Advice Memo: Guidance on time frames of water quality responses to the implementation of good management practices

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The Otago Regional Council is currently following government advice and legislation to improve water quality in Otago. This document draws on literature to explain nutrient lag times.

Anthropogenic sources of nutrients were identified as the main factor responsible for lowering water quality in the region. Nutrient sources can either be identified as point sources, coming from one single point in the environment, or diffusive sources, when several sources in a landscape contribute nutrients over a spatial scale to surface and groundwater. Examples for point sources are wastewater discharges from urban or industrial facilities, stormwater outlet pipes and sewage tanks. Nutrients coming from these sources can often be identified with relative ease, i.e. a visible pipe discharging brown water might indicate malfunction of a wastewater treatment plant, or are discovered by ongoing monitoring, i.e. spikes in faecal bacteria concentration can indicate leakage from sewage tanks. Mitigation of high nutrient loads from point sources is often achieved by upgrading of facilities and/or setting more stringent limits on discharges. These mitigating actions, lowering nutrient loads to freshwaters, often lead to immediate responses in water quality and often give the false impression that mitigating actions work on very short time scales (days to months).

Conversely, diffusive sources are not only hard to identify, it also takes more time for mitigating actions to show effects. Examples of diffusive nutrient sources are fertilizers applied in agriculture, pesticides applied in agriculture and forestry and road runoff. These nutrient sources are often only controlled by the implementation of management practices such as stock exclusion or reforestation of eroded land with native forest. In areas that are intensively farmed since several decades, diffusive sources are not only influencing water quality directly, for example via runoff, but also as 'legacy' nutrients that are stored within the ecosystem (1). These legacy nutrients persist in several forms in the environment and contribute steadily to the total nutrient input that freshwaters receive.

Several scientific studies tried to identify the magnitude of accumulation and preservation of these nutrients in agriculturally impacted landscapes over time and the following literature review is aimed to give the reader an understanding of legacy nutrient 'lag' times. Lag is the time nutrients are retained in an ecosystem, following nutrient increases above the natural concentration by anthropogenic activity (2). Nitrogen (N) and phosphorous (P) are identified as the two most important nutrients that are derived from agricultural practices (1). Both nutrients have the potential to smother freshwater quality and lower ecosystem functions. The effects of these nutrients on water quality go beyond the frame of this review and are already explained well in the scientific literature (1, 3–7) and the following will focus mainly on legacy nutrient lag times.

As a first step, it is important to identify that nutrients can exist in several chemical and physical forms in the environment and that these forms influence the respective time a nutrient is present in a system. For example, in soils biogeochemical legacies of N are present as soil organic nitrogen and P is often present bound to particulates, but both can become available over time (8–11). In addition, nutrients can persist in more soluble forms in groundwater and can reach surface waters via the hydrological cycle. This means that N, as well as P, are both stored in soil and groundwater but have different lag times, depending on their chemical properties (2, 9, 12) (Figure 1). The timescales that nutrients are stored can differ widely. For example, reference (13) found that lag times for positive water-quality responses to occur in mixed agricultural (several different agricultural practices) meso-catchments (1–100 km^2) ranged from 1.5 to 10 years. In comparison, the Clutha catchment, the largest in Otago, has an area of ~20.000 km^2 (14), the Taieri catchment measures ~6000 km^2 (15) and the Pomahaka catchment is ~2000 km^2 and lag times are expected to increase with catchment size (16).

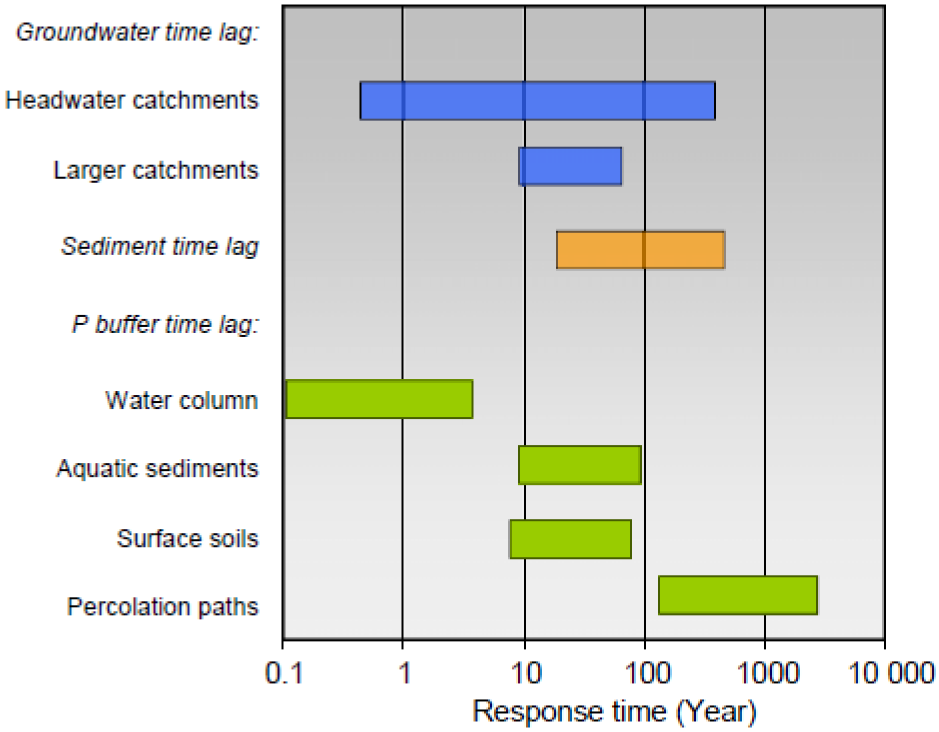

Figure 1: Estimated lag times for nitrogen and phosphorous in different natural nutrient stores. Figure taken from (12)*.*

It is further important to distinguish between hydrological legacies (i.e. groundwater) and biogeochemical legacies (i.e soils). Nutrients enter groundwater via diffusion through the soil layer and the time nutrients take to be flushed out of groundwater stores are at minimum the time that groundwater resides in an aquifer. The existence of the hydrologic lag time is well accepted, with a variety of hydrogeologic controls having been found to result in travel times ranging from days to decades (11). This means that in the UK nitrogen is continuing to increase in some lowland aquifer regions due to fertilizer N inputs from over 50 years ago (17) and a study conducted on lag times in the Mississippi catchment estimates N legacy lag times of 35 years from the point of total cessation of inputs (11). To quantify NZ specific N lag times for 77 river catchments from 1990 to 2018 reference (18) took catchment specific hydrological groundwater residence times into account and estimated lag times of 1 to 12 years (median 4.5 years) for legacy N in NZ groundwater. However, this study did not account for the total depletion of N in groundwater as suggested by (12) which is generally assuming that N residence time is three times the hydrological residence time. This would mean that N in NZ groundwater has an approximate lag time to changes in management practices of 12-36 years. The NZ specific study (18) also notes that longer lag times than found in their study were found via other data driven approaches. Lag times for N in other studies range between 2 and 50 years, depending on lithology, groundwater flows and location/elevation (19–21) and all studies note that biogeochemical processes could likely extend the tail of N lag times calculated.

For P legacies a study conducted in the UK suggested that it could take up to 50 years to reduce the P that accumulated in soils since World War II with the current rates of P removal by crops (8). Several studies conducted on P residence times following agricultural practices, derived at biogeochemical residence times of 7.5 to 15 years (9). Additionally, a lag time of <1 year up to several decades for P stored in bulk sediment of river channels is reported by several studies (9). Reference (22) calculated the phosphorus buffering capacity threshold based on accumulation data over 110 years in 23 watersheds of a large North American river basin with globally representative agricultural soils and concluded that it would take between 100 to 2000 years to eliminate legacy P by soil runoff (Figure 2). However, they also note that "*The estimated time to return to a level of low risk for P transfers to surface waters may be overestimated by these depletion curves because the model does not account for the more permanent storage of P that is strongly occluded by soil particles*". A report by Jarvie (10) makes a very good effort at explaining P legacies and lag times in general and the interested reader is referred to this article and reference (12) in particular to gain further insights. The major lag times for legacy N identified by (10) are shown in Figure 3.

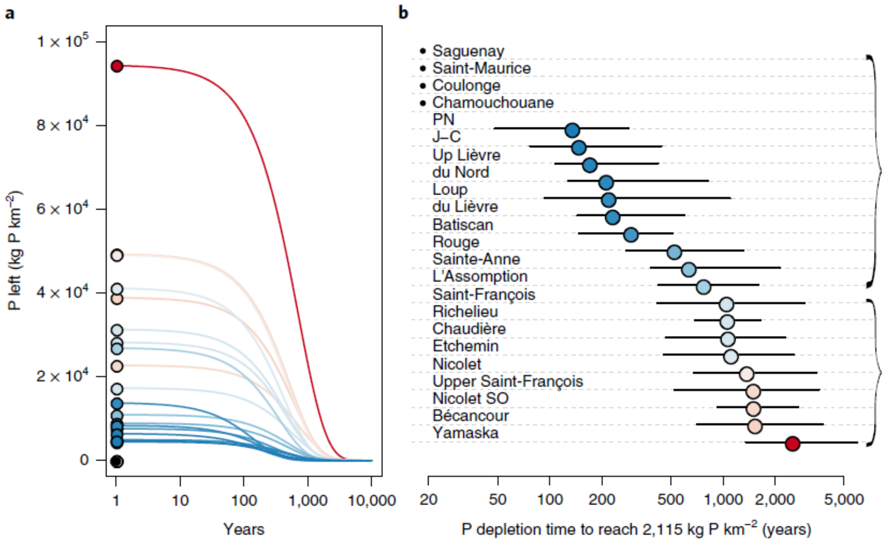

Figure 2: Lag times in P retention until soil P concentrations equal to those pre 1901 are reached in different North American watersheds (right). Figure taken from (22).

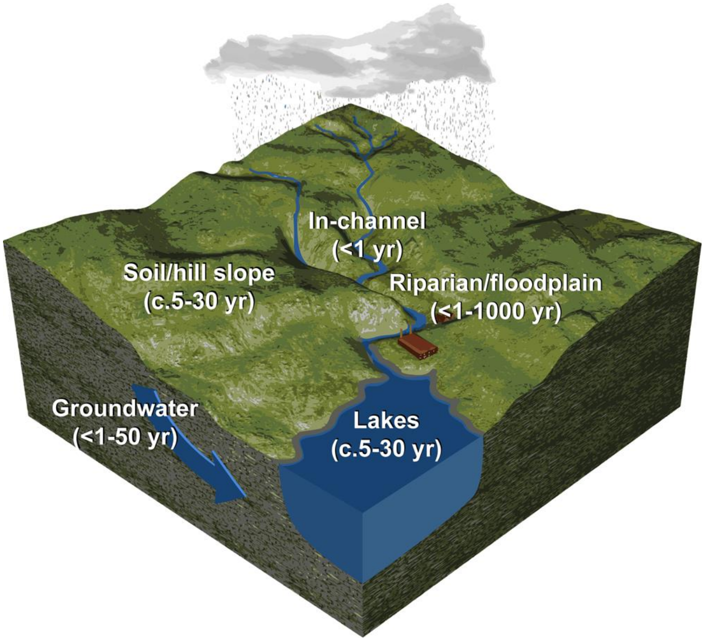

Figure 3: Typical time scales for phosphorus (P) retention and recycling in watershed and waterbody legacy P stores. These result in a continued chronic release of "legacy P", impairing downstream water quality over time scales of years to decades, or even centuries (from data provided by Sharpley et al, 2013). Figure taken from (10)*.*

The processes that lead to the accumulation of N and P and the associated risk factors are discussed by (12) and Figures 4 and 5 are taken from this reference to help the reader of this summary understanding background processes. Acknowledging the timescale these processes work on and the inability to sample some of them, modelling is often the only way to estimate nutrient lag times. An explanation of existing models would go beyond the scope of this review, but the interested reader might want to refer to (12, 16, 23, 24) and references therein to enhance their knowledge on modelling approaches. For example a modelling exercise targeting N legacies in a 502 km^2 watershed estimated that of the N surplus applied to soils between 1950 and 2016, 25% accumulated at the root zone, 14% accumulated in groundwater, 34% were denitrified and 27% were lost via riverine transport. For the future scenario modelled, a 100% reduction in fertilizers led to a 79% reduction in stream N load but the results also suggested that it would take up to 84 years to achieve this reduction (23).

With nutrient legacies in mind, one needs to further consider the time it takes for farmers to implement best management practices on their farms. A study conducted on agricultural innovation in Australasia found that average peak adoption time is around 16-20 years from implementation of policies (25) which means that it is likely that reduction of legacy nutrients in a system starts to occur several years after policy implementation only. Subsequently, targeted reductions of nutrient concentrations in freshwater will take even longer (policy implementation time + nutrient lag time) until measurable in the environment.

Conclusively, it is also important to note that existing legacies offer the potential for agriculture to reduce fertilizer input, and thereby costs, while retaining crop yield. This is further discussed by (2) and references therein:

"Strategy 2—legacy as a resource. The existence of soil N legacies implies that, where soil N availability is high, lower fertilizer application rates may not lead to notable declines in crop yields. Indeed, a global meta-analysis of N sources to cereal crops used 15N-labelled fertilizer to show that only a fraction of N in crops (41% for maize, 32% for rice and 37% for small grains) is from current-year N fertilizer while the remaining comes from mineralization of soil organic N. Field studies also indicate that lowering fertilizer application rates does not necessarily impact crop yields, alluding to the existence of legacy N stores in the landscape."

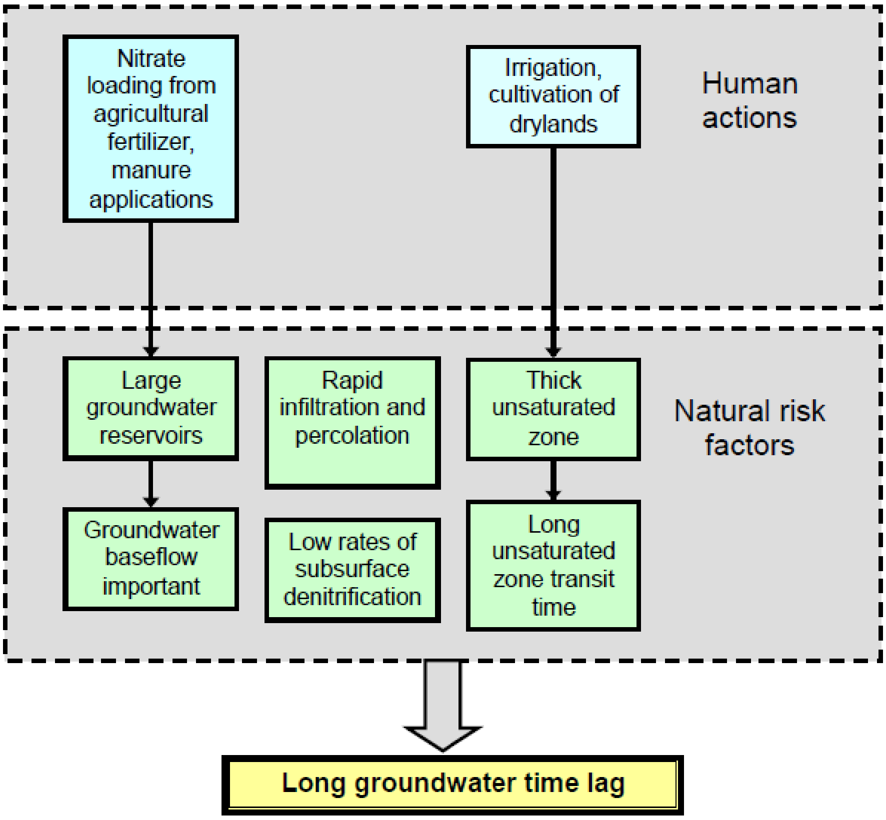

Figure 4: Factors leading to the accumulation of N in groundwater. Figure taken from (12).

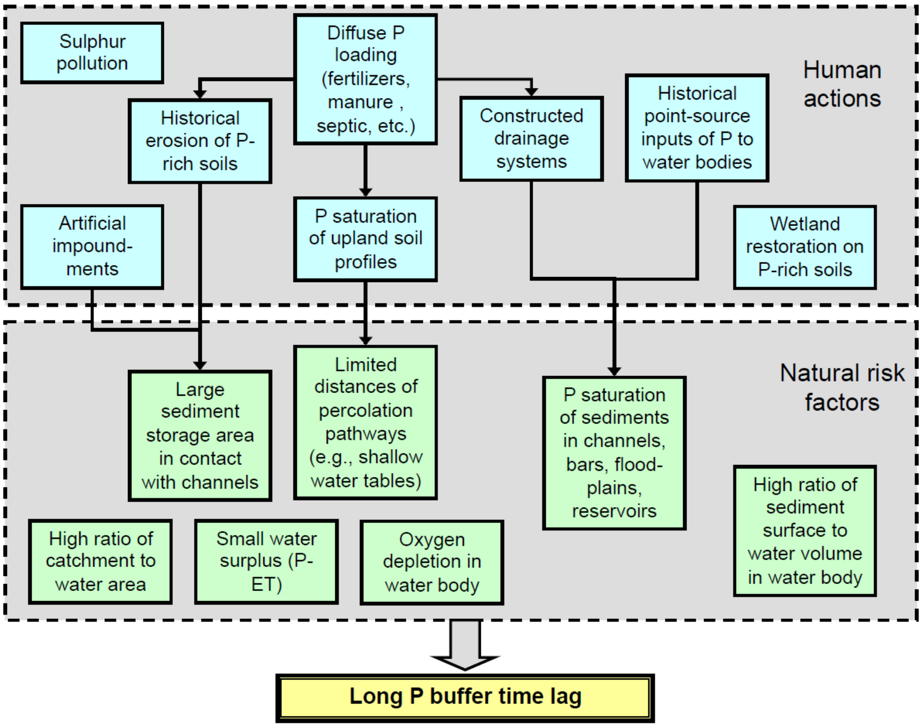

Figure 5: Factors leading to the accumulation of P in groundwater. Figure taken from (12).

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