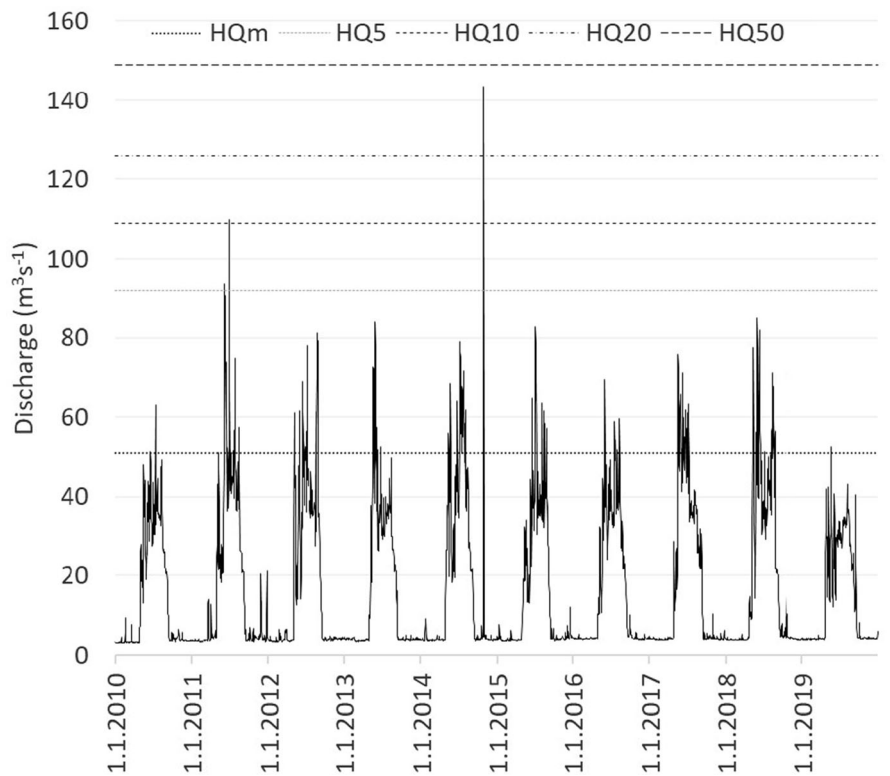
Fig. 15 Discharge curve for Aurlandselva 2010–2020

(Pulg et al., 2013; Pander et al., 2015). Those sites had a higher degree of damming, erosive land use, and higher fine sediment supply (suspended load > 12 mg l^{-1}, Pulg, 2009; Hauer et al., 2013). The longer life span of the studied gravel augmentations in Norway can be explained by the relatively stable morphodynamics due to semi- and non-fluvial geomorphology and low suspended load (Hauer and Pulg, 2020). According to Harrison et al. (2019), the spawning gravel augmentation measure with the longest life span documented so far, was a 14-year-old project for Chinook in Merced River, California. The documented life span of the measure in Matreelva exceeds this period (18 years). The expected life span will probably be even longer because the test sites were still functioning when sampled. A simple linear regression and upscaling suggest that it will take 24 years in Aurlandselva, 54 years in Matreeelva, and 422 years in Flekkeelva until the gravel is completely scoured or overgrown by macrophytes (Matreelva). However, the life expectancy and success of such measures will be affected by irregular events such as large flood events or landslides with fine sediment

input as well as gravel moved and transported gradually by spawning fish (Merz et al., 2006; Sear & DeVries, 2008a; Unfer et al., 2011; Hauer et al., 2018a, b). Lifespan is therefore probably much shorter than the linear upscaling suggests. Based on the flow data and recurrence calculation (Figs. 15, 16, 17) it can be concluded that the measures have tolerated 10 years flood events in Flekkeelva and 20-year flood events in Matre- and Aurlandselva. This would indicate a lifespan of at least 10 years for the site in Flekkelva and 20 years for the sites in Aurlandselva. The observed scouring of gravel, however, has followed a surprisingly linear process (Fig. 12, Aurlandselva), though there were significant flood events in the period (Fig. 15). This can be explained by the choice of locations which aimed at favorable hydraulics. The augmentations were conducted at stretches with the lowest slope available (0.002–0.005) and included stabilizing small-scale features such as boulders (Hauer et al., 2020). Therefore, gravel in Aurlandselva has not been scoured in one event but rather gradually, a process that also may have been influenced by the gradual gravel movement of nest
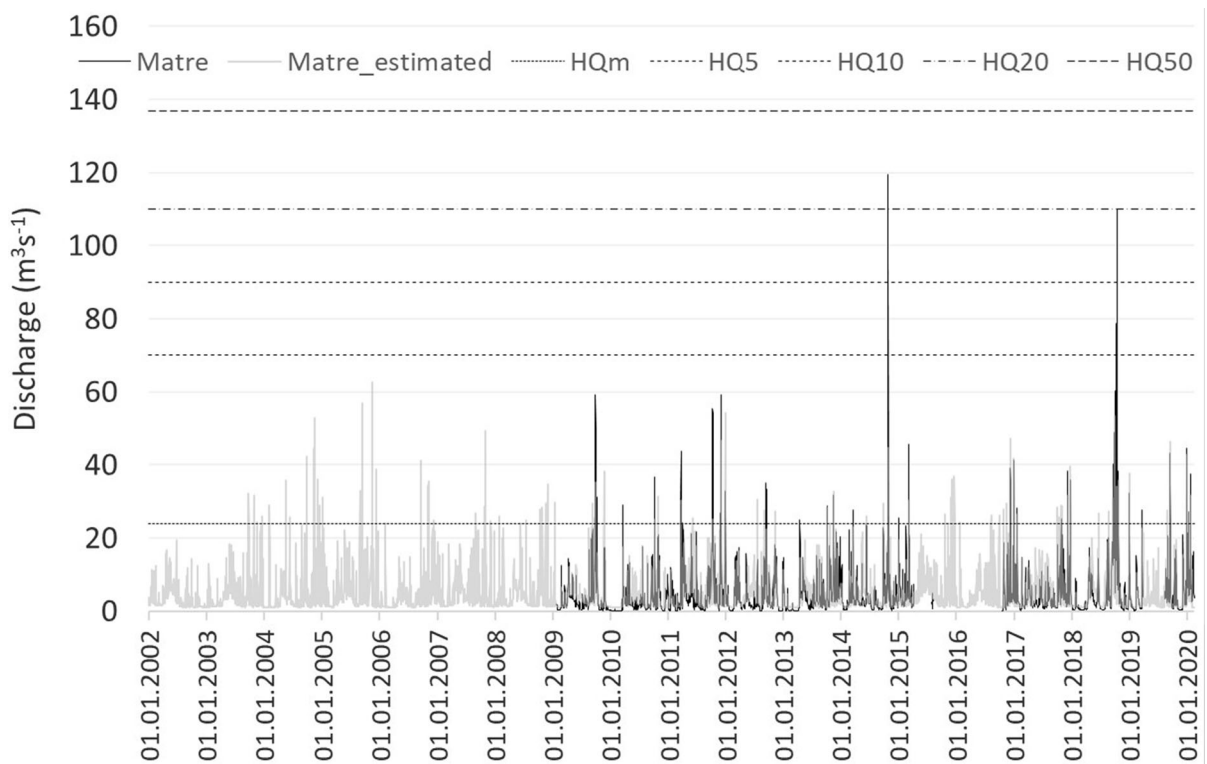
Fig. 16 Discharge curve for Matreelva 2002–2020

building spawners. The sufficient design and placement of the gravel augmentations may also explain why the spawning sites have had a longer life span than similar gravel augmentations in the region that were scoured after the first floods (Barlaup et al., 2008; Hauer et al., 2020).

Many natural gravel spawning habitats in Western Norway are situated on glacial tills or glaciofluvial deposits at lake outlets, e.g. at lake Vassbygdvatnet before regulation (Ugedal et al., 2019), at Lake Eidfjordvannet, Lake Strynsvatnet, Lake Evangervatnet, as observed by Skoglund et al. (2018) during spawner counts. These spawning habitats cannot be supplied by fresh gravel from upstream because the lakes are sediment traps. Our results suggest that such spawning sites nevertheless may function over a long time period since there is no mandatory accumulation of fines at such places in this region of the world (Fig. 11. Flekkeelva). We hypothesize that such lake outlets may have functioned as spawning habitats since their formation after deglaciation 9800–8800 years BP (calibrated), the following bed forming floods during glacier melt (Rye & Faugli,

1994; Hauer & Pulg, 2020) and since colonization by gravel bed spawning salmonids (Huitfeld-Kaas 1918). Thus, the sediments on these locations may have served as spawning habitats for more than 8000 years in the semi- and non-fluvial river environment with low suspended load (Hauer & Pulg, 2018). The cleaning effect of floods and spawning fish was probably enough to maintain good spawning conditions in these lake outlets. In dynamic fluvial gravel bed river reaches spawning habitats may just reach a short life span of a 1–6 years due to morphodynamics, but also because of human-made interference such as increased fine sediment loads and impoundments (Pulg, 2009; Pulg et al., 2013; Pander et al., 2015; Hauer et al., 2018a, b).

Restoring the study rivers including natural fluvial processes such as lateral sediment transport by removing the regulation impacts, as suggested by Beechie et al. (2010), would probably lead to a permanent increase of spawning habitat in the regulated rivers Matre- and Aurlandselva where bank protection and diminished flood discharges have reduced lateral gravel supply. Maintenance or refilling
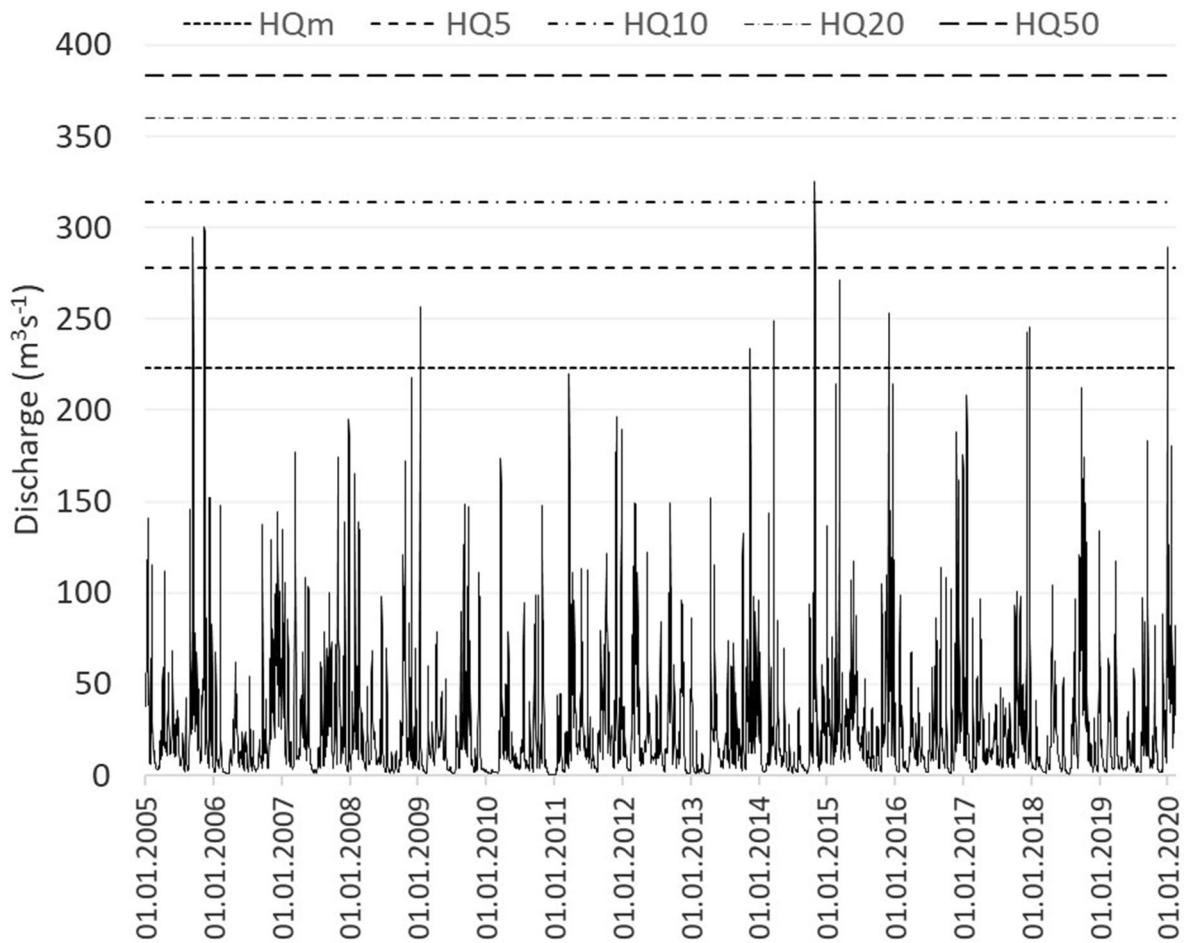
Fig. 17 Discharge curve for Flekkeelva 2005–2020

of gravel is needed when the regulation and river utilization is to persist, as described in the concept of "environmental design" in regulated rivers (Forseth et al., 2014). To provide a permanent high-quality spawning habitat in such a situation, it is necessary to monitor the measures regularly and not to wait until the gravel is scoured heavily. When exactly to replenish gravel is a topic for management targets but has been suggested when ca. 66% of the original area remains (Ugedal et al., 2019). This takes approximately 10 years in Aurlandselva. It also has to be considered that scoured gravel may accumulate downstream the sites, new spawning habitat may develop there (Merz et al., 2006). In Matreelva, the accumulation of fines may limit the ecological functioning of the spawning habitat in future, but the gravel is still providing good reproduction conditions after

18 years. Further research is needed to see if the sediment composition is getting insufficient or if it will be maintained by spawning fish who clean the substrate for fine sediments and for macrophytes (Velle et al., 2021). The very small accumulation of fines (0.02%) and small reduction of spawning area (3%) at the lake outlet site in Flekkeelva (energy slope 0.001) shows that the spawning habitat has functioned well for at least 13 years without maintenance. Fine sediment is trapped in the lake and scouring has not been severe. Since floods have only just exceeded HQ10, further monitoring is needed to measure life span and potential refilling needs.

To conduct a cost–benefit analysis of the gravel augmentations, we suggest dividing the monetary cost of enhancement by the average of gained spawning area and its life span. In Aurland, the measures had an

average cost of 114 NOK m^{-2} and functioned for 10 years, thus the costs were 11.4 NOK (1.14 €) m^{-2} year^{-1} so long. The site in Matreelva had a cost of 2,883 NOK m^{-2} corresponding to 160 NOK (16 €) m^{-2} year^{-1} (18 years). The site in Flekkeelva had a cost of 130 NOK m^{-2} and 10 NOK (1 €) m^{-2} year^{-1}. On average among the seven pure gravel addition sites in the present study (all despite Matreelva since the costs there included terrain adjustments), the cost–benefit was 11.2 NOK (1.12 €) m^{-2} year^{-1}. In the case of longer life spans for the measures, which is likely, these costs will be reduced accordingly. Due to low construction costs and long life span the gravel augmentations on these sites are considered as rather cheap and cost-effective measures. Costs for planning, design and monitoring could not been documented exactly since they were included in larger research projects combined with other tasks. This should be considered when estimating total costs of similar measures, especially since our results suggest that longevity demands proper mapping, choice of placement and design. In retrospective, planning costs were estimated for the 6 sites in Aurlandselva resulting in an estimate of 180.000 NOK (18,000 €), suggesting a doubling of the total costs when including planning in the case (2.28 € m^{-2} year^{-1}, so far). Monitoring of the six sites with the methods chosen are estimated to 130.000 NOK (13,000 €) per season.

The results contribute to fill knowledge gaps identified in the literature on lacking cost-efficiency data of river restoration and habitat enhancement (Roni et al., 2008; Friberg et al., 2016; Louhi et al., 2016; Roni, 2019; Staentzel et al., 2020). Because they are derived from case studies, the results cannot be transferred to other potential gravel augmentation sites. The test sites chosen were not representative for other gravel augmentations and do not reflect an average performance. The results rather show that well-designed gravel augmentations are not necessarily short lived as experienced in several studies in highly impacted rivers (Barlaup et al., 2008; Pander et al., 2015; Roni, 2019), but may function over decades depending on the river type, geomorphology, sediment supply, and river regulation. Our results indicate that low suspended loads and little discharge of fines have contributed to a long life span of spawning gravel augmentations. Other explanations for the observed longevity are the cleaning activity of spawning fish as well as a sufficient choice of gravel

placement and design balancing hydraulics over a broad flow range. The results may contribute to a more precise planning and maintenance of gravel bed spawning habitats, which is especially relevant for the implantation of the Water Framework Directive in the Europe, for mitigation measures in regulated rivers, as in the environmental design approach, but also for works in the context of the UN decade of ecosystem restoration and the many other attempts to improve habitat for fish in rivers. Spawning gravel augmentations may not only be considered as habitat enhancement, but may also function as a tool for process-based river restoration in some cases (Beechie et al., 2010; Pulg et al., 2013), for example, at lake outlets where gravel augmentations restore historic glaciofluvial gravel banks and can provide enduring spawning habitats. We recommend further investigations and data collections of such measures including costs to improve the knowledge base and to monitor the measures' total life span.

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