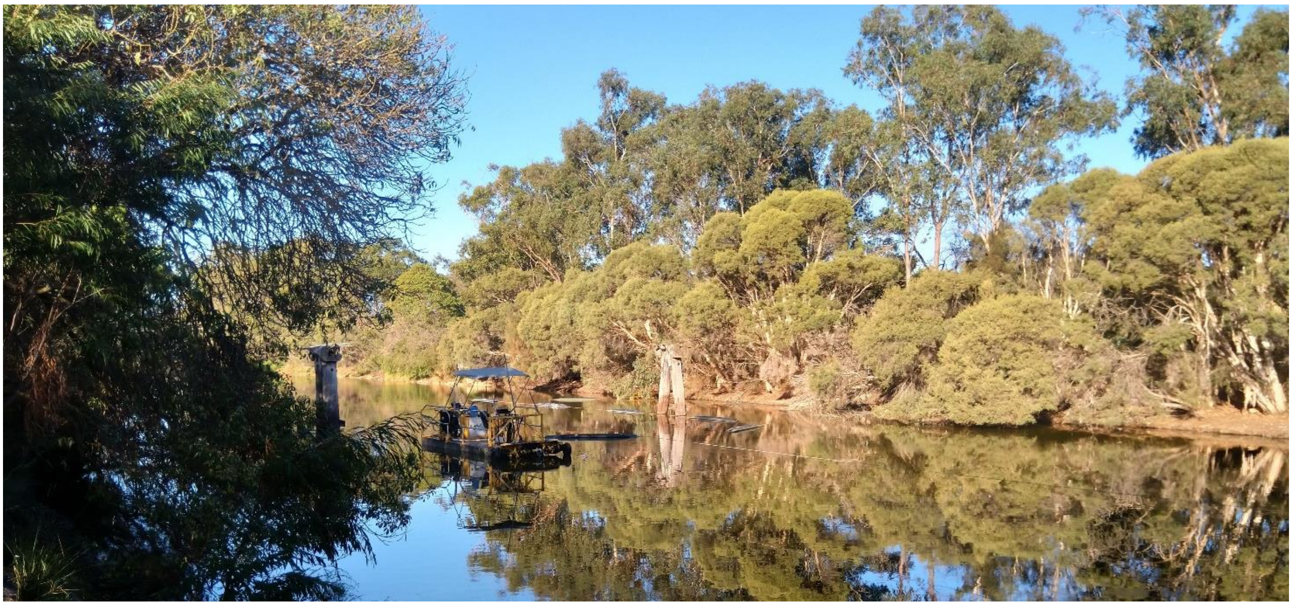
Peer Review of the Living Streams Concept



Report prepared by:

David P. Hamilton, Michele A. Burford, Fran Sheldon

Australian Rivers Institute, Griffith University

For:

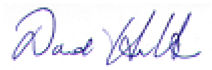
City of Busselton

June 2022

Approvals

Author signature: Date 30 July 2022

Author Name: David Hamilton



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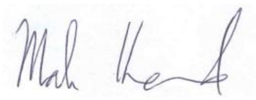
Name: Mark Kennard



Author contact details

✉ david.p.hamilton@griffith.edu.au

https://www.griffith.edu.au/australian-rivers-institute

Report citation

Hamilton DP, Burford MA, Sheldon F. 2022. Peer Review of the Living Streams Concept. ARI Report No. 2022-008 to City of Busselton. Australian Rivers Institute, Griffith University, Brisbane

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Table of Contents

Figure captions

1. Executive summary

The Lower Vasse River (LVR) is a highly seasonal freshwater river system which is usually protected from ingress of estuarine brackish water in summer by a range of controls, including natural wetland vegetation and a downstream weir. The hydrology of the system is also strongly modified by an upstream diversion drain. The system is seasonally eutrophic, with algal blooms attenuated in late winter and early spring by the lower temperatures and seasonal flushing flows that do not allow adequate time for phytoplankton to proliferate despite strongly elevated concentrations of dissolved inorganic nutrients (nitrate, ammonium, and phosphate). As temperature increases and flow recedes during summer, cyanobacteria grow rapidly and remain resident in the LVR, taking up available nutrients and depleting them to concentrations that ultimately limit their further proliferation, but attaining concentrations that allow them to form blooms by floating to the water surface in calm conditions.

Alluvium was commissioned by the City of Busselton to develop a Living Streams concept design for the LVR, to reduce the extent, severity, frequency and duration of toxic cyanobacterial blooms. The Griffith University authors reviewed the Alluvium reports and offer various levels of endorsement and critique on the recommendations made in the reports. The Alluvium reports include three main stages, which recommend 1) removal of sediments extending to different distances upstream, 2) recirculation of water through one or two modified and/or constructed wetlands, and 3) construction of in-stream vegetated structures to reduce volume and create wetland habitat within the LVR.

The Griffith University reviewers endorse a staged intervention approach recommended by Alluvium but do not agree with the recommended implementation of all stages of the Living Streams concept, at least not until Stage 1 is implemented in full and its effects assessed. Dredging of the whole reach of the LVR is considered necessary to adequately offset the very high nutrient loads received in winter-spring flows from the catchment. A large proportion of these nutrients is likely to reside in the LVR and be recycled during summer-autumn, enhanced by anoxia of bottom waters, and fuelling cyanobacteria blooms. The dredging therefore needs to be accompanied by a major focus on nutrient load reductions from the catchment and use of a flocculant (e.g., Phoslock®) to offset potential negative impacts of dredging (i.e., from resuspended sediments) and in a broader application in the river system, to increase the inactivation of phosphorus present in the water column and bottom sediments. Appropriate safeguards and mitigations for the effects of dredging are required in addition to the flocculant application.

Stage 2 involves recirculation of water through one or two modified/constructed wetlands. We recommend this stage should not be undertaken until Stage 1 is completed and assessed. There are risks with Stage 2 that the wetland enhancement and construction will not meet expectations for cyanobacteria control because of insufficient duration of shading of cyanobacteria in the wetland (five-day residence time) that will not offset their ability to grow in the LVR (20-day residence time). Ongoing operational costs from pumping water from the LVR into the wetlands are a further consideration. This option may reduce nutrients, but hydrological and hydraulic modifications may provide an additional lever, noting that culverts have already been implemented to reconnect the Vasse Diversion Drain to the Lower Vasse River and extend the period of flushing freshwater flows without undue increase in the risk of flooding in the LVR.

At this stage the reviewers do not recommend implementing Stage 3, involving construction of in-stream vegetated structures and associated wetland habitat. The reviewers believe it would be useful to assess Stages 1 and 2 effects before proceeding with Stage 3. The Stage 3 in-stream structures may reduce the depth of the river in some places and impede flushing flows in some localised areas. These factors would need to be assessed against some increase in the proportion of the total water volume within the wetlands and which would be partially shaded and therefore limit cyanobacteria growth.

2. Background

The City of Busselton requested Griffith University to review reports by Alluvium (2021a, 2021b) who were originally commissioned by the City of Busselton to develop a Living Streams concept design for the Lower Vasse River (LVR) in Busselton, Western Australia. The aim of the concept design is to reduce the extent, severity, frequency and duration of toxic cyanobacterial blooms.

The purpose of the peer review is to provide an evaluation that:

1. considers the validity of the design science, inputs and assumptions;
2. addresses whether the design objectives have been met;
3. identifies strengths and weaknesses of the design;
4. assesses whether the proposed design provides best triple bottom line value; and
5. if appropriate, makes high level suggestions for improvements/amendments to the design.

The Alluvium report included:

1. building on previous management and research related to the LVR and relevant other research and case study literature;
2. considering and responding to environmental, hydrological, physical and heritage site constraints;
3. incorporating the principles of a Living Stream approach as outlined in the Lower Vasse River Waterway Management Plan (LVRWMP) and including or facilitating implementation of other management strategies as appropriate.
4. building on existing hydrological modelling work by Department of Water and Environmental Regulation and undertake more detailed modelling of hydrology and hydraulics to ensure feasibility in terms of flood prevention and stability of works.
5. allowing for enhanced interaction between people and the river;
6. defining the regulatory framework for implementation;
7. highlighting areas requiring further research or trials; and
8. providing for prioritised, staged implementation.

Alluvium identified three stages of the concept design for Vasse River restoration, targeting a 3.3 km length of the LVR from the Butter Factory weir to the Busselton bypass; the LVR itself extends further to the Vasse Diversion Drain. Stage 1 recommended the removal of sediments between the Butter Factory weir and the old boat ramp (or to the Busselton Bypass). Stage 2 included recirculation of water through a constructed wetland near the light industrial area. Stage 3 involved the construction of in-stream vegetated structures that displace water and create more water within the wetland habitat. This review has focused on these three stages and has also embedded the work within a broader consideration of the current state of the LVR.

3. Evaluation

3.1 Introduction

The LVR has been extensively modified hydrologically, mostly for the purpose of flood control for the City of Busselton via the Vasse Diversion Drain but also with a weir at the Butter Factory (constructed in the 1930s), to prevent upstream ingress of saline water into the freshwater region of the LVR Weir and maintain water levels in river in summer. The weir boards were permanently removed in 2018, with subsequent ingress of salt water linked to management of the Vasse Estuary (artificially higher water levels to manage water quality, reduce the risk of fish kills and improve amenity for residents) as well as the removal of the weir boards. Past ingress of saline water has led to deoxygenation of bottom waters and has likely been associated with increases in cyanobacterial blooms from anoxia-stimulated nutrient releases as well as death of freshwater mussels (Carter's freshwater mussel, listed as Vulnerable under the Environment Protection and Biodiversity Conservation Act). River diversions for flood control, along with agricultural development have strongly reduced freshwater flow in the river, with compounding effects from the build-up of organic matter and nutrients in the bottom sediments, and eutrophication of the LVR (e.g., Fig. 1). These factors act synergistically to contribute to cyanobacteria blooms. Additionally, rainfall in southwest Western Australia has declined in recent years, due to cyclical climatic patterns and long-term climate change that is consistent with global and regional climate model projections.

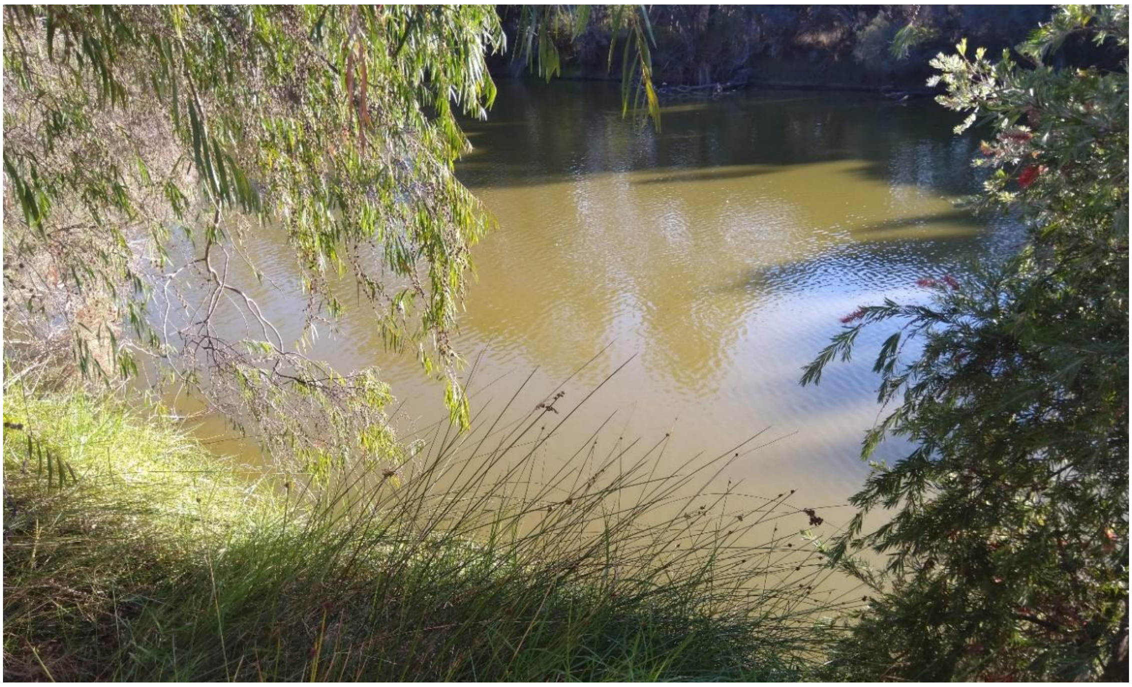

Figure 1 Lower Vasse River near City of Busselton council buildings, May 9, 2022. Note the highly brown-green colouration of the water, indicative of eutrophic conditions, but no apparent surface-reaching cyanobacteria blooms at the time.

Alluvium report - critique

The Alluvium report (Alluvium 2022a) identifies the causes of cyanobacteria blooms in the LVR. Section 2.2 (Causes of blue-green algae blooms) lists five of the causal factors for cyanobacteria blooms. The first factor is the initial cell count in the water column at the beginning of the growing season. We do not necessarily disagree with the assertion that this is an important determinant of the bloom but point out that cyanobacteria in the sediments may potentially contribute substantially to the initiation of blooms. For example, *Microcystis* spp. can overwinter in vegetative form in the sediments for months or even years, while *Dolichospermum* can germinate from akinetes in the sediments, to colonise the water column under favourable conditions (Borges et al. 2016). The assertion in the report that there is a "chemocline where cyanobacterial cells persist through the flow season" and that "a substantial number of cells are more or less permanently present" is highly debatable. Persistence of cyanobacteria in the bottom sediments is a more plausible mechanism to support the rapid onset of blooms in spring or early summer. We highlight this point because it has important implications for dredging operations that, while primarily targeting removal or organic material and associated nutrients, may also beneficially remove stocks of cyanobacteria cells or akinetes in the bottom sediments.

In Section 2.2 it is also stated that "cyanobacteria can fix nitrogen". In freshwater, only heterocystous cyanobacteria can fix nitrogen (i.e., those with specialised cells that are used to take dissolved nitrogen gas in the water and incorporate it into cellular tissue). Heterocysts normally only develop and persist under nitrogen (N)-limited conditions when the supply of inorganic nitrogen limits growth (Oliver et al. 2012). *Dolichospermum, Aphanizomenon* and *Rhaphidiopsis* are genera of cyanobacteria that can potentially fix N, while *Microcystis* cannot, although the '*Microcystis* biome' contained within the *Microcystis* colony sheath may contain some bacteria with ability to fix N (Cook et al. 2020).

Section 2.2 of the report suggests using isotopic identification of phosphorus and nitrogen sources throughout the growing season to understand the formation of cyanobacteria blooms. We agree that this methodology may be useful for nitrogen, particularly for understanding the relative contribution of N fixation to the cyanobacteria cell N quota and to total nitrogen in the water column but it is likely to required skilled assessments for interpretation of phosphorus sources and cycling.

Factors 4 and 5 identified by Alluvium (2022a) to cause cyanobacteria blooms include water temperature and stagnation of the water body, respectively. These two factors are associated with water column stratification, where a warm (or fresh) surface layer overlies of colder (or saltier) layer underneath. Stratification plays an important role in bloom formation as most bloom-forming cyanobacteria are buoyant and can float to the surface under calm conditions when they are not entrained in vertical turbulent motions during periods of mixing. Small gradients in temperature or salinity are often considered as an indication that there is no stratification but, as shown by Sherman et al. (1998), gradients of temperature of as little as 0.05 ^{o}C between adjacent vertical thermistors (a temperature gradient of 0.25 ^{o}C over 1 metre) can be sufficient to induce the stratification necessary for buoyant cyanobacteria to float, when they would otherwise be distributed more evenly through the water column. The Reviewers therefore consider that a careful assessment of stratification is required aligned with the occurrence of cyanobacteria blooms.

Section 4.1 (Ecological principles) of the Alluvium (2020a) report promotes the concept of recreating the historical connection between the LVR and the surrounding seasonal wetlands within the constraints of urban infrastructure and flooding. It could have also been noted here that the Butter Factory weir prevents the natural historical hydrological connection in which saline water was likely to have intruded into the LVR during the low-flow summer conditions. There would now be substantial risk of loss of freshwater-adapted riparian vegetation if the weir was permanently removed; to minimise this risk, in February 2022 a temporary sand levee was used to prevent upstream intrusion of salt water. Further considerations and model scenarios for a range of flow conditions have been undertaken by Marillier (2018) noting that there is limited opportunity for floodplain connection above the weir.

Section 5.1 includes four "Central interventions" but has not mentioned application of Phoslock® or any other type of nutrient-binding compound among the inventory of intervention options to reduce nutrient levels. Given that Phoslock® is regarded as environmentally low risk (Behets et al. 2020) and has been used in the LVR and other systems in Western Australia (e.g., Robb et al. 2003), it could have been considered in this section. Additionally, in this section the effects of shading by wetland plants on cyanobacteria was not well described. Shading will reduce or negate growth of cyanobacteria but does not directly "kill them" or "eliminates BGA cells" (table 2 on p. 16 of the report). Indeed, many cyanobacteria are well adapted to low light levels and a ratio of 5 days in shade (under wetland plants) and 20 days in the open (LVR channel) is unlikely to substantially affect cyanobacteria biomass, with some doubt that Stage 3 would substantially alter this ratio. Table 2 also indicates that low light bleaches cells and cites a reference to support this case. This is not the case and under low-light conditions cyanobacteria are more likely to increase chlorophyll (i.e., become greener) in response to low-light conditions. In general terms we support opportunities to connect constructed wetlands to the river, but we believe the potential role of shading on cyanobacteria by wetland plants is overstated. A further issue in considering residence times is that natural systems have complex mixing patterns where the *mean* water residence time will likely differ from the residence time of buoyant cyanobacteria cells and colonies in the system; cyanobacteria are often concentrated in calm backwaters and shorelines out of the mainstem flow and can therefore persist even when the mean water residence time would suggest that they would be flushed from the system. This should be an important consideration in Stage 3 involving construction of in-stream wetlands.

Table 2 considers a "Flocculate nutrients" option and indicates it could add to the nutrient load in the sediment. We agree but we caution that this consideration may be simplistic if a material like Phoslock® inactivates phosphorus and prevents it from being released back into the water column under the range of environmental conditions expected in the LVR. This table also considers an option to "fertilise [the] diatom community with silica". This option can only be effective if silica concentrations in LVR are depleted to a level where silica is a limiting nutrient for diatom growth.

Generally, we support the underlying concept in the report that light and nutrients, below certain thresholds, will reduce the magnitude of cyanobacterial blooms. However, it is challenging to determine whether the reduction in these physicochemical parameters will be adequate to excerpt substantial control on cyanobacteria biomass. The clay dosing recommended in Stage 3 of the constructed wetlands may assist with reducing nutrients in the LVR but such an indirect application of the clay to the wetlands, over a large area, is an indirect method of cyanobacteria control compared with the more targeted Phoslock® application mentioned above. The Reviewers consider that the clay application in the constructed wetlands should only be considered after careful analysis of the other recommended actions in stages 1 and 2.

3.2 Additional considerations – observational data

There is an assumption in the report that the species responsible for the blooms is *Microcystis* but the data provided to us by Department of Water and Environmental Regulation (DWER) indicates a broader assemblage, often with *Dolichospermum* (basionym *Anabaena*) present, particularly earlier in summer, followed by *Microcystis* in late summer and autumn. The importance of this succession is that *Microcystis* does not fix nitrogen while *Dolichospermum* may fix nitrogen under conditions of nitrogen limitation.

The DWER dataset (2015-2022) has nitrate concentrations that are low to undetectable for about half the year (Jan-Jul), usually coinciding with elevated cyanobacteria biomass. Ammonium concentrations show a similar pattern of strong depletion in summer (Dec-May) but offset 1-2 months earlier than nitrate and with occasional spikes in summer. The pattern can be surmised as high levels of ammonium and nitrate delivered in late winter flows once the catchment has received substantial winter rainfall, followed in early summer by rapid depletion of ammonium from nitrification, and depletion of both ammonium and nitrate as cyanobacteria biomass increases and flushing is reduced with the flow recession. Occasional spikes in ammonium in summer are likely due to partial mixing events (e.g., from rapid cooling and/or wind) that circulate bottom waters with high levels of ammonium into surface waters where uptake by phytoplankton again rapidly reduces the ammonium concentration. Phosphate concentrations show a similar pattern to nitrate and ammonium but the duration of low concentrations in summer is reduced. Phosphate concentrations are concerningly high (often > ~100 µg L^{-1}) in winter and indicate potential to support very high concentrations of cyanobacteria biomass, as well as strong likelihood of phytoplankton nitrogen limitation in spring; a likely precursor to nitrogen fixation by *Dolichospermum* and other N-fixing cyanobacteria (e.g., *Pseudanabaena*).

3.3 Staged approach to intervention

We endorse the staged approach mentioned in the report and recommend even more rigidly developing this approach to provide a basis for adaptive management, so that the effects on water quality at each stage are validated with monitoring data before proceeding to the next stage. This approach should not hinder ongoing catchment works and management, however, as the highly elevated nutrient concentrations in winter flows indicate an urgent need for strong catchment management actions (i.e., aligned with Best Management Practices). Targets for reductions in nutrient concentrations in winter flows need to be set in order that investments in interventions in the LVR (i.e., the potential implementation of the three stages) are not wasted or need to be repeated at short intervals.

Stage 1 in the Alluvium (2020a, 2020b) report considers sediment removal by dredging the lower reach (Fig. 1) (Butter Factory weir to the old boat ramp) at an estimated cost of $1,046,000 or dredging the whole study reach ($2,136,000), with both costs inclusive of approvals. The reviewers endorse this approach and strongly recommend dredging the whole reach (Butter Factory weir to the Busselton Bypass) to achieve 'system-wide impacts' of removal of organic, nutrient-enriched sediments, along with appropriate mitigation actions to protect biota (e.g., Carter's freshwater mussel, endemic freshwater fish) and any unintended side effects from the dredging (e.g., sediment and nutrient resuspension, runoff from dredged spoil and spoil management). The latter effects may require supplementation with various flocculating agents (e.g., alum, polyaluminium chloride (PAC) or Phoslock®). The reviewers also suggest that the timing of applications of flocculating agents (likely Phoslock®, targeted at P adsorption) be aligned with completion of dredging in sections of the LVR, i.e., soon after the dredging, to lock up P in resuspended sediments. Depending on the depth of sediment removal, there may be increased volume in the LVR to improve flood mitigation. Careful monitoring is important, particularly because it has been shown that Phoslock® may increase the release of ammonium under anoxic conditions (Zeller and Alperin 2021).

Stage 2 involves recirculation of water through one or two constructed wetlands. Stage 2A involves modification of the wetlands in a bushland site in the light industrial area, mostly focusing on the lower reaches of the LVR. Stage 2B involves constructing a wetland in an area near Molloy Street. The authors have several concerns about Stage 2 and these concerns reinforce their viewpoint that completion and evaluation of effects of Stage 1 are a necessary prerequisite for Stage 2. Some of the potential issues of Stage 2 have been mentioned above, including the likelihood that cyanobacteria biomass may not be adequately controlled by the proposed wetlands (even with Stage 3), but also issues related to the succession and density of plants in the wetland to adequately exert nutrient and light control on cyanobacteria in the wetland-LVR system.

The reviewers also highlight the ongoing costs from pumping water up to the wetlands from the LVR. The views expressed about Stage 2 should not be interpreted that the reviewers are not supportive of opportunities for wetlands to improve water quality but there is a high degree of uncertainty associated with aspects of Stage 2 that suggest that Stage 1 should be undertaken in full and monitored carefully.

The authors have some concerns about Stage 3 involving the construction of in-stream vegetated structures that displace water and create wetland habitat within LVR. This approach may reduce the volume of LVR and its residence time, but it also risks dividing the river into small areas that create stagnant areas and enhance stratification, i.e., the environmental drivers of cyanobacterial blooms. The proposed areas will create little additional habitat for biota, especially compared with restoring riparian buffers and natural areas.

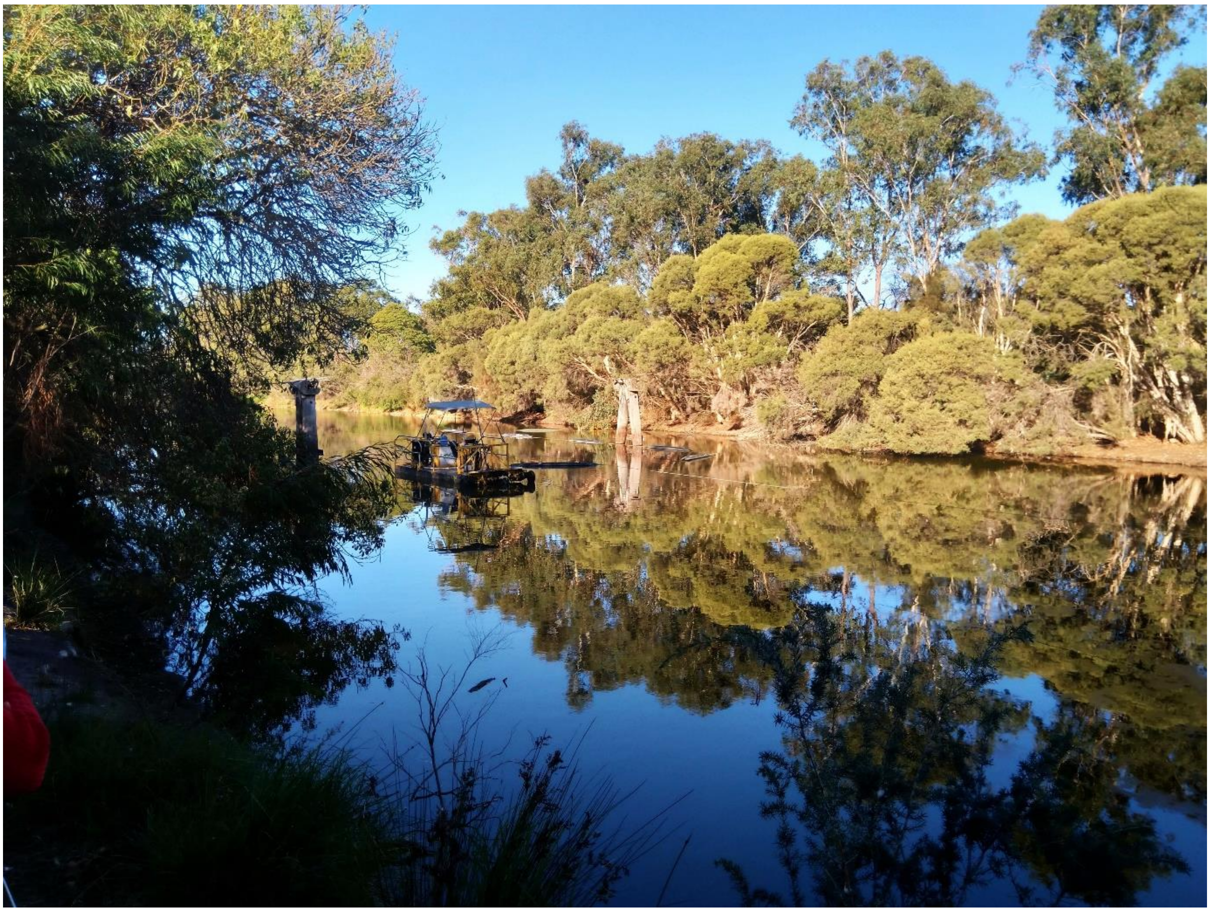

Figure 2 Dredging operation underway in the Lower Vasse River, May 9, 2022.

4. Recommendations

Based on the review of the Alluvium reports and from the information available to the Griffith University researchers, we make the following recommendations:

1) The Stage 1 dredging should be completed in full for the LVR, to address legacy issues of build-up of organic matter and nutrients in the bottom sediments. Associated with the dredging should be use of a flocculant (e.g., Phoslock®) to (a) offset localised effects of the dredging operation (resuspended sediments, spoil supernatant and spoil itself) and (b) be part of a plan to inactivate phosphorus throughout the LVR including releases from the bottom sediments.

2) Stage 2 should not be undertaken until Stage 1 is completed and assessed. There are risks with Stage 2 that the wetland enhancement and construction will not meet expectations for cyanobacteria control because of insufficient duration of shading of cyanobacteria in the wetland (five days) that will not offset their ability to grow in the LVR (20 days). The application of clay to reduce phosphorus availability in the wetland, and by implication in LVR, is a less direct method of control than the proposed P-locking in LVR in Stage 1 and may be part of the staged assessment approach, i.e., following implementation of Stage 1.

3) Stage 3 involving the construction of in-stream vegetated structures to displace water and create wetland habitat requires the wetlands to be in place from Stage 2. The benefits of this approach in reducing volume and increasing flushing rates in LVR could be countered by reduced flood volume storage and creating favourable conditions for the proliferation of cyanobacteria (e.g., increased temperature, stagnation and stratification) due to greater heterogeneity of flow within the LVR.

5. Acknowledgements

The authors are grateful to Paul Needham (City of Busselton) for taking the time to take David Hamilton and Michele Burford around the field site on 9 May 2022. Malcolm Robb and Linda Kalnejais (Department of Water and Environmental Regulation) are thanked for provision of data on Vasse River from the department. Mathilde Breton is thanked for assisting the authors with logistics and questions related to the project.

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