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EDGE OF FIELD MITIGATION POTENTIAL IN THE UPPER PIAKO CATCHMENT

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Introduction

Edge of field mitigations can complement on-farm actions to reduce agricultural contaminant losses. The cumulative effect of different mitigation options in the upper Piako catchment was evaluated using a water quality model (DELWAQ; Deltares,2023) coupled to a dynamic, semi-distributed hydrological model (HYPE; Singh et al., 2021). We also assessed optimised mitigation placement. The study looked at three types of mitigation options: woodchip bioreactors (Schipper, et al. 2010), constructed wetlands (Tanner et al., 2022) and filamentous algae nutrient scrubbers (FANS; Hariz, et al. 2024), both in-line and off-line (land-based). A method was developed to identify suitable sites for. sites for off-line FANS and constructed wetlands by considering proximity to, and height difference with, local streams, as well as presence of roads and infrastructure. Similarly, sites for in-stream FANS were identified based on stream sinuosity and bank height derived from LiDAR. For bioreactors, no precise device locations were identified. Instead, the likely extent of tile drained areas was delineated using existing methods and fed into the water quality model. Spatial processing methods developed in this project rely on readily available datasets, making them applicable to large parts of New Zealand and ready to help assess the applicability of FANS and wetlands in other pastoral catchments. We present modelled contaminant reductions across the contrasting mitigation options.

The study area of this project is the catchment of the Piako River at Kiwitahi (site EW-00057) in the Waikato Region. This is a 10,000 ha area for which LiDAR data was available when starting this project.

Siting of -in-line wetlands

In-line constructed wetlands turn sections of stream and surrounding low-lying land into wetlands. They target lower order streams and can be composed of several levels cascading into each other. Ideal sites are stream reaches with enough surrounding low-lying land for the wetland to expand into. Ideally, the size of a wetland should be at least 1% of its upstream area. In the Upper Piako Stream appropriate sites occur in shallow gullies where construction of low bunds can create a series of shallow wetlands constrained within the gully banks.

The siting methodology starts by selecting stream reaches draining between 20 and 50 ha. This avoids tiny streams and limits the catchment size such as to omit higher order streams. In the Upper Piako, this resulted mostly in 1st, 2nd and 3rd order streams, as defined in the River Environment Classification v2 (NIWA, 2019). Next, for each selected stream, surrounding land not higher than 0.5m relative to the closest stream portion was delineated. Known roads were masked out of the resulting low-land coverages and continuous patches were assigned a unique identifier. The area upstream of each path was delineated to and used to calculate the relative area of each path (path area / upstream area). Patches with a relative area under 1% were discarded. The resulting collection of wetland sites was further refined by excluding any sites without any productive land use in their respective upstream area. The final collection comprised 67 sites with a combined wetland area of 41 ha and a combined upstream area of 2192 ha.

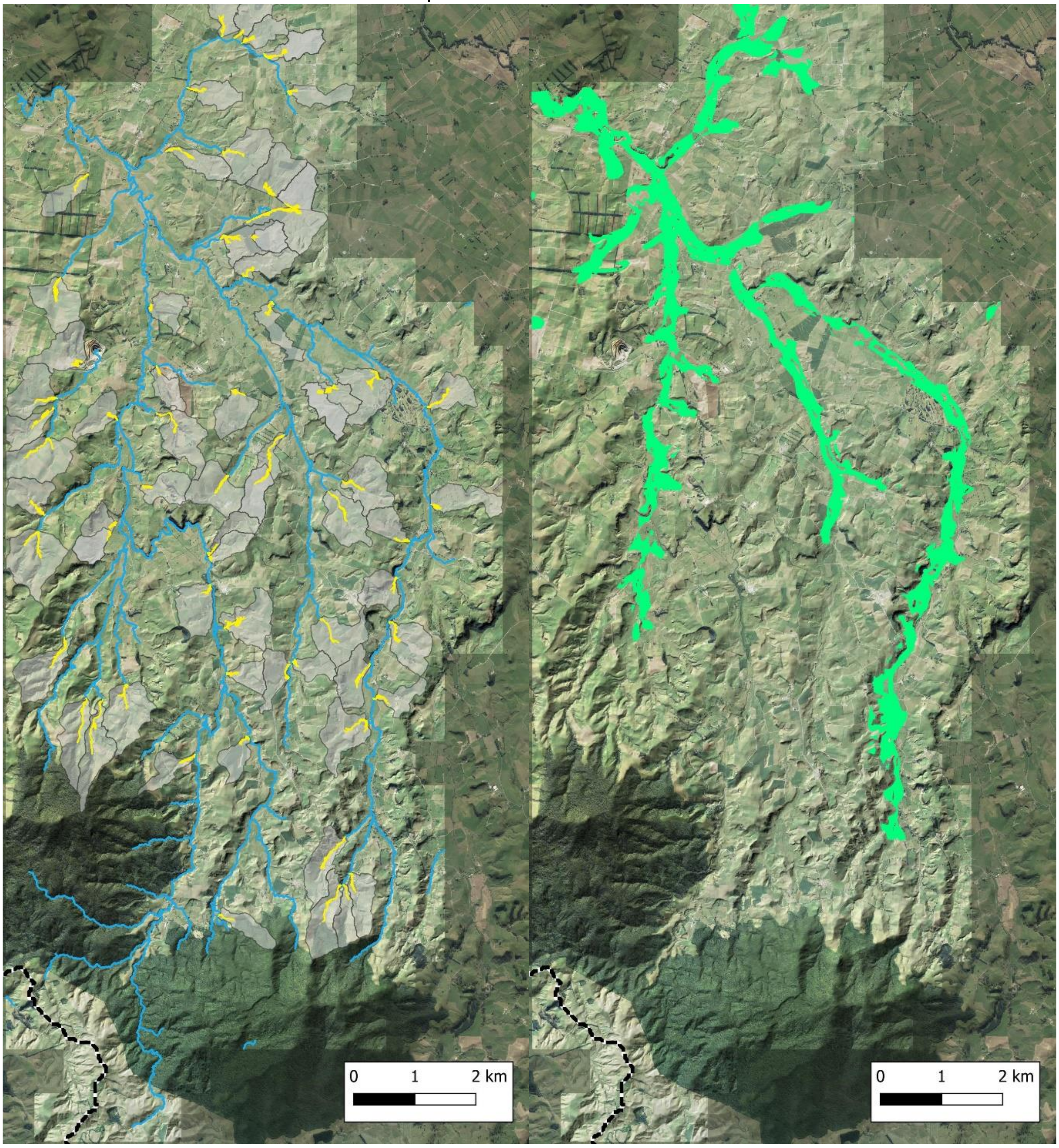

Figure 1: Potential sites for in-line wetlands (left) and estimated bio-reactors capture zones (right)

Siting of potential bioreactor locations and their capture zones

Woodchip bioreactors come in various forms such as denitrification walls intercepting sub-surface flows, in-stream bioreactors placed directly in channelised drains or buried woodchip volumes collecting tile drain effluent . Only the latter was considered in this study. Identifying precise locations for such bioreactors would require detailed knowledge of where tile drains (and their outlets) are located, which cannot be derived from readily available datasets. Instead, we delineated areas likely to be tile drained which could potentially be targeted by woodchip bioreactors. While not practical for actual device placement, this layer is still useful to include the capture zone and potential impact of bioreactors in the water quality model.

The generation of this coverage used an existing approach to map estimated artificial subsurface drainage (Pearson, 2015). The method classifies landscape into 5 classes: very low (1), low (2), moderate (3), high (4) and very high (5) subsurface drainage density based on slope, soil permeability and soil drainage capacity. Land with slopes higher than 8 degrees are assigned to the first (lowest) class, regardless of soil properties. Classes 1, 2 and 3 were discarded and remaining areas with slopes under 1 degree were excluded too to account for the fact that some hydraulic head is required to drive water through bioreactors. The final coverage spanned some 818 ha across the study area, concentrated around the main stream network.

Siting of in-stream FANS

In-stream FANS involve geotextile mats or ropes on which filamentous algae can grow. Such devices require relatively straight reaches with permanent flows and easy access for harvesting and maintenance, which excludes reaches with high/steep banks or abundant vegetation.

A stream network was extracted from the 1m DEM. To exclude low order streams with insufficient flow and dimensions, the stream network was constrained to cells with a minimum of 2000 ha upstream area. Local stream bank height was assessed for each stream by determining local height differences within 10m either side of a stream cell. This was achieved by sampling all elevation points within 10m of a stream cell and calculating the local height difference (LHD) for each of those points. The LHD of each point was derived by subtracting the lowest elevation within a 4m window around the target point from the elevation of the point itself. The highest LHD value within 10m of a stream cell was assigned to that stream cell. Stream cells with an assigned LHD over 2m were marked as unsuitable for in-stream FANS. The difference between DSM and DEM elevations was used as a proxy to infer presence and height of vegetation (or other obstacles) around stream reaches. Vegetation was deemed to become an accessibility issue if more than 50% of the area within 5m of a stream cell had vegetation exceeding 50cm.

Continuous straights of suitable stream banks were further filtered based on length and straightness. Reaches less than 50m in length were discarded. A straightness index was derived for the remaining reaches based on the ratio of their extent and stream length. A cutoff value of 1.5 was determined through visual assessment to differentiate straighter reaches from more meandering ones.

Across the study area, a total of 13 reaches matching all selection criteria were identified for a total combined length of 1,100 m. Local stream widths at minimum annual low flow (MALF) were retrieved from NZ River Maps (NIWA, 2022) and multiplied with reach lengths to derive stream area at MALF. Assuming in-stream FANS would cover up to half of the MALF stream width, there were 2774 m^2 available for FANS.

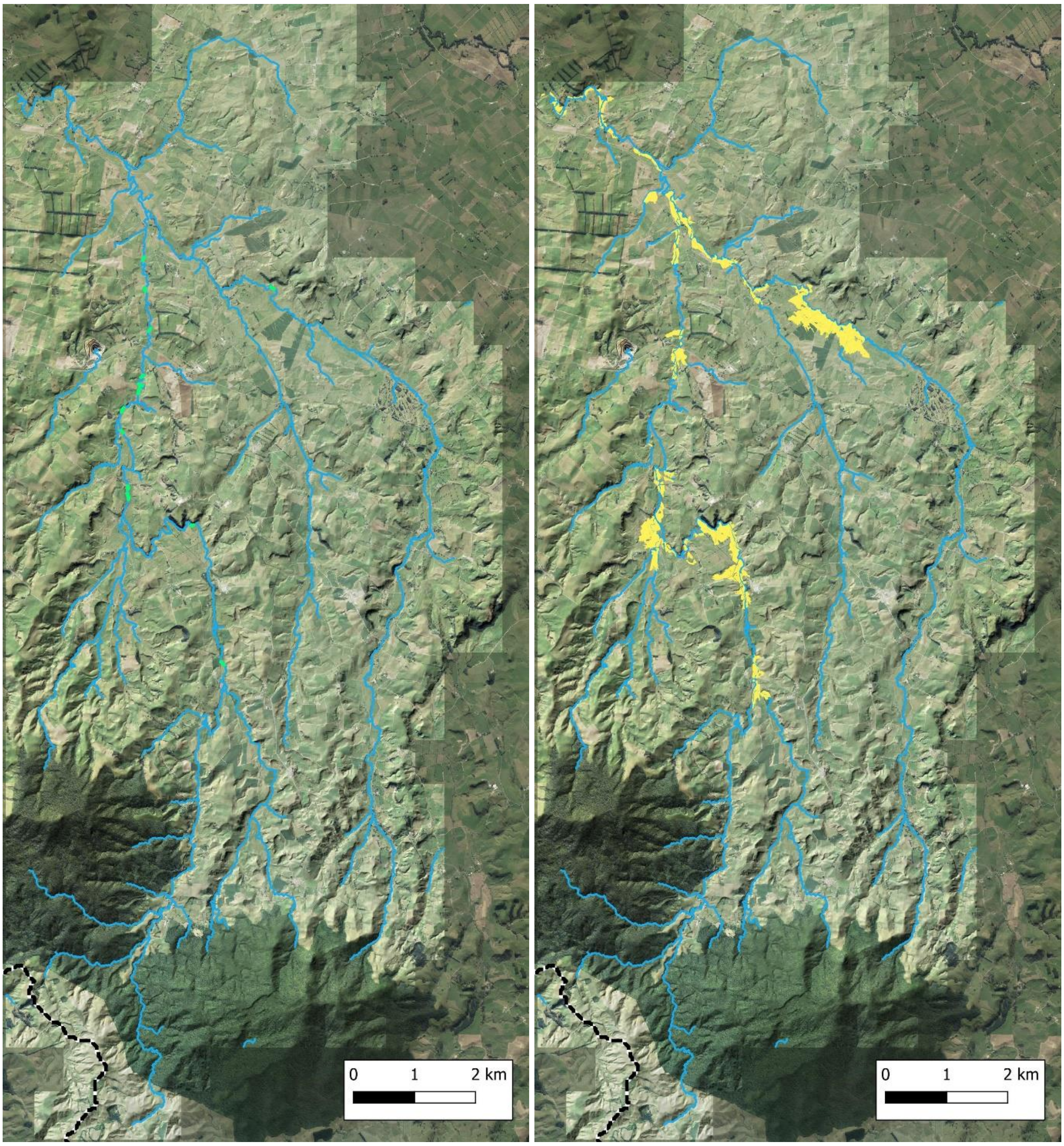

Figure 2: Potential sites for in-stream FANS (left) and off-line FANS or wetlands (right)

Siting of off-line FANS and constructed wetlands

Off-line sites refer to land-based FANS or constructed wetlands. Such sites require a gently sloping patch of land in proximity of a stream to allow for low (preferably nil) energy requirements for diversion of stream water through the device. Alternatively, pump driven systems could be placed in areas up to 3m above the stream. Given their larger size, they are generally more suited to higher order streams/drains providing enough flow and flatter land.

The 1m DEM was used to delineate areas with an elevation difference, relative to the nearest stream cell, of up to 3m. Land with slopes exceeding 5 degrees was discarded and the remaining coverage got grouped into continuous patches, also considering the presence of mapped roads. Of the resulting patches, only the ones with a total area of at least 0.1 ha were retained. Distance to the nearest stream and distance to the nearest building (proxy for power source) were calculated for each patch. A total of 84 potentially suitable sites were identified, for a total available area of 113 ha.

Catchment model

The purpose of the water quality model is to assess the potential impact of identified edge of field mitigation opportunities on nitrogen loads.

Hydrology

An existing hydrological model of the Upper Piako catchment, developed by NIWA using HYPE (Singh et al. 2022) software (SMHI, 2021), was repurposed for this project. HYPE models are semi-distributed, meaning they are composed of several interconnected basins. The spatial schematisation at which the model operates is identical to the basins delineated in REC 2. Each basin is further subdivided into various computational units representing different surface and sub-surface compartments. Partitioning of flows across surface and sub-surface flow-paths can be parameterized at the basin level and calibrated based on observed hydrographs. The modelled domain starts downstream of Morrinsville and includes all areas upstream of that point, including our study area. The model was run with a daily timestep, generating daily outputs for a period of 4 years (2012-2016).

Water quality model

The dynamic water balance generated by the HYPE model was used to build a DELWAQ (Deltares, 2023) model of the same area. A land use layer was used to derive annual nitrogen loss for each basin. The annual losses were distributed in time based on the temporal distribution of observed in-stream concentrations. A first-order decay process was added to DELWAQ segments corresponding to HYPE's third soil layer (one of HYPE's compartments) to reproduce nitrogen load attenuation between rootzone losses and in-stream loads.

Mitigations

Custom processes were implemented in DELWAQ to represent each mitigation option. All mitigation options were modelled using a zero-order specific removal rate (SRR), scaled by site-specific attributes.

For land-based FANS, the specific removal rate was set to 0.33 g/m2/d, informed by data collected from pilot scale trials (Hariz et al. 2024). The available area for each site was restricted by the available stream flow, assuming an intake of half the mean annual low flow (MALF, retrieved from NZ River Maps) of targeted stream and specific inflow of 0.25 l/minute per m^2 of FANS. The restricted total available area within the study area from 113 ha to 25.2 ha.
No trial data was available of in-stream FANS so their SRR was set to the same 0.33 g/m2/d used for land-based FANS. The effective area of each in-stream FANS site was obtained by multiplying the sites stream length with its with at MALF.

In-line wetlands had site-specific SRR values as a function of relative wetland area (RWA), the ratio between wetland area and upstream area, according to following relation: SRR = -0.158 * ln(RWA) – 0.2948. This resulted in SRR values ranging from 0.18 to 0.43 $g/m^2/d$ for 5% and 1% relative area values respectively. Wetlands with a relative area outside of this range were not included in the model.
Bioreactors were modelled using a specific removal rate of 3 g/m3/d (expressed per unit volume of woodchips, pers. comm. Lee Burbery), and 2 correction factors: one representing the areal fraction of a basin within the mapped capture zone of bioreactors and the other representing the estimated fraction of subsurface flow captured by the drainage network.

All removal fluxes were constrained by the available nitrogen mass in targeted segments.
The bioreactor process was configured to act on DELWAQ segments corresponding to HYPE's local stream compartment. Land-based FANS, in-stream FANS and in-line wetland processes were enabled in DELWAQ segments corresponding to HYPE's main river components.

Modelled reductions

Two model runs were performed over the full 4-year period, one without any mitigations and the other including all 4 where suitable, as determined by the GIS mapping. Loads and concentrations at the outlet of the modelled catchment (site EW-00057) were compared to assess the impact of modelled mitigations.
Observed and modelled concentrations for site EW-00057 are shown in Figure 3, together with modelled flows. Overall, the mitigations achieved a 16% load reduction while the median concentration (over the simulated 4-year period) was reduced by 98%. This last figure needs to be interpreted carefully because the model tends to overestimate the reference concentrations during low flow conditions.

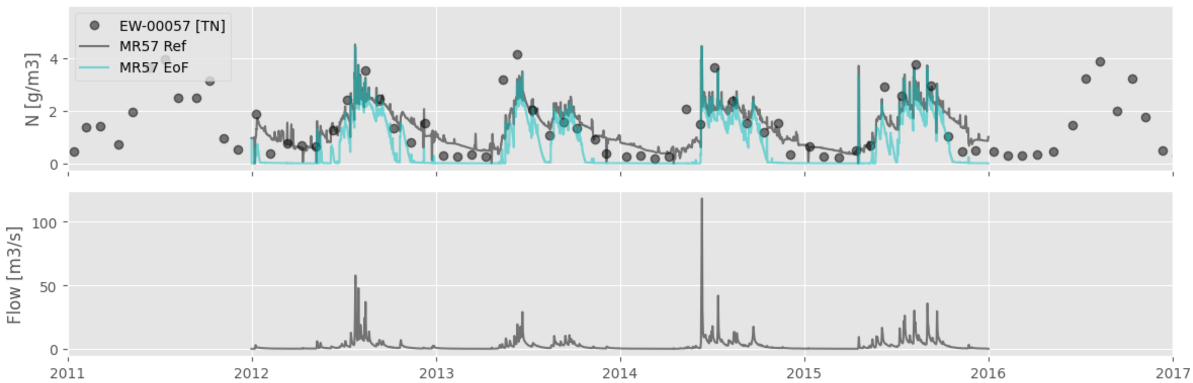

Figure 3: Top: Observed monthly TN sample concentration and modelled concentrations with (cyan) and without (grey) edge of field mitigations. Bottom: HYPE-modelled flows in m3/s at location of site EW-00057 (Piako at Kiwitahi).

The values in Table 1 show the combined size of each mitigation option across the study area. For bioreactors, this is the area of the capture zones. Combined with specific removal rates, this gives a potential reduction achievable under ideal conditions (i.e. no N shortage). The third column shows the modelled reduction as an absolute value and expressed as a percentage of total achieved reduction (across all mitigation options). The last column shows the modelled reduction as a percentage of the potential reduction.

Land-based sites contributed 86% of the achieved load reduction, on average operating at 53% of their capacity. In-line wetlands, despite having a higher potential, only contributed 10% to the achieved load reduction, reaching only 4% of their capacity. In-stream FANS had the best utilization (77%) but only contributed 1% to the overall load reduction because of their relatively smaller size. Finally, bioreactors contributed 3% of the load reduction.

Table 1: Potential and modelled N removal

	Combined size	Potential removal (kg N / year)	Modelled removal (kg N / year | % of total removal)	Modelled / potential
Off-line FANS	25 ha	30,000	15,991 | 86%	53%
In-line wetlands	41 ha	49,000	1,816 | 10%	4%
In-stream FANS	2770 m2	334	257 | 1%	77%
Bioreactors	818 ha	*9,000	488 | 3%	5%

*Assuming 10 m^3 of woodchip per drained ha

The somewhat underwhelming load reduction is explained by the temporal distribution of N loads. With high concentrations coinciding with high flows, the bulk of the N load flows through or by the mitigation sites in relatively brief periods, outpacing their removal capacity. At the same time, lower concentrations coinciding with low flow periods means there often isn't enough nitrogen available to leverage the full removal capacity.

The noticeably poorer performance of in-line wetlands in this specific scenario is attributed to them targeting low order streams which, in this study area, only receive a tiny fraction of their basin's water volume. The HYPE-modelled hydrology shows that, on average, 75% of the flows between 1st and 2nd order basins in that area occur through sub-surface flow paths. This figure drops to 35% for flows between 2nd and 3rd order basins and down to 5% at the outlet of the study area (a 5th order stream).
Finally, it is important to note that the model does not account for possible hydrological changes resulting from the presence of edge-of-field mitigations. For instance, in-line wetlands are expected to increase residence times and storage capacity, which would at least somewhat smooth out the temporal distribution of N loads, boosting the performance of downstream off-line sites as well. This effect is not captured in the model.

Conclusions
Siting methodologies relying on readily available high resolution elevation data were described for offline sites (FANS and constructed wetlands), in-stream FANS as well as in-line wetlands. The impact area of woodchip bioreactors was estimated using slope and soil data. A dynamic, semi-distributed catchment model was used to assess the cumulative impact of mapped mitigation sites on nitrogen loads. The results showed that local hydrology is a key determinant of edge-of-field efficiency and should be considered when assessing the applicability of edge-of-field solutions in a particular area.

Acknowledgements
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