Framework to identify and mitigate water storage contamination concerns at NSW and ACT production nurseries

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Disclaimer

This document and all associated maps, factsheets and other resources delivered through the NGINA project are intended to support storm and flood hazard and risk awareness in the production nursery industry. They should not be used for storm or flood risk assessment, or for site operational planning.

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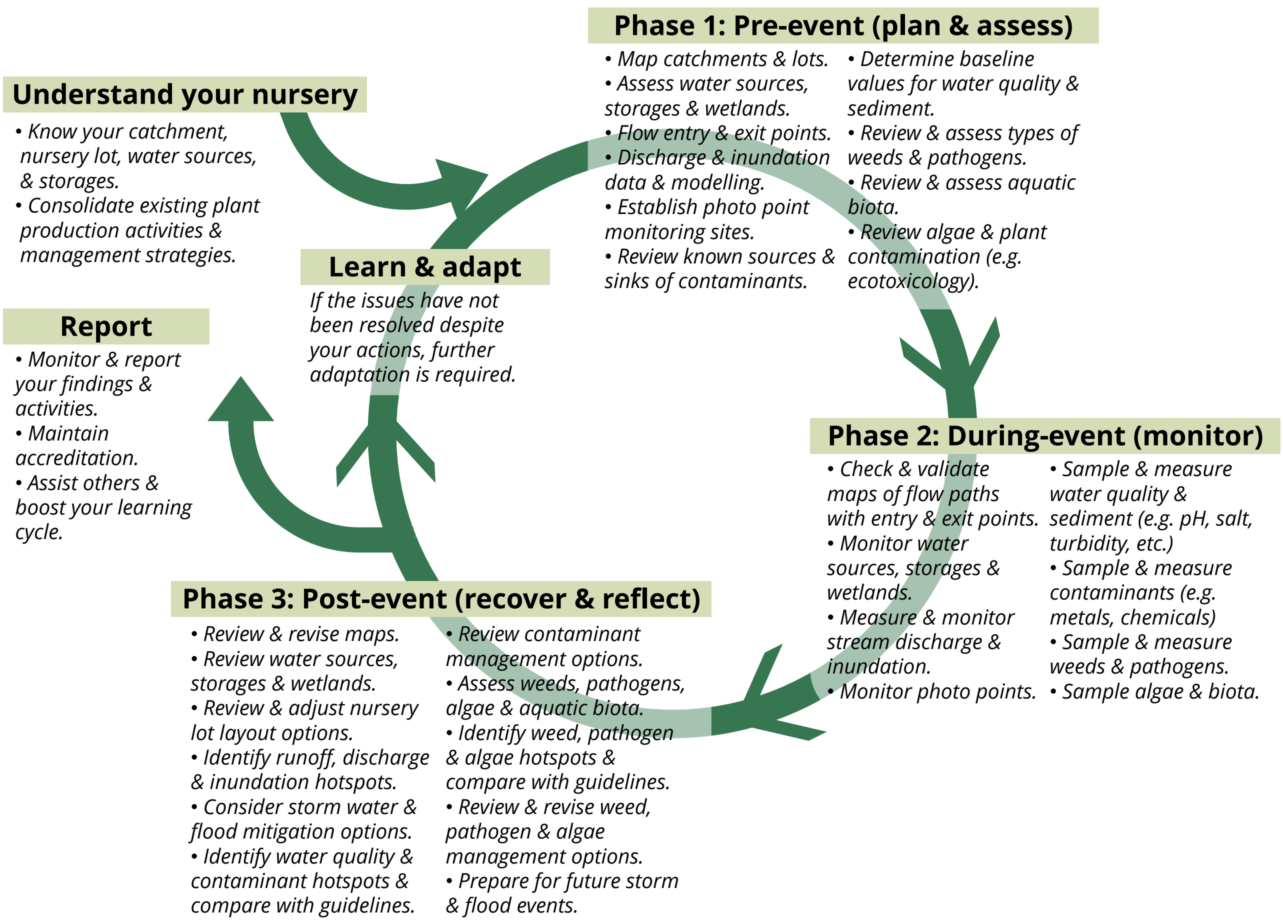
Executive summary

Water is an essential resource for production nurseries in the horticultural industry. Storms and floods that cause runoff and contaminant transfer pose significant risks to water storages used for irrigation. This framework was developed to help identify and mitigate water storage contamination concerns at production nurseries in NSW and the ACT. This stems from a project undertaken by Macquarie University in collaboration with the Nursery and Garden Industry NSW and ACT (NGINA) following major floods in 2021 that had severe impacts on the horticultural industry in eastern Australia. The project aimed to assess and understand the potential impacts of storm- and flood-related water contamination at production nurseries, and to provide guidance to support the NSW and ACT industry in its goal to become more resilient in the face of future storm and flood events.

The three core objectives were to: 1) assess post-flood contamination risks in production nursery water storages, 2) increase industry awareness of the risk factors, and 3) develop a framework to guide prevention and mitigation of contaminant risk. Key outputs include: 1) a literature review summarising concepts and information on water quality and contaminants, 2) a series of maps of NSW and ACT production nursery locations, catchments, potential flow paths, water storages, and potential inundation hotspots, 3) understanding of water-borne contaminants at production nurseries in the Northern Rivers, Central Coast, and Northern Sydney regions, 4) water quality fact sheets for key contaminants and their management, and 5) a framework, summarised below, to understand and manage water quality and contamination concerns before, during and after storm and flood events.

The findings from this project are applicable to NSW and ACT production nurseries and to the broader agricultural sector using water storage and recycling for irrigation. Integration of scientific expertise and industry knowledge ensures practical, scalable solutions that contribute to improved water quality, economic resilience, and ecological sustainability over local and regional scales.



1. Introduction

Production nurseries are a key element in the horticultural supply chain, providing starter material to vegetable farmers through seedlings, and fruit and nut orchardists through young trees. The industry also supports the ornamental horticulture sector, as well as landscaping, urban greenspace and revegetation sectors. Water is an essential resource required by production nurseries; without it the industry cannot sustain the products it produces or commit to producing more products. The overwhelming majority of the industry undertakes water recapture activities following irrigation and rainfall and stores this on site through either dams or tanks. As part of normal production processes this water is usually treated for phytopathogens and amended for basic qualities such as pH. However, there is no general requirement for regular water testing that would provide an early warning system for water-borne contaminants or related concerns that could help safeguard water quality.

Storm and flood events pose significant risk of contamination to water resources at production nurseries via a range of pollutants including sediment, salt, nutrients, heavy metals, increased phytopathogen load, and weed seeds. These contaminants may come from within a nursery lot or from elsewhere uphill or upstream of a nursery, and either end up in water storages or may be transported off-site to downstream areas. As a result of major storm and flood events in 2021, NSW production nurseries were subjected to conditions that had significant implications for the quality of water which is retained on-site or distributed through the surrounding landscape as runoff. During normal rainfall periods, on-site water is usually able to be treated prior to its reuse, however, during peak rainfall and runoff events, the water treatment capacities of nurseries may be exceeded. Consequently, large volumes of water, potentially contaminated with high silt loads and a range of chemical pollutants (e.g. fertilisers and herbicides), as well as other biological material (e.g. weeds and pathogens) are stored and reused on-site and may be redistributed in the landscape via runoff. This poses a significant risk to on-site practices requiring water, as well as the health of on-site and off-site aquatic ecosystems receiving the contaminated waters. To address potential issues related to excess water with contaminants during and after flooding, an understanding of the contaminants and their loadings, as well as how these are distributed throughout the landscape, is required.

It is essential to understand which contaminants may affect production nursery water storages during and after storm and flood events, to have resources to promote industry awareness, and to have an adaptive framework to guide activities that avoid or mitigate water quality issues. Such a framework will allow the production nursery industry to recover post-event and return to trade with minimal disruptions and impacts to nursery crops in the short- and long-term. It may also help to assist other horticultural sectors in their recovery efforts through limited disruption to the supply chain.

This project focused on assessing catchment and nursery conditions as well as water quality issues and management options that can be helpful for mitigating water-borne contaminants to improve water quality and crop productivity at production nurseries in three disaster-declared regions of NSW: Northern Rivers, Central Coast, and Northern Sydney. Ultimately, this will enhance the ability of the industry to identify key risks to water storages and runoff into receiving waterways, and to build resilience in the face of future storm and flood events. The project is founded on the approach that identifying primary contaminants that occur before, during and after storm and flood events can allow extrapolation of the potential hazards and risks. The project was conducted by a multi-disciplinary team with extensive experience in river and wetland hydrology and geomorphology, human impacts on waterways and terrestrial systems, sediment and contaminant assessment, spatial data analysis, vegetation and weed dynamics, freshwater aquatic biota, ecotoxicology, and environmental risk analysis. The data collected in conjunction with this expertise allowed a robust framework to be developed to support decision-making and risk assessment for industry. To ensure the project outcomes have utility to industry, the Nursery and Garden Industry NSW and ACT (NGINA) provided guidance and liaison to the project and undertook extension and communication activities to ensure industry input and adoption. While the focus of this project was within three production regions of NSW, the results and outputs are relevant and applicable to the nursery sector as a whole and potentially to other agricultural enterprises using water capture, storage and irrigation practices.

2. Objectives and outcomes

The overarching objective of the project was to enhance resilience to storm and floods events and recovery processes in the NSW production nursery industry. There were three sub-objectives:

1) To assess post-flood water storage contamination risk.
2) To increase industry awareness around the risk factors.
3) To develop tools and guidance to support risk mitigation activities.

The focus of the project was on identification of water quality issues and possible contaminants that would affect production nursery water storages related to storm and flood events, and to develop resources to guide water management strategies. This information is brought together in this adaptive framework document to support the production nursery industry to recover with minimal disruptions following major flood and storm events. The three project-level outcomes were:

1) Scoping and assessment of catchment conditions and contaminants for NSW production nurseries, including landscape setting, runoff and hydrology, water and soil contaminants, plant pathogens, and aquatic biota.
2) Validation and monitoring data for storm and flood impacts associated with water storages and runoff at focus nurseries in three disaster-declared production regions of NSW.
3) Spatial data, a decision-support framework and associated resources to assist the NSW production nursery industry with water contamination mitigation efforts and best management practices for storm and flood events.

The project combined broad-scale (e.g. catchment) and site-specific (e.g. nursery lot) assessment techniques to analyse flow pathways and water quality processes, and to understand potential sources, storages, and dispersal pathways of pollutants. In doing so, the project fills a critical gap for multi-scale assessment and management of water-borne contaminants at production nurseries and in the surrounding environment. Socio-economic benefits stemming from the project may include improved water quality and utility, enhanced plant productivity, and greater agricultural resilience against storm and flood impacts for the nursery industry in NSW.

Major outputs from the project were:

1) A literature review summarising concepts and information on water quality and contaminants (Gomes et al., 2025; https://doi.org/10.1016/j.scitotenv.2024.178084).
2) A series of maps of NSW and ACT production nursery locations, catchments, potential flow paths, water storages, and potential inundation hotspots.
3) Understanding of the key types and amounts of water-borne contaminants at production nurseries in the Northern Rivers, Central Coast, and Northern Sydney regions.
4) Water quality fact sheets explaining potential contaminants and their management (Ralph et al., 2025; https://doi.org/10.25949/JH43-4N56).
5) An adaptive framework to understand and manage water quality and contamination concerns before, during and after storm and flood events (this document).

3. Approach

The problems associated with contaminants affecting water quality and crop productivity at production nurseries occur within and between lot boundaries, and in catchments that may cross regional and/or local administrative boundaries. A multi-scale approach is critical for the development of an adaptive framework to guide appropriate assessment and mitigation of water-borne contaminants related to production nurseries. A broad-scale understanding of where nurseries are located within catchments and what potential flow paths and inundation factors may occur is needed to guide industry-level planning. Although the spatial resolution is limited, this information may also guide further work on lot-scale planning at individual nurseries. Detailed site-specific measurements and monitoring of water quality and contaminants at selected nurseries are also critical, as they provide examples of on-ground issues and validation of the approaches developed at the regional scale, while also allowing information to be extrapolated and fed back into the project during evaluation and recommendation stages. Sharing knowledge and expertise is pivotal for the industry, because it promotes awareness and understanding of water quality issues and can link to best management practices under the relevant agricultural and environmental conditions.

To achieve the project objectives and outcomes, and to contribute to the overall objective of enhancing resilience to storm and flood impacts in the NSW production nursery industry, a knowledge and research strategy encompassing five key themes was developed and employed. The research conducted by Macquarie University was coupled with extension and outreach activities conducted by NGINA. The research themes addressed were: 1) landscape setting, 2) runoff and stream hydrology, 3) water and soil contaminants, 4) plant pathogens and weeds, and 5) aquatic biota (Figure 1). Based on important factors across these five themes, water quality and contamination concerns were linked to a three-phase nursery preparation and recovery concept that forms the basis of the adaptive framework presented in this document. The first phase – *Pre-event planning and assessment* – involves assessment of catchment conditions, hydrology and a suite of contaminants to provide a baseline of understanding for nurseries. The second phase – *During-event monitoring* – involves measurement and monitoring of hydrology and contaminants, and validation of catchment-scale and site-scale spatial information. The third phase – *Post-event recovery and reflection* – involves experiences and understanding to be reviewed and revised to inform recovery actions and planning for storms and floods. There is a link from phase 3 back to phase 1 via a learning loop, otherwise known as an adaptive management cycle, that allows insights to feed into future prevention and mitigation steps within the production nursery industry, promoting longer-term resilience and sustainability (Figure 1).

The focus of the project at the broadest scale was to quantify and understand the locations of production nurseries within catchments from which they source water or may be exposed to storm and flood hazards, including water-borne contaminants. This was mainly covered by the first two research themes, where catchment- and lot-scale mapping and modelling was done for 95 out of 106 members in the NGINA database as of 2023. Links to water and soil contaminants, pathogens and aquatic biota were addressed at a broad scale by industry and expert opinion and a literature review. At the site-scale, detailed mapping, ground-truthing, water quality measurements and monitoring, contaminant sampling and assessment, and a trial of pathogen assessment and monitoring, was conducted in selected water storages at ten focus nurseries in three key production regions of NSW.

A five-stage plan was developed and employed to address the project themes and associated activities: 1) understand the problem through discussions and engagement with the NSW nursery industry; 2) develop conceptual models to describe and predict water-borne contamination within a nursery site, and also contamination to off-site areas; 3) spatial data collection and analysis to characterise production nurseries by their size, landscape position and context, including contributory flow and runoff areas; 4) site-specific assessment of water quality and contaminants at selected nurseries, and; 5) develop a decision-support framework and resources, based on findings from stages 1 to 4 (Figure 2).

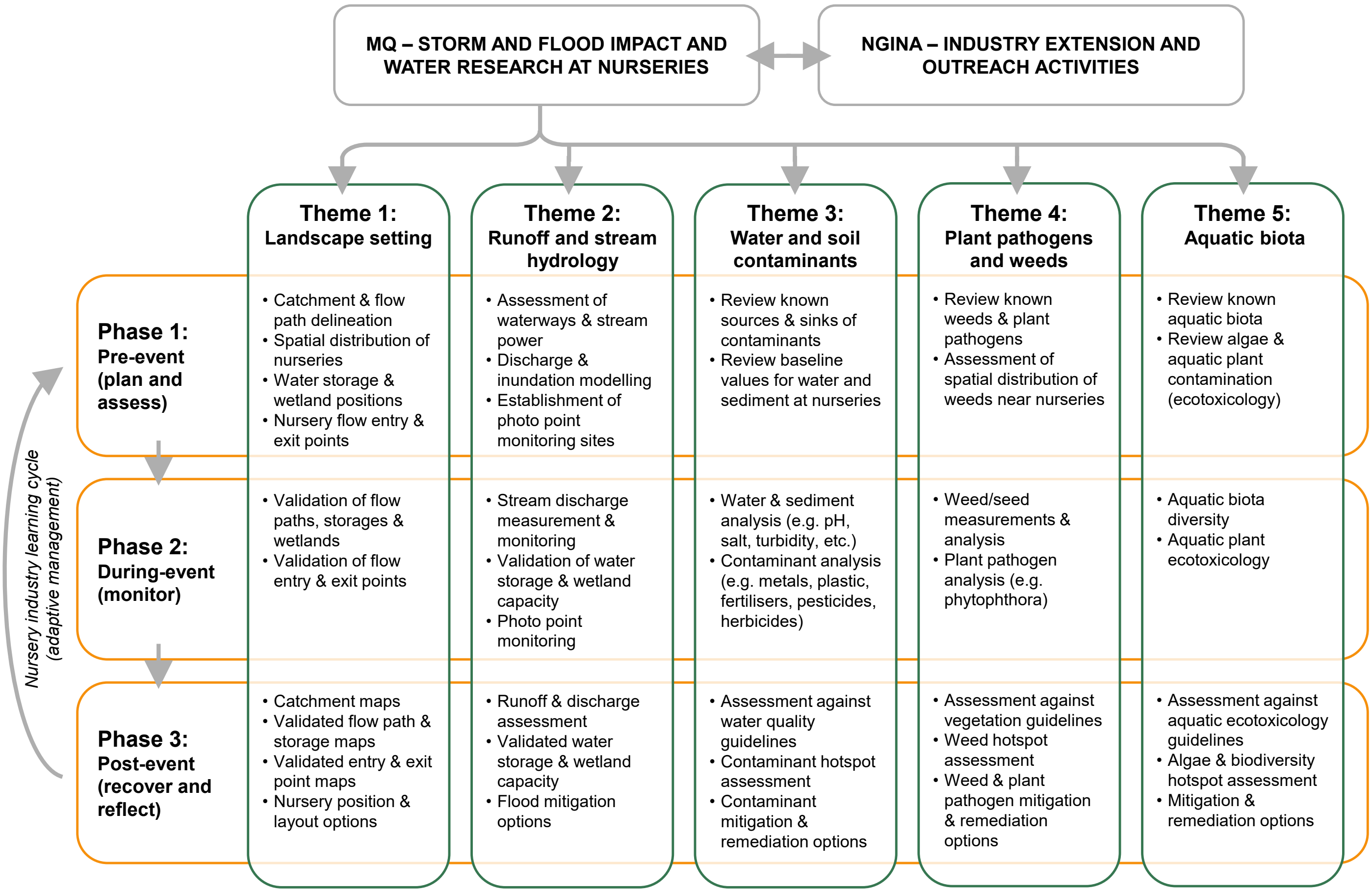


Figure 1. Project knowledge and research strategy with five key themes, and associated activities and planned outputs aligned to a three-phase nursery preparation and recovery framework concept.

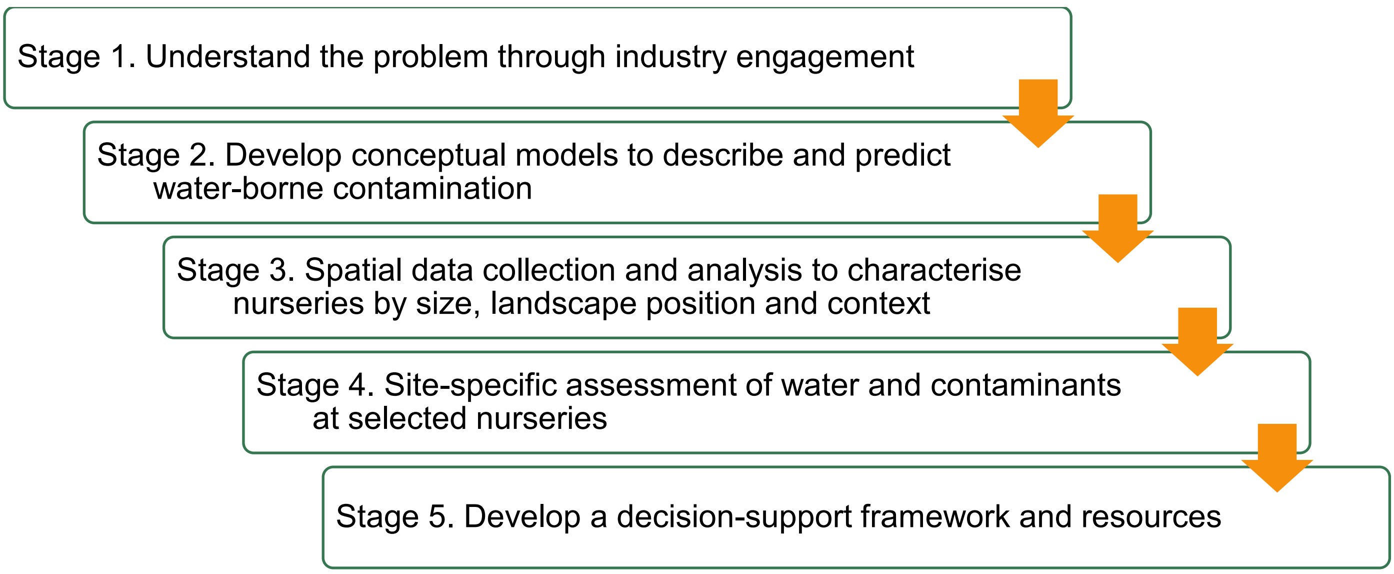


Figure 2. The five-stage project plan.

3.1. Understand the problem

Stage 1 was linked to Outcome 1 and involved online and in-person workshops and meetings with production nursery industry representatives facilitated by NGINA, including owners, managers and staff. These meetings were aimed at identifying the key water quality issues and concerns that production nurseries faced and to gain insights into site-specific details of how water was captured, stored, treated, used and recycled. Nursery managers and staff identified water-borne contaminants on the ground and in water storages to be some of the main issues likely to affect their nurseries, with particular concern about the role of contaminants threatening plant production and health. During this process, ten focus nurseries were identified and permission obtained from them to undertake detailed spatial analysis and on-ground measurements and monitoring of water quality and contaminants in three disaster-declared production regions of NSW, including: 1) Northern Rivers (four nurseries), 2) Central Coast (two nurseries), and 3) Northern Sydney (three nurseries).

In parallel to these industry workshops, discussions and site visits, a detailed scientific review was conducted to assess existing datasets available and to summarise key elements from published international and Australian literature and grey literature (e.g. reports and websites) that considered catchment conditions and contaminants for nurseries. The literature review by Gomes et al. (2025) is openly accessible and provides a thorough overview of well-known and emerging water-borne contaminants relevant to production nurseries, the catchment characteristics and hydroclimatic factors that influence the transfer of contaminants to nurseries, how irrigation water quality impacts plant growth and health, the potential for leachate-rich runoff from nurseries to negatively affect downstream ecosystems, and potential management strategies that may reduce contamination risk to production nurseries and the environment (Figure 3).

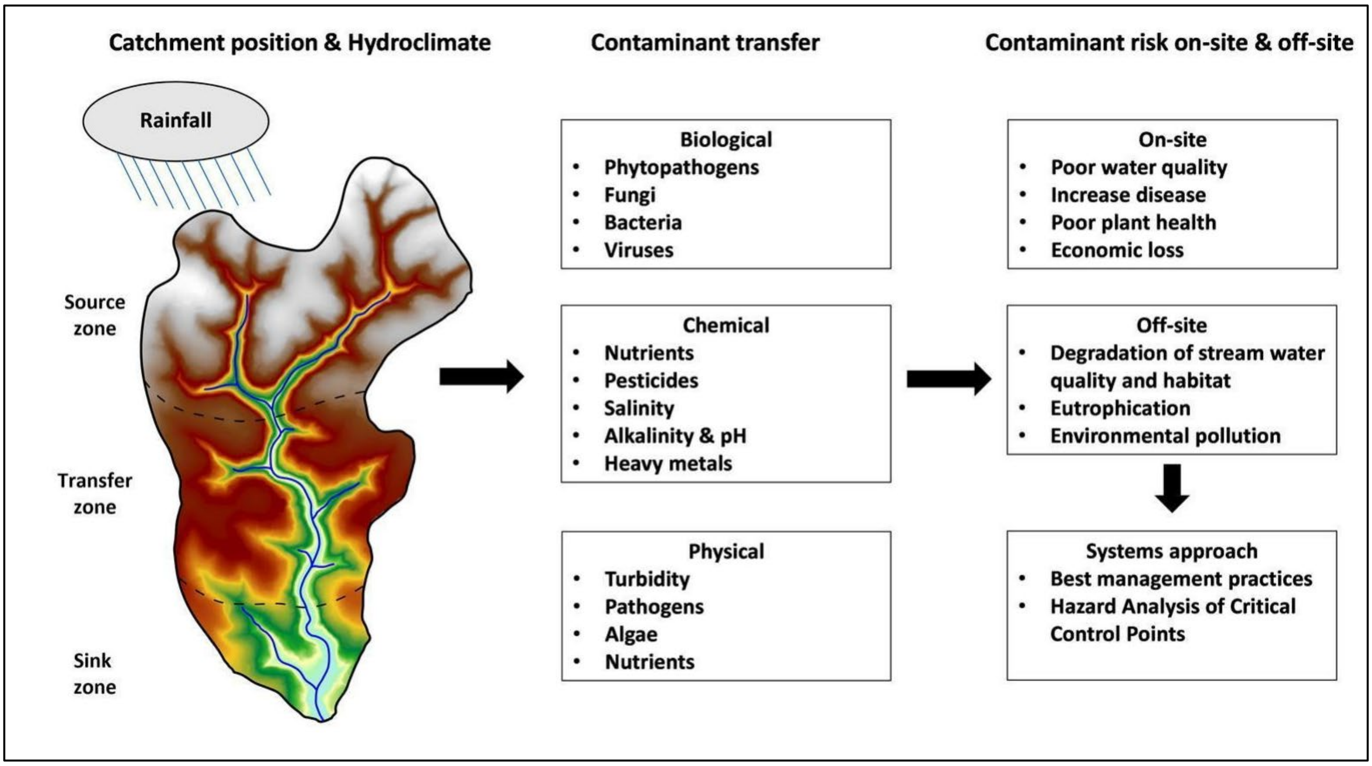


Figure 3. Summary of factors including catchment position and hydroclimate that influence the transfer of biological, chemical and physical contaminants at production nurseries, leading to contamination risks in on-site, off-site and downstream systems (Source: Gomes et al., 2025).

3.2. Develop conceptual models

Stage 2 was linked to Outcomes 1, 2 and 3, and was informed by discussions and engagement with industry members, together with collation of information on catchment setting and production nursery types, and the detailed literature review of relevant contaminants to develop a set of conceptual models. Scenarios were considered for nurseries that receive significant volumes of water from upstream (i.e. from runoff generated elsewhere in the catchment) and, at the other end of the spectrum, for nurseries that only receive direct rainfall and do not receive runoff from elsewhere. The potential role of the production nurseries as sources and sinks of contaminants was considered for a range of catchment settings and storm and flood events. The conceptual models summarise the links between physical and water quality hazards and contaminant risk (Figure 4), and how run-on from elsewhere can affect water quality and contamination at production nursery sites and lead to runoff into receiving waterways with potential downstream contamination impacts (Figure 5).

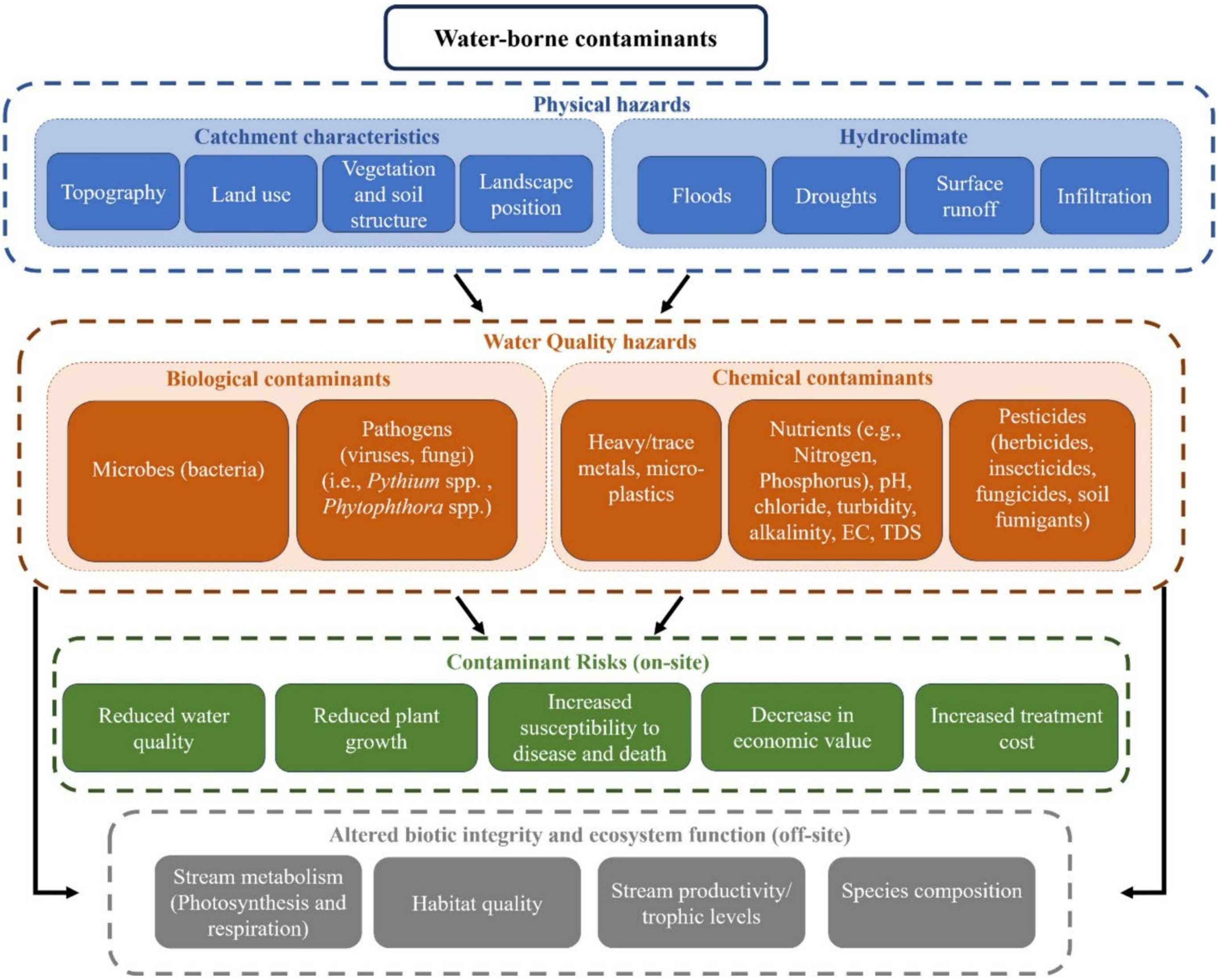


Figure 4. Conceptual model illustrating the impacts of catchment characteristics and hydroclimate (blue boxes) on water quality (orange boxes), and how contaminant hazards pose a risk to nursery plant production (green boxes), and biotic integrity and ecosystem functioning (grey boxes). Arrows indicate pathways of influence. Dashed boxes represent distinct levels of impact, and boxes within them represent the main components pertaining to that risk (Source: Gomes et al., 2025).

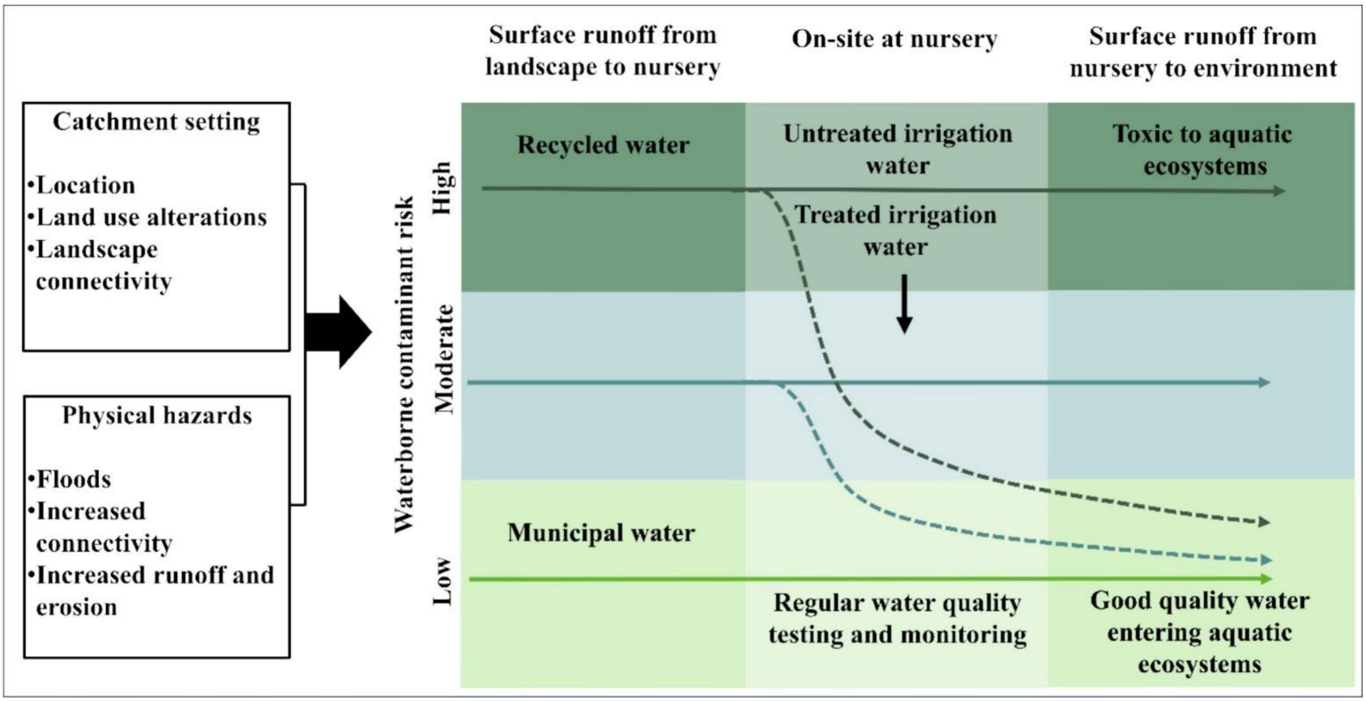


Figure 5. Conceptual diagram highlighting the factors that influence water-borne contamination risks to and from production nurseries (Source: Gomes et al., 2025).

3.3. Spatial data collection and analysis

The first part of Stage 3 was spatial data collation, analysis and mapping of catchments and production nursery lots linked to Outcomes 2 and 3. Compilation of data from publicly available sources and analysis within Geographical Information System (GIS) software allowed the characterisation of production nurseries in NSW and the ACT by their size, landscape position and catchment context (Figure 6). Nurseries were identified using their address and lot numbers and once their locations were known the catchment boundaries relevant to them were extracted from the Australian Hydrological Geospatial Fabric (AHGF) database (BOM, 2022). Catchment boundaries for the ten focus nurseries from the Northern Rivers, Central Coast and Northern Sydney regions were refined using a digital elevation model (DEM) with 1 m resolution (DCS, N.D.a).

Within all nursery catchments, potential surface water flow paths were derived using a flow accumulation model based on slope from a 5 m DEM (DCS, N.D.b). The D8 single-flow direction model was used to simulate surface water flow paths where each cell is assigned a flow direction toward the steepest downslope neighbour among its eight surrounding cells. To ensure consistency across different DEMs, a contributing area threshold of 10,000 m^2 (equivalent to 1 ha or 0.01 km^2) was applied using the CON tool in ESRI ArcPro v3.2. For the ten focus nurseries, the same tool was used with the 1 m DEM to delineate potential flow paths at a finer scale, and the location and extent of these flow paths were checked on the ground using a combination of field survey techniques. Site surveys and photographs were compiled to help explain and understand water movement within production nursery lots (Figure 7). Lot boundaries were derived from publicly available cadastre data (DCS, 2021), land use from public data (DPE, 2017), and water storages were digitised manually in GIS using high-resolution satellite imagery (ESRI, 2020) (Figure 6).

Production nursery catchment and waterway characteristics (e.g. catchment and lot area, flow paths, number of entry and exit points, etc.) were extracted from the spatial data, a database built, and maps created in GIS. Maps for all the NGINA production nurseries included in the project show key features at the lot scale and at the broader catchment scale. Of the 106 production nurseries in the

NGINA database, 11 were not included in the project because they were located on major river floodplains where the mapping, modelling and analysis approaches were not suitable (i.e. their flood risks were not related to local catchment or lot characteristics). The final maps are indicative of catchment boundaries, flow paths, flow entry and exit points, water storages, and potential inundation hotspots, but are not intended for detailed site operational planning.

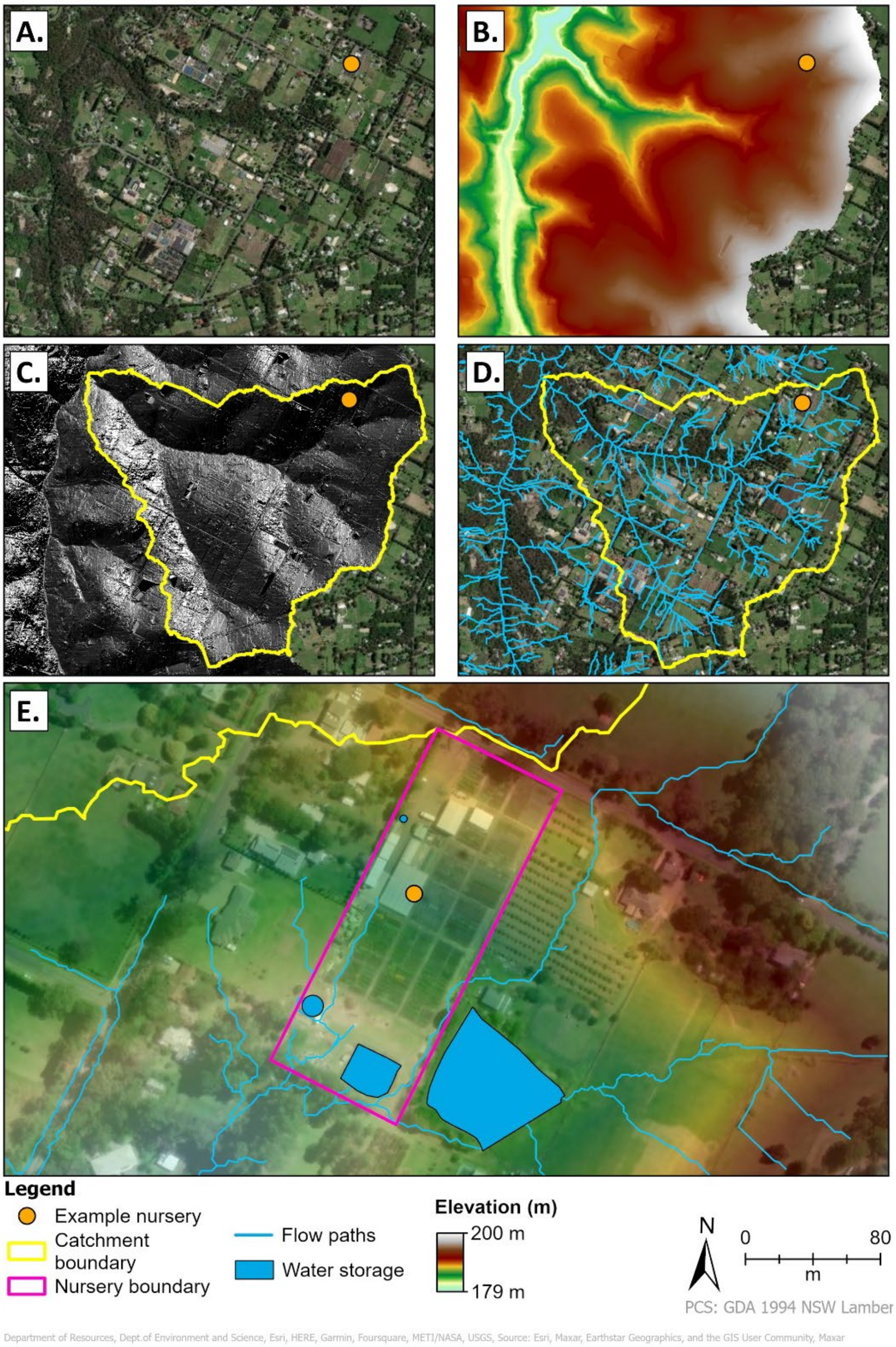


Figure 6. An example of spatial data used for catchment and flow path mapping for a nursery, showing A) the location of a production nursery overlain on satellite imagery, B) a 5 m DEM indicating topography in the landscape, C) a DEM-derived slope layer illustrating flatter and steeper areas within a catchment boundary which was used to generate potential flow paths, D) flow paths derived from flow accumulation modelling using the slope layer within the catchment boundary, and E) a lot-scale map of a production nursery with water storages and flow paths entering and exiting the property boundary.

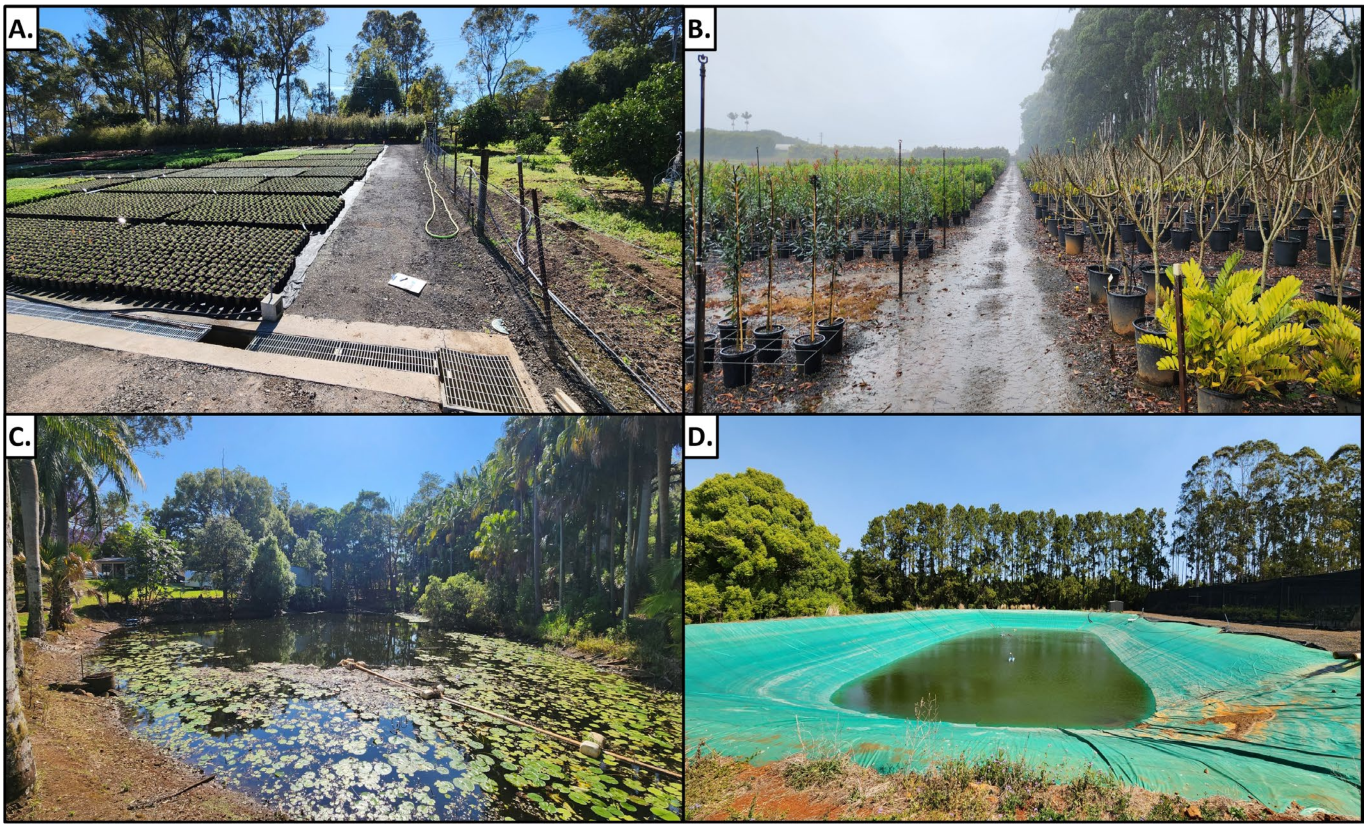


Figure 7. Examples of site survey photographs to help ground-truth maps and to understand flow paths and water storages at production nurseries with A) plants on gravel beds with drains, B) plants on gravel beds with storm water on a nearby track, C) an unlined water storage dam, and D) a lined water storage dam.

The second part of Stage 3 used a combination of GIS-based calculations and 2-dimensional (2D) flow routing models to determine areas within catchments and lots that may potentially be wet, may be susceptible to relatively high energy water flows, and that may be considered potential inundation hotspots under a range of modelled rainfall-runoff scenarios (Figure 8).

Topographic Wetness Index (TWI) is a hydrological metric derived in GIS from DEMs to provide an estimate of the spatial distribution of water accumulation potential across landscapes (Figure 8). TWI was generated in the ESRI ArcPro Raster calculator tool using catchment area and slope metrics following the methods of Gallant and Wilson (2000). TWI categories were defined using typical values for upper, middle, and convergent lower slopes (Gallant and Austin, 2012):

- Minimal water accumulation (~ 5.5): Typically found on upper slopes with steep gradients and limited upslope area.
- Moderate water accumulation (~ 7.3): Found on mid-slopes where water begins to converge.
- Water accumulation (~11.5): Occurs in lower, convergent areas. Note, values >12 may be less reliable due to DEM limitations in flat or channelised regions.

The Stream Power Index (SPI) is a topographic metric derived in GIS from DEMs to provide an estimate of the relative energy of surface flow and its spatial variability across a landscape (Figure 8). It combines the effects of upstream catchment area and slope to identify areas with some potential for erosion. SPI was generated in the ESRI ArcPro Raster calculator tool following the methods of Moore et al. (1988; 1991). Generally, higher SPI values indicate areas with greater flow accumulation and steeper slopes, which may be more prone to erosion than areas with lower SPI values.

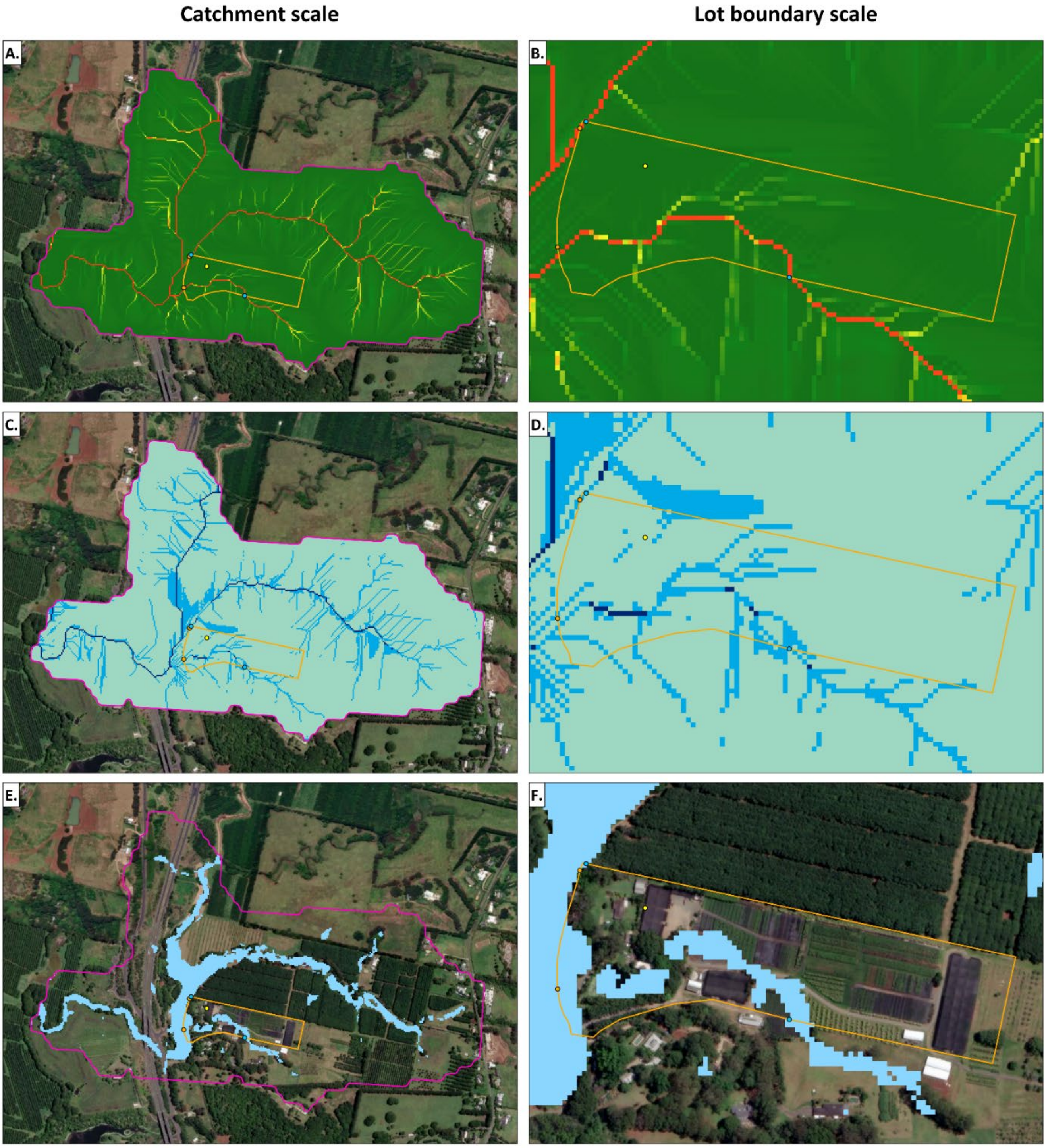


Figure 8. Examples of GIS outputs showing A) Stream power index (SPI) at the catchment-scale and B) SPI at the lot-scale which may be indicative of higher erosion potential (red cells) compared with moderate potential (yellow cells) and low potential (green cells) for erosion. C) Topographic wetness index (TWI) at the catchment-scale and D) TWI at the lot-scale indicating where water may accumulate in the landscape. In the catchment source zone, there is minimal water accumulation (light green cells), whereas in the transfer and sink zones there is moderate (light blue cells) and higher (dark blue cells) potential for water accumulation. E) Potential inundation hotspots (blue cells) at the catchment-scale and F) at the lot-scale. The catchment boundary is indicated in pink, lot boundary in orange, and production nursery centroid in yellow.

Potential inundation hotspots were derived using outputs from HEC-RAS v5.0.1 which is publicly available software that has 2D channel and floodplain modelling capabilities (HEC, 2016). The modelling was conducted twice for each production nursery at the catchment- and lot- scales but was not able to be calibrated or validated for each nursery. Several input datasets were used including the 5 m DEM, previously derived catchment and lot boundaries and flow paths forming the river network, and Manning's n roughness values for the terrain (HEC, 2022). RAS-mapper was used to convert the DEM to a Digital Terrain Model (DTM) which was then used to compute the 2D catchment and flow areas, water surface elevations, and discharge from unsteady flow simulation results, and to visualize the channel and floodplain geometry as per standard methods (HEC, 2022). Raster layers were exported from HEC-RAS and imported into GIS to create overlays and maps.

Ten plans representing different potential rainfall intensity scenarios were used to simulate inundation events in HEC-RAS. The design rainfall values are derived from a national-scale Bureau of Meteorology data system (BOM, 2016) incorporating over 30 years of rainfall records and which uses standardised statistical methods for estimating rainfall intensities across Australia. Each scenario represents rainfall depth at a particular location within a defined duration and this likelihood is classified by Exceedances per Year (EY) or the Annual Exceedance Probability (AEP). The rainfall scenarios used in the project had probability 12 EY, 4 EY, 2 EY, 50 % AEP, 10 % AEP, 5 % AEP, 2 % AEP, 0.5 % AEP, 0.1 % AEP and 0.05 % AEP (Table 1). It is important to note that design rainfalls are based on a probabilistic estimate and therefore are not real or observed rainfall events, rather, they indicate the likelihood of occurrence of a specific rainfall event. The scenarios used range from frequent events not expected to cause flooding, to rare and extreme events expected to cause severe flooding.

Table 1. Rainfall scenarios used for potential inundation hotspot modelling in HEC-RAS, based on ten plans from the 2016 design rainfall database (BOM, 2016).

Plan ID	**Design rainfall class**	**Probability**	**Frequency of occurrence and description**
P1	Very frequent design rainfalls	12 EY (12 in 1 yr)	Very frequent; rainfall expected to be exceeded 12 times per year on average (once every ~1 month)
P2	Very frequent design rainfalls	4 EY (4 in 1 yr)	Very frequent; rainfall expected to be exceeded 4 times per year on average (once every ~3 months)
P3	Very frequent design rainfalls	2 EY (2 in 1 yr)	Very frequent; rainfall expected to be exceeded 2 times per year on average (once every ~6 months)
P4	Intensity frequency duration	50 % AEP (1 in 2 yr)	Frequent; a rainfall event equivalent to a 2-year average recurrence interval (ARI)
P5	Intensity frequency duration	10 % AEP (1 in 10 yr)	Infrequent; a rainfall event equivalent to a 10-year ARI
P6	Intensity frequency duration	5 % AEP (1 in 20 yr)	Infrequent; a rainfall event equivalent to a 20-year ARI
P7	Rare design rainfalls	2 % AEP (1 in 50 yr)	Rare; a rainfall event equivalent to a 50-year ARI
P8	Rare design rainfalls	0.5 % AEP (1 in 200 yr)	Rare; a rainfall event equivalent to a 200-year ARI
P9	Rare design rainfalls	0.1 % AEP (1 in 1000 yr)	Rare; a very rare rainfall event equivalent to a 1000-year ARI
P10	Probable maximum rainfall	0.05 % AEP (1 in 2000 yr)	Extremely rare; an extreme rainfall event equivalent to a 2000-year ARI

The potential inundation hotspots shown on the maps represent the cells that were modelled as being inundated in all ten design rainfall scenarios, so these are conservative estimates of potential recurrently wet areas related to a range of possible rainfall scenarios (Figure 8). It is important to note that the modelling results and maps presented are illustrative only and should not be used for risk assessments or planning purposes. The models have not been validated due to the lack of river discharge data for the production nurseries and their catchments. As such, the potential inundation hotspot maps simply highlight areas that may be consistently prone to surface water.

3.4. Assessment of water and contaminants

Stage 4 was linked to Outputs 2 and 3 and built on the first three stages to assess water and contaminants directly at ten focus production nurseries in three regions of NSW that were severely impacted by storms and floods in 2021, including the Northern Rivers (e.g. Lismore, Alstonville, and Ballina), Central Coast (e.g. Gosford and Wyong), and Northern Sydney (e.g. Kenthurst and Dural). Within each of these regions, permission was obtained from nurseries for detailed analysis and monitoring of water quality in their on-site storages. Water sampling and monitoring sites were chosen at each nursery based on the site plans, water storage and use arrangements, proximity of water storages to flow entry and exits points, and other physical and operational factors.

Photo point monitoring is a useful tool to assess changes in a system over time. It involves the establishment of specific points where photographs are consistently taken allowing visual documentation of change. The images acquired provide valuable insights into water storages, the extent and severity of extreme events (e.g. storms, floods, bushfires, etc.), and may show the effect of management strategies (e.g. weed control, revegetation, irrigation techniques, dam usage, etc.). Photo point monitoring was undertaken in collaboration with nursery staff to capture regular images of water storages and to allow event-based information on flood or flow conditions during rainfall and runoff events over the life of the project (Figure 9). The photo point monitoring data were used to help differentiate rainfall and runoff conditions and to validate water storage levels and flow path activity.

Figure 9. Example of a photo point monitoring setup at a production nursery showing A) Camera trap fitted with solar panels overlooking a water storage, and B) A photo taken by the camera trap of the water storage.

Within the water storages of the ten focus production nurseries, water quality parameters and contaminants including silt, salt, nutrients, heavy metals and other elements were monitored and sampled for a period of nearly one year (Figure 10). Water sensors were installed in representative areas of the water storages to collect hourly data for water depth, electrical conductivity (EC), pH, and temperature. The sensors were calibrated prior to deployment and installed at an appropriate depth (usually ~1 m from the bottom of the water column) using floats and anchors (Figure 9). The sensors allowed continuous data logging and were retrieved at intervals for maintenance and data download. The sensor readings were validated periodically with handheld meters to ensure that the data could be used to assess water quality fluctuations and to inform management strategies.

In addition, monthly water samples were collected by nursery staff from the edge of the water storages and submitted to the NSW Department of Industry (DPI) Environmental Laboratory at Wollongbar where they were tested for pH, EC, chloride, turbidity, alkalinity, total dissolved solids, hardness, saturation index, sodium absorption ratio, a full 20 element scan, nitrate, nitrite, ammonia, phosphate, and sulfate using standard methods (Table 2). Quarterly sediment samples were collected by Macquarie University staff from the bottom of the water storages and were submitted to DPI at Wollongbar where they were tested for parameters including pH, EC, elements, nutrients, total and organic carbon using standard methods (Table 3).

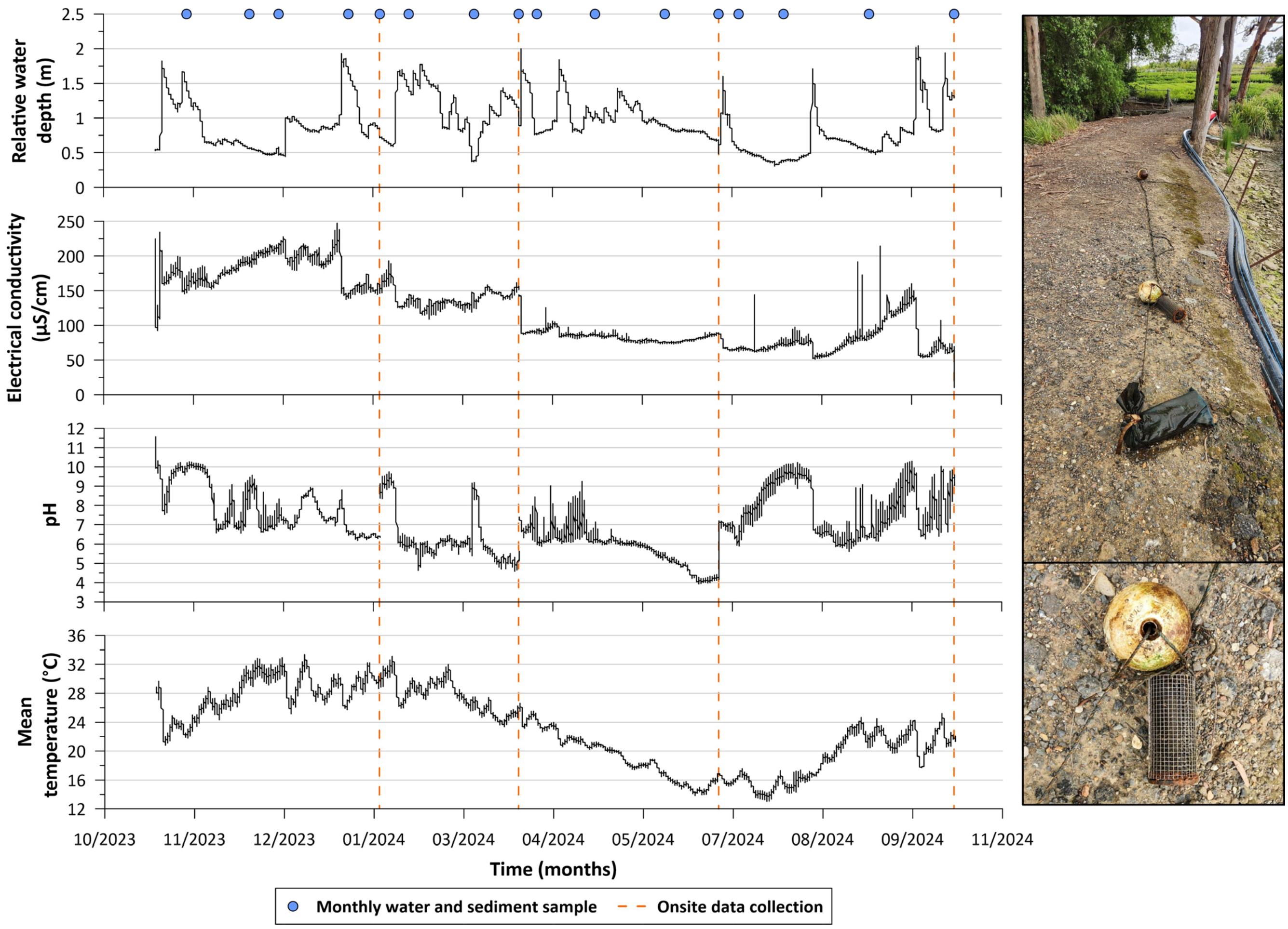


Figure 10. Example of a water quality monitoring timeseries, including water depth, electrical conductivity, pH and temperature at hourly steps. Blue dots indicate when water samples were collected manually from the reservoir and sent to DPI for laboratory analysis. Orange lines indicate when sediment sampling and sensor maintenance was undertaken. The photographs show the rope, float and anchor setup used to deploy sensors in the water storages, laid on the ground during a maintenance visit. All the sensors were housed in a small stainless-steel cage to protect them from disturbance while being deployed, retrieved or sitting in the water.

Table 2. Summary of water analysis methods used by DPI Wollongbar.

DPI method ID	Analysis method
W107	EC, pH, Alkalinity & Chloride in water by autotitrator
C806	Calculations
W112	Turbidity of water
W124	Chloride in water by FIA
M670	Elements and Metals by ICP-AES
C804	Hardness
C801	Calcium Carbonate Saturation Index
C802	Sodium Adsorption Ratio
W130	Sulfate in water by ICP
W141	Ammonia Nitrogen by FIA
W151	Nitrite Nitrogen by FIA
W153	Oxidised Nitrogen by FIA
W160	Free Reactive Phosphorus in water

Table 3. Summary of soil and sediment analysis methods used by DPI Wollongbar.

DPI method ID	Analysis method
S201	Soil pH in 1:5 water or 1:5 $CaCl_2$ suspension
S202	Soil Electrical Conductivity (1:5 soil/water extract)
S266	Available Sulfur by KCl_{40} extraction
SP901	Soil colour and texture
S262	Colwell, Bicarbonate Extractable Phosphorus in soil by FIA
S236	Organic Carbon by Walkley & Black
M630	Total Carbon and/or Total Nitrogen by Dumas Combustion
S224	Chloride in soil by FIA
S265	Calcium Chloride Extractable Boron
S267	DTPA Micronutrients (Cu, Zn, Mn, Fe)
S273	Gillman & Sumpter Exchangeable Cations
S021 & M670	Elements by block digest and ICP-AES analysis
P051 & M670	Elements by microwave digest and ICP-AES analysis
M671	Elements and Metals by ICP-MS

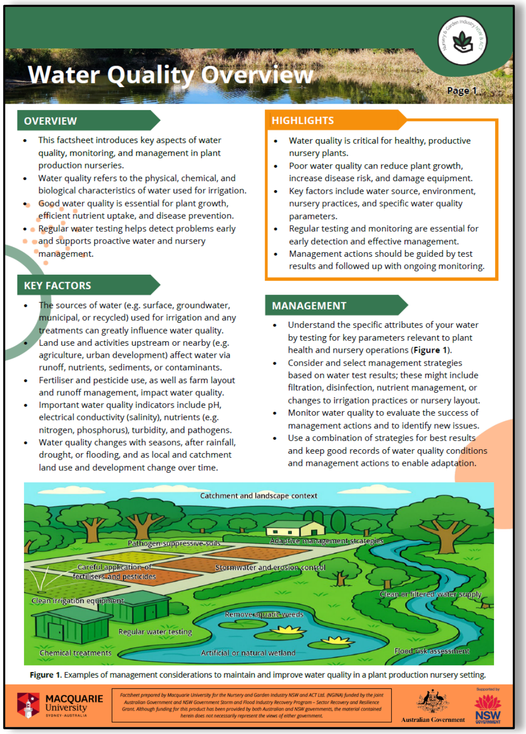
The Plant Clinic at the Botanic Garden of Sydney was commissioned to provide *Phytophthora* detection in selected production nursery water storages. Dams at four of the ten focus nurseries were tested for *Phytophthora* over eight sampling periods during the project. This involved installing multiple bait stations to test three depth levels below the surface in each of the four dams: 0.1 m, 0.5 m and 1 m. Three agar baits were installed per depth and incubated onsite for 7 days. The baits were then enriched for 4 days before DNA extraction. *Phytophthora* detection used a community DNA extraction approach followed by real-time PCR and positive samples were selected for species identification. Full details of the methods were provided in a Plant Clinic report (Plant Clinic, 2024). Weeds and aquatic biota were not directly measured as part of the project.

3.5. Develop a decision-support framework and resources

Stage 5 was related to Outcomes 1, 2 and 3, and focused on development of this adaptive framework and accompanying resources to promote understanding of hazards and risks associated with water contamination based on the findings from the project. The framework incorporates feedback from extension activities as well as scientific data on the landscape context and examples of water and contaminant profiles from the production nurseries in the three key regions. The main aim of the framework is to assist production nursery owners and managers to understand how and where water may move to and from at local and catchment levels, what water-borne contaminants may occur, and where storm and floods hazards and risks are likely to occur. The framework provides ready access to this information for incorporation into total farm planning. Before storm and flood events it may support preparation of sites to prevent water contamination, during events it could guide water sampling and options for water storage isolation and treatment, and after events it could guide assessment and reflection on water quality issues.

Fact sheets were developed as industry resources (see Ralph et al., 2025) based on information gathered for the literature review (see Gomes et al., 2025) and informed by project activities and findings. The fact sheets cover the following topics:

1. Water Quality Overview
2. Catchments and Waterways
3. Storms and Floods
4. Water Sampling
5. pH and Alkalinity
6. Salinity
7. Water Hardness
8. Heavy Metals
9. Nutrients
10. Turbidity
11. Sediment
12. Pathogens
13. Aquatic Biota
14. Weeds
15. Adaptive Management


Water Quality Overview
Page 1

OVERVIEW
- This factsheet introduces key aspects of water quality, monitoring, and management in plant production nurseries.
- Water quality refers to the physical, chemical, and biological characteristics of water used for irrigation.
- Good water quality is essential for plant growth, efficient nutrient uptake, and disease prevention.
- Regular water testing helps detect problems early and supports proactive water and nursery management.

HIGHLIGHTS
- Water quality is critical for healthy, productive nursery plants.
- Poor water quality can reduce plant growth, increase disease risk, and damage equipment.
- Key factors include water source, environment, nursery practices, and specific water quality parameters.
- Regular testing and monitoring are essential for early detection and effective management.
- Management actions should be guided by test results and followed up with ongoing monitoring.

KEY FACTORS
- The sources of water (e.g. surface, groundwater, municipal, or recycled) used for irrigation and any treatments can greatly influence water quality.
- Land use and activities upstream or nearby (e.g. agriculture, urban development) affect water via runoff, nutrients, sediments, or contaminants.
- Fertiliser and pesticide use, as well as farm layout and runoff management, impact water quality.
- Important water quality indicators include pH, electrical conductivity (salinity), nutrients (e.g. nitrogen, phosphorus), turbidity, and pathogens.
- Water quality changes with seasons, after rainfall, drought, or flooding, and as local and catchment land use and development change over time.

MANAGEMENT
- Understand the specific attributes of your water by testing for key parameters relevant to plant health and nursery operations (**Figure 1**).
- Consider and select management strategies based on water test results; these might include filtration, disinfection, nutrient management, or changes to irrigation practices or nursery layout.
- Monitor water quality to evaluate the success of management actions and to identify new issues.
- Use a combination of strategies for best results and keep good records of water quality conditions and management actions to enable adaptation.

Figure 1. Examples of management considerations to maintain and improve water quality in a plant production nursery setting.

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Factsheet prepared by Macquarie University for the Nursery and Garden Industry NSW and ACT Ltd. (NGINA) funded by the joint Australian Government and NSW Government Storm and Flood Industry Recovery Program – Sector Recovery and Resilience Grant. Although funding for this product has been provided by both Australian and NSW governments, the material contained herein does not necessarily represent the views of either government.

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Figure 11. Example of a water quality fact sheet developed in the project (Source: Ralph et al. 2025).

4. NSW and ACT production nurseries

4.1. Location of NGINA members

A total of 95 production nurseries were included in the project, and ten agreed to be involved in a more detailed capacity as the focus nurseries. Most NGINA member production nurseries are situated near the east coast on NSW, with large clusters near Sydney and Northern Rivers (Figure 12). Four focus nurseries were in the Northern Rivers region, four in the Northern Sydney region, and two in the Central Coast region. Results from water quality monitoring and other activities at the focus nurseries are used to extrapolate information about general water contamination concerns across the industry, although the data and findings presented from the focus nurseries have been anonymised for this purpose (each focus nursery was assigned a letter ID at random from A to J).

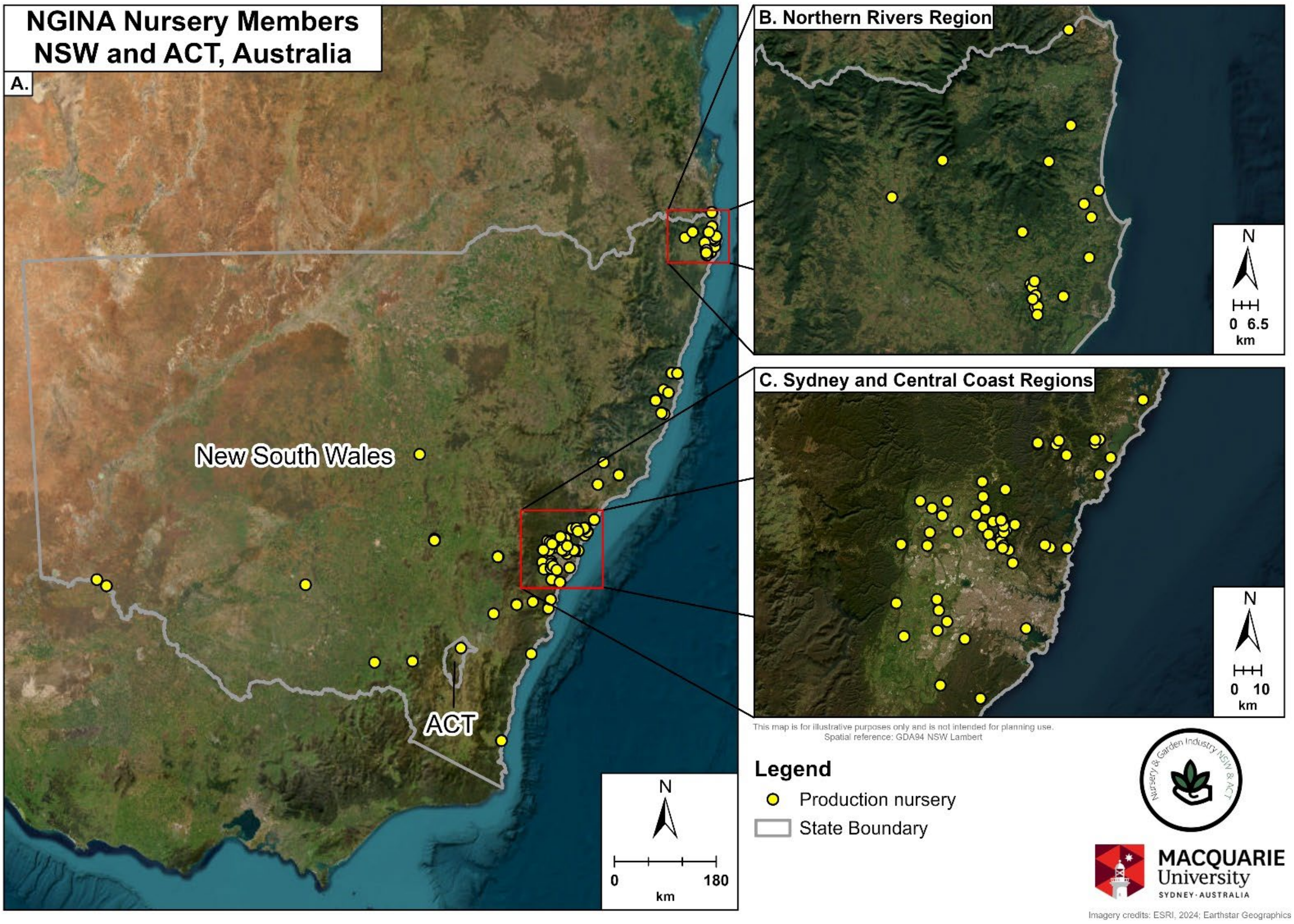


Figure 12. The location of 95 NGINA member production nurseries (yellow circles) included in the project and distributed across A) NSW and ACT, including the 2021 disaster-declared production regions B) Northern Rivers and C) Sydney and Central Coast. Four focus nurseries were situated in the Northern Rivers region, four in the Northern Sydney region, and two in the Central Coast region.

4.2. General catchment and nursery lot metrics

Catchment area of the production nurseries varied across all key production regions and within regions, with a mean area of 5.6 km^2 (min 0.56 km^2 and max 19.5 km^2) (Figure 13A). The majority of catchments (80 %) were smaller than 8 km^2. Production nursery lot size also varied within and between regions, with a mean nursery lot boundary area of 0.16 km^2 (min 0.005 km^2 and max 2.23

km^2) (Figure 13B). Some 37 % of the nursery lot boundaries were greater than 0.1 km^2. The average drainage line length (i.e. length of flow paths) and drainage density of the catchments were 25 km (min 2.3 km and max 90 km) and 5 km (min 3 km and max 7 km), respectively (Figure 13C and D). The mean number of entry flow points onto production nursery properties was 21 (min 9 and max 60). Similarly, the mean number of exit flow points from nursery properties was 21 (min 5 and max 56) (Figure 13E and F). The mean area of water storage dams on nursery properties was 3.2 km^2 (min 0.1 km^2 and max 50 km^2) (Figure 3G).

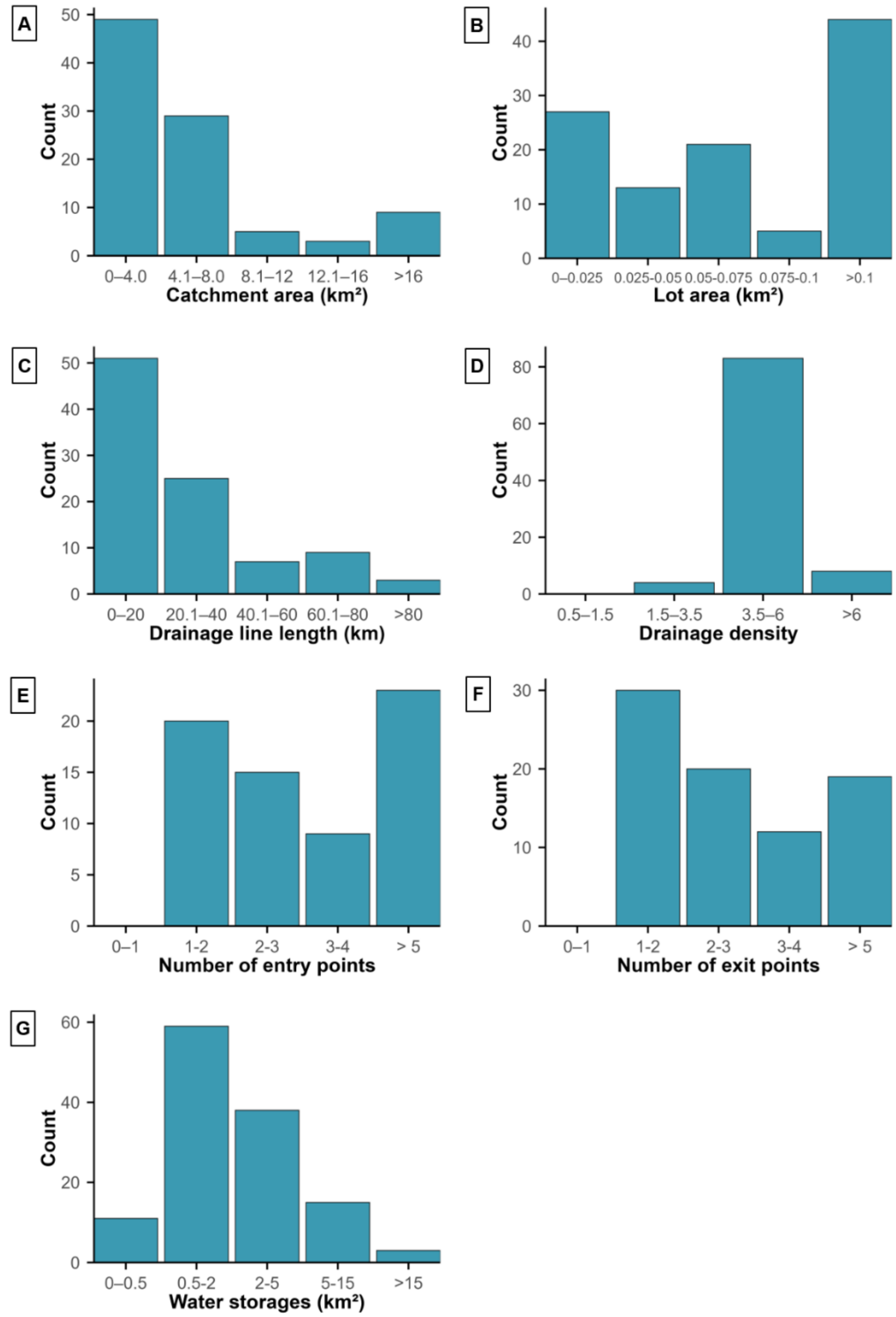


Figure 13. Catchment and lot metrics for all the production nurseries included in the project, including A) catchment area, B) nursery lot area, C) drainage line length, D) drainage density, E) number of flow entry points onto nursery properties, F) number of flow exit points off nursery properties, and G) size of water storage dams on nursery properties.

Catchment characteristics are also important to consider when understanding the likelihood of inundation and potential storm and flood impacts. The topography of a catchment is a good predictor of where water is likely to accumulate in the landscape and can provide information on areas that could potentially be inundated during a range of rainfall events. For the 10 design rainfall scenarios modelled in HEC-RAS, the percentage of likely inundation hotspot area was normalised to catchment size and plotted to show the overall trend for production nursery catchments. The results indicate that while potential inundation does increase with more extreme rainfall scenarios, less than 50 % of the area of all catchments were likely to be inundated under all rainfall scenarios (Figure 14A).

Similarly, the percentage of likely inundation hotspot area was normalised to nursery lot size and plotted to see the overall trend related to the 10 modelled rainfall scenarios. The results indicate that the potential inundated area of the production nursery lots increases quite rapidly with higher rainfall scenarios, and that under extreme rainfall scenarios the percentage inundation area of the lots becomes very high (Figure 14B). This suggests that moderate, large and extreme rainfall events have the potential to inundate a significant area of the nursery lots, with some perhaps experiencing 100 % inundation under the most extreme and infrequent events modelled.

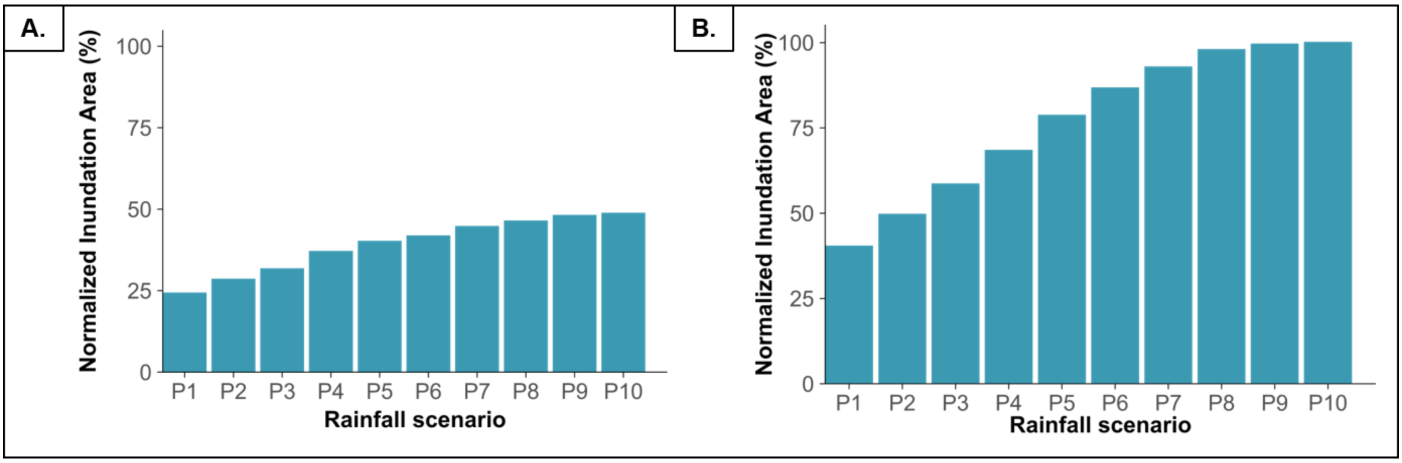


Figure 14. The percentage of inundation area for the A) catchment area and B) nursery lot area under different modelled design rainfall scenarios for the 95 nurseries included in the project. Inundation area is normalised for catchment size and lot size in each graph. The design rainfall scenarios used are explained in Table 1.

5. Framework for adaptive management

The adaptive management framework designed and implemented in this project addresses the main objectives, to assess and understand the potential impacts of storm- and flood-related water contamination at production nurseries, and to provide guidance to support the NSW and ACT industry in its goal to become more resilient in the face of future storm and floods events. An adaptive management cycle is a structured, iterative process for decision-making and focuses on adjusting management strategies based on outcomes and new information. An adaptive management approach will assist production nurseries to anticipate, respond to, and recover from storm and flood events. The approach emphasises three phases, including: 1) before a storm or flood (pre-event prevention and planning; 2) during a storm or flood (during-event monitoring and action); and 3) after a storm or flood (post-event recovery and assessment) and outlines key steps to take in each phase (Figure 15).

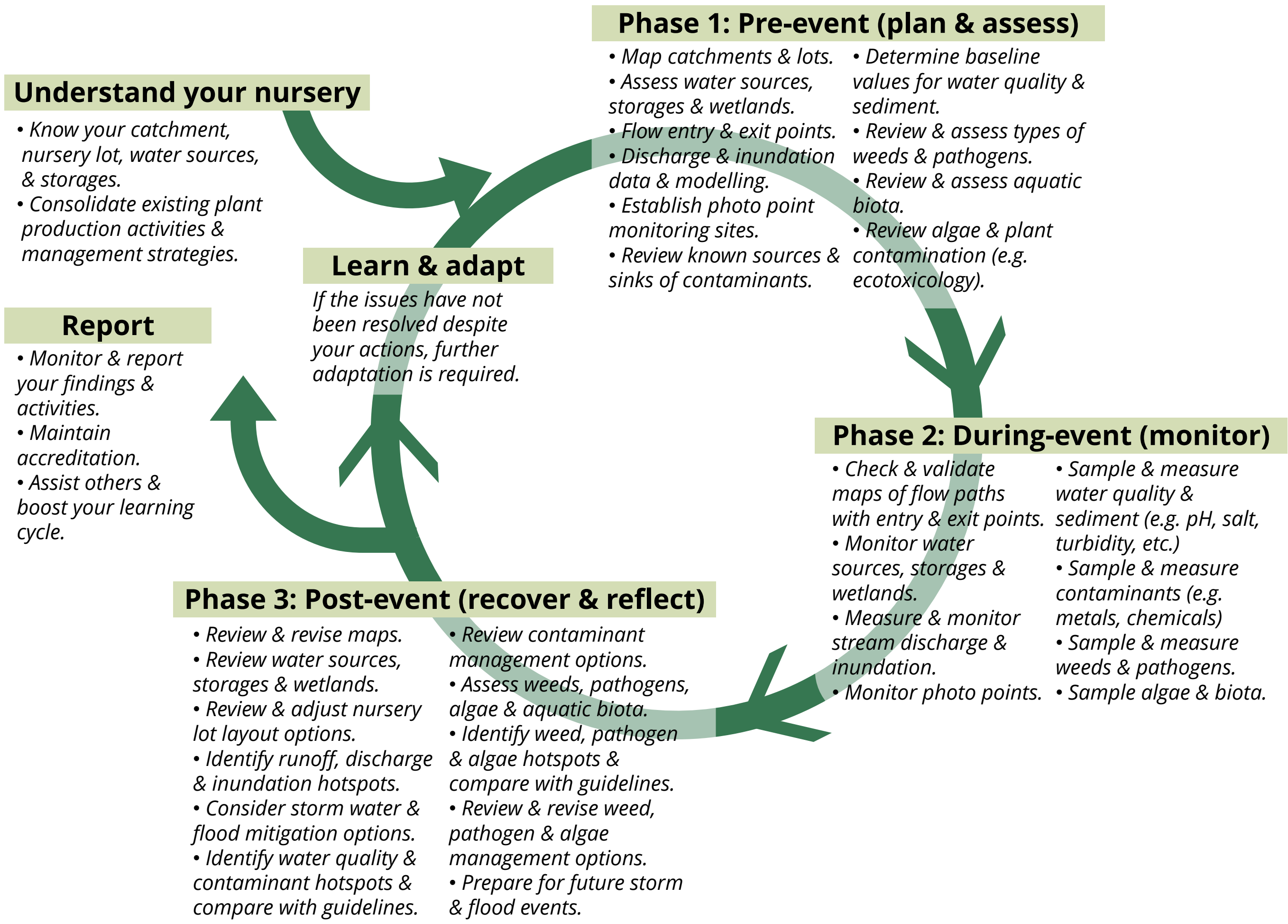


Figure 15. Summary of the framework for adaptive management of water storage contamination concerns at production nurseries.

5.1. Phase 1 Pre-event (plan and assess)

Phase 1 focuses on understanding potential water contamination issues and identifying measures that can be put in place to prevent or reduce hazards and risks to water quality associated with storm and flood events. To do this, owners, managers and staff must know their nursery and their catchment, including flow paths, water sources, storages, and their existing plant production activities and management strategies. Prevention involves assessing and identifying water-borne contamination risks using available information and having a short-list of measures to reduce the impacts. It includes actions like preparing maps of flow paths and catchments, locating and observing potential inundation hotspots or other flood-prone areas, understanding baseline water quality conditions and likely changes over time, maintaining and improving drainage systems, implementing infiltration systems (e.g. vegetated buffer strips or constructed wetlands), and planning water storage capacity to mitigate overflow impacts during storm and flood events. Prevention options may also include moving valuable stock to higher ground or fortifying infrastructure to withstand flood impacts, linked back to a holistic production nursery management strategy and existing site operational plans and actions.

5.2. Phase 2 During-event (monitor)

Phase 2 focuses on actions that can be taken during storm and flood events to help reduce the impacts of poor water quality on plant production activities and infrastructure. For instance, regular water and sediment sampling and testing (or monitoring) are important during an event to gain real-time insights into any changes that are occurring and the potential for negative impacts on the nursery. This can be performed using handheld meters to directly test the water or by collecting samples to be sent away for more detailed laboratory analysis. Site water and sediment sampling can also be supplemented by photo points to allow assessment of water levels, turbidity and algal patterns that visibly change over hours and days during storm and floods events. Collecting samples from multiple locations within a production nursery (e.g. standing water around plant beds and containers, running water in drains, overflow water in channels) provides a comprehensive view of water quality allowing early detection and potentially tracking of contaminants. It is also critical to observe and assess water flow paths and storages during the event to ensure that water moves and accumulates in the predicted spots. Validation of catchment and lot maps is important if the maps are to be updated and reused in the future. If algae or water-borne plant pathogens were a problem, or aquatic biota was heavily affected by the storm or flood events, then observations of those factors will help moving into phase 3. Specific strategies for those may be developed if they were not considered beforehand.

5.3. Phase 3 Post-event (recover and reflect)

Phase 3 focuses on recovering and reflecting on the events and responses from phases 1 and 2, to assess whether the steps taken before and during those phases were effective, and which can be adjusted to improve overall water quality and production nursery management outcomes. Recovery involves reviewing and refining information and actions based on site-specific experiences. Storm and flood mitigation options should be revisited as needed, and guidelines for water quality checked considering the observations made and samples or measurements of water quality obtained during recent storm and flood events. On-ground actions may include repairing soil and plant damage, restoring affected infrastructure and areas, treatment of contaminated water, and updating site layout options and water management plans based on new information. Specific strategies for algae or water-borne plant pathogens management may need to be developed, or for aquatic biota in unlined dams with high ecological value, based on the observations from recent events. Reporting is also a key aspect of phase 3, when findings and experiences can be shared with neighbours, to assist others, to boost the learning cycle and to maintain industry accreditation, as needed.

A critical aspect of this phase of the adaptive management cycle involves learning and adapting to storm and floods events, and production nursery responses to these events, to address or resolve issues and to prepare for the future. The learning cycle aims to provide opportunities for continuous improvement, where insights gained from each phase is used to inform better planning, faster responses, and more effective recovery in the future. The benefits of implementing adaptive management include: 1) flexibility, enabling production nursery managers to adjust their strategies as new information becomes available; 2) management of risk, by incorporating multiple approaches to deal with a problem; and 3) strengthening operations, by improving short- and long-term outcomes through the integration of knowledge through each management cycle.

6. Science and resources supporting the framework

The adaptive management framework is supported by the five key research themes of this project, including landscape setting, runoff and hydrology, water and soil contaminants, plant pathogens and weeds, and aquatic biota. Within each of the five themes, specific research objectives were addressed using data collected and analysed for all the nurseries. The framework draws on this information to identify and prioritise actions and to emphasise an adaptive management cycle that can help build resilience in the production nursery industry to future storm and flood events.

6.1. Landscape setting

KEY POINTS

- Understand your catchment, nursery lot, water sources, and water storages.
- Maintain up-to-date maps of catchments and nursery lots and water-related features.
- Monitor catchment conditions and update information as required.
- Review and revise maps to plan for the future.
- See fact sheets 1, 2, 3, 11 and 15.

The landscape setting and catchment characteristics of a production nursery play an important role in water management. Specifically, catchment position and geomorphic characteristics (i.e., topography, vegetation, surrounding land use type) can influence surface runoff dynamics. The catchment position of production nurseries influences whether they are at a higher or lower risk of receiving water with contamination from uphill or upstream. Production nurseries near the upper catchment boundary are mainly exposed to rainfall but will have runoff to downstream areas. Nurseries located in the middle catchment will be exposed to water from hillslopes, upstream, rainfall, and will generate runoff. Nurseries near the bottom of the catchment will be exposed to water from hillslopes, flood waters from the river, rainfall, and will have runoff into rivers.

Landscape setting should be considered in all three phases of the management cycle (Figure 16).

Phase 1: Before an event, understanding the position of a production nursery in the landscape and its flow paths and water storage locations can help mitigate storm and flood risks (Figure 17). Priorities include:

- ***Catchment and flow path mapping:*** Map sub-catchment boundaries around the nursery properties as well as the main flow paths to identify where water flows across the landscape to inform where potential floodwater may be routed (Figures 18 and 19).
- ***Water storage and wetland positions:*** Map all reservoirs, dams, tanks and any natural or artificial wetlands. In anticipation of heavy rainfall, capacity can be increased in storages by lowering the water level to temporarily store excess water and act as a buffer to flooding.
- ***Nursery flow entry and exit points:*** Identify and map where water typically enters and exits the nursery properties during rainfall events. These points are crucial for assessing flood risk and ensuring that controlled drainage paths funnel water away from sensitive areas and into water storage facilities efficiently.

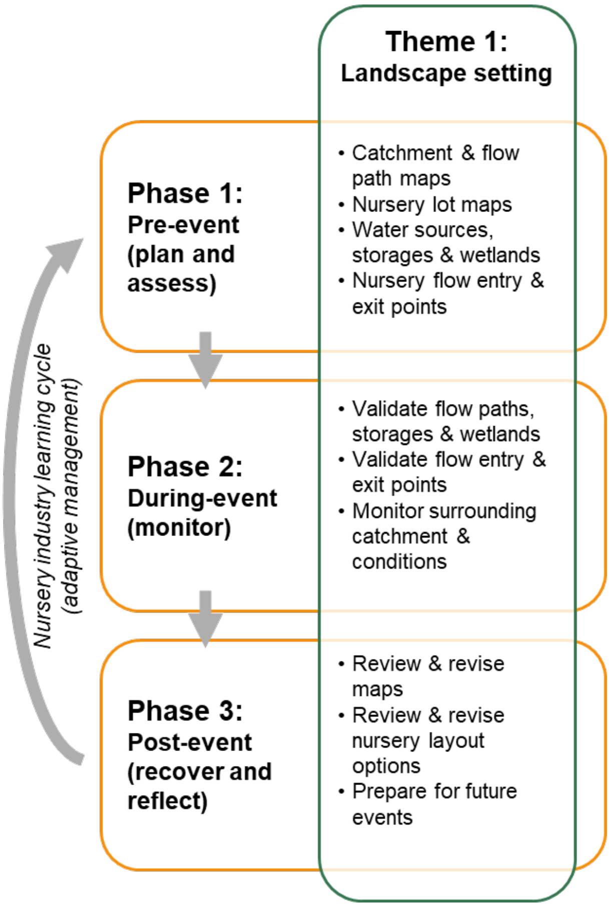


Figure 16. Priorities for landscape setting across the three phases of the cycle.

Phase 2: During an event, real-time observations, monitoring and validation of flow paths and assessments of catchment and infrastructure functions are essential. Priorities include:

- ***Validation of flow paths, storages, and wetlands:*** Ground-truth the flow paths to confirm that they are correct. Monitor water storage facilities and wetlands (if present) to assess whether they are functioning as planned. By validating and monitoring the flow paths, maps can be updated, and management strategies prioritised.

- ***Validation of flow entry and exit points:*** Check that water is entering and exiting the nursery through the mapped points. If these points are breached or blocked during heavy rainfall, measures can be put in place to help redirect flow to minimise damage and flooding.
- ***Monitoring catchment conditions:*** Routinely check what is going on around the nursery lot.

Phase 3: After an event, a thorough assessment of water damage to the property and infrastructure will help inform and improve management plans and flood response to future events. Priorities are:

- ***Review catchment maps:*** Update and refine catchment maps based on observed flood behaviour, to better reflect actual water movement and flow paths across the landscape.
- ***Review flow path and water storage maps:*** Adjust maps to accurately reflect flow paths, water storage locations, and entry and exit points. Assess whether drainage, water storages, vegetative buffers or wetlands were effective at reducing flood impacts.
- ***Review lot options and prepare for future events:*** Decide whether additional measures need to be installed or otherwise employed to reduce surface runoff on the property.

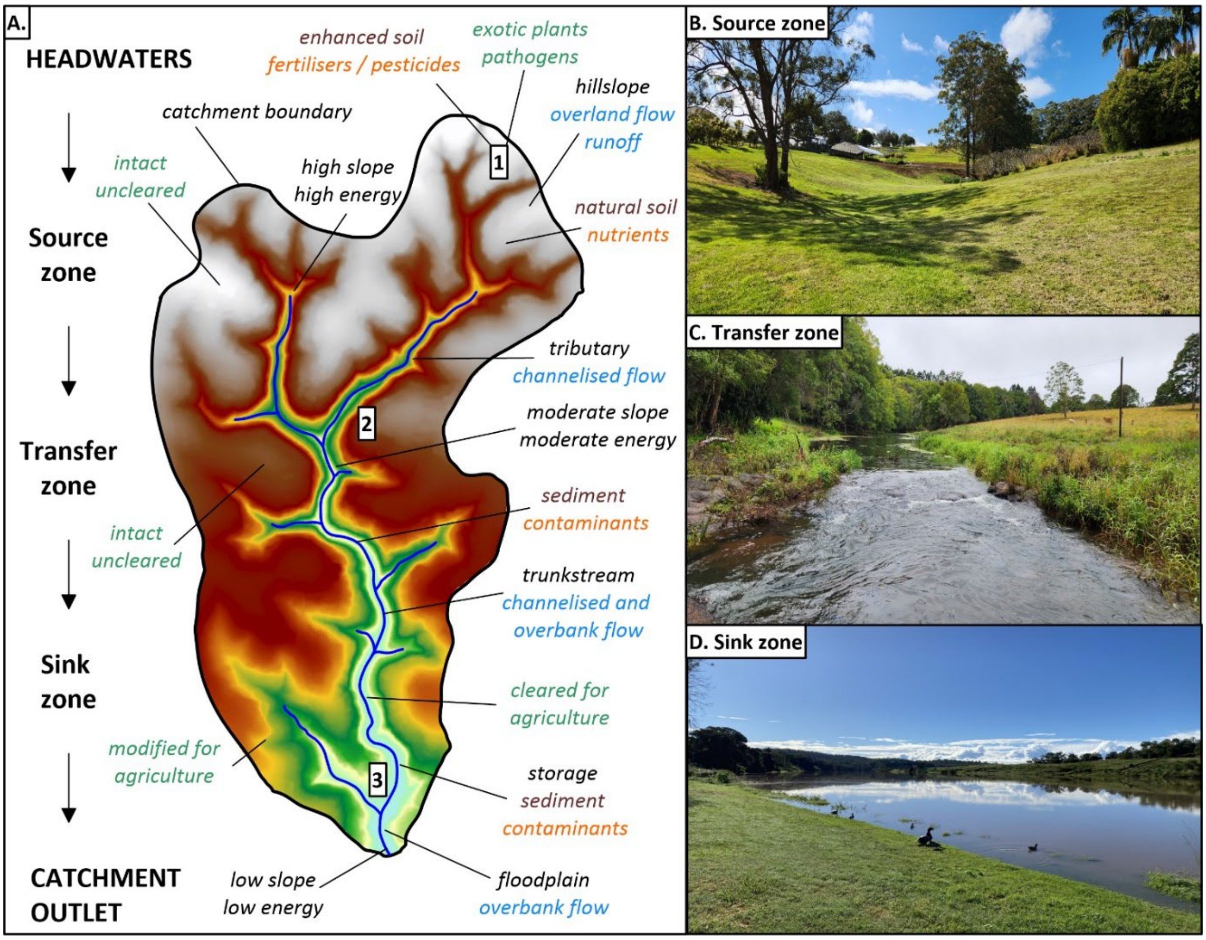


Figure 17. Schematic diagram of A) catchment characteristics and processes that may influence the transfer of water and contaminants to and from production nurseries. A nursery at position 1 near the catchment boundary in the source zone (photo B) is mainly exposed to rainfall but will have runoff to downstream areas. A nursery at position 2 in the middle catchment transfer zone (photo C) is exposed to water from hillslopes, upstream, rainfall, and will generate runoff. A nursery at position 3 in the catchment sink zone (photo D) is exposed to water from hillslopes, flood waters from the river, rainfall, and will have runoff into the river. Text colours in A) represent physical features (black), soil and sediment processes (brown), water processes (blue), contaminant and nutrient processes (orange), and vegetation processes (green) (Source: Gomes et al., 2025).

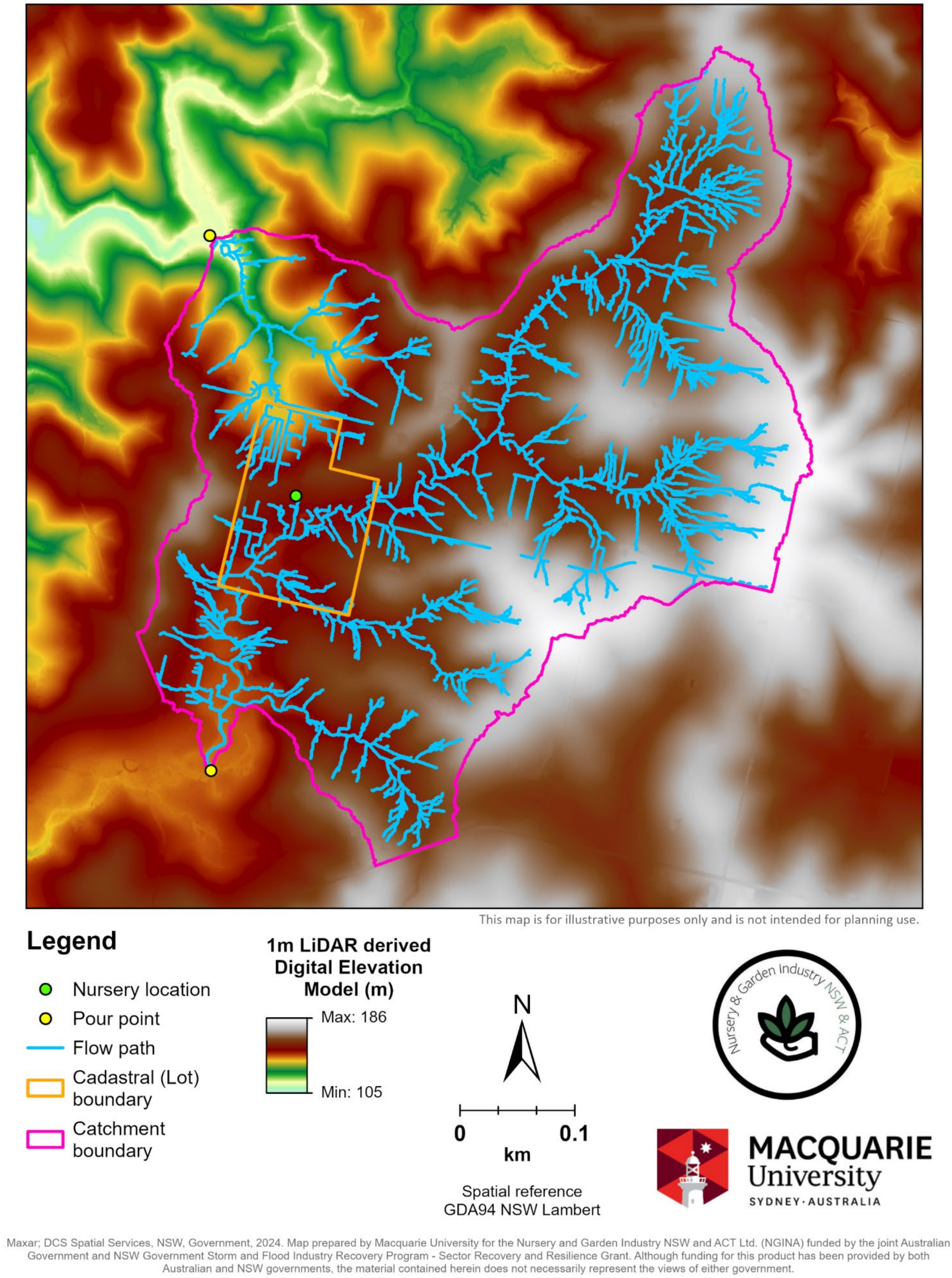
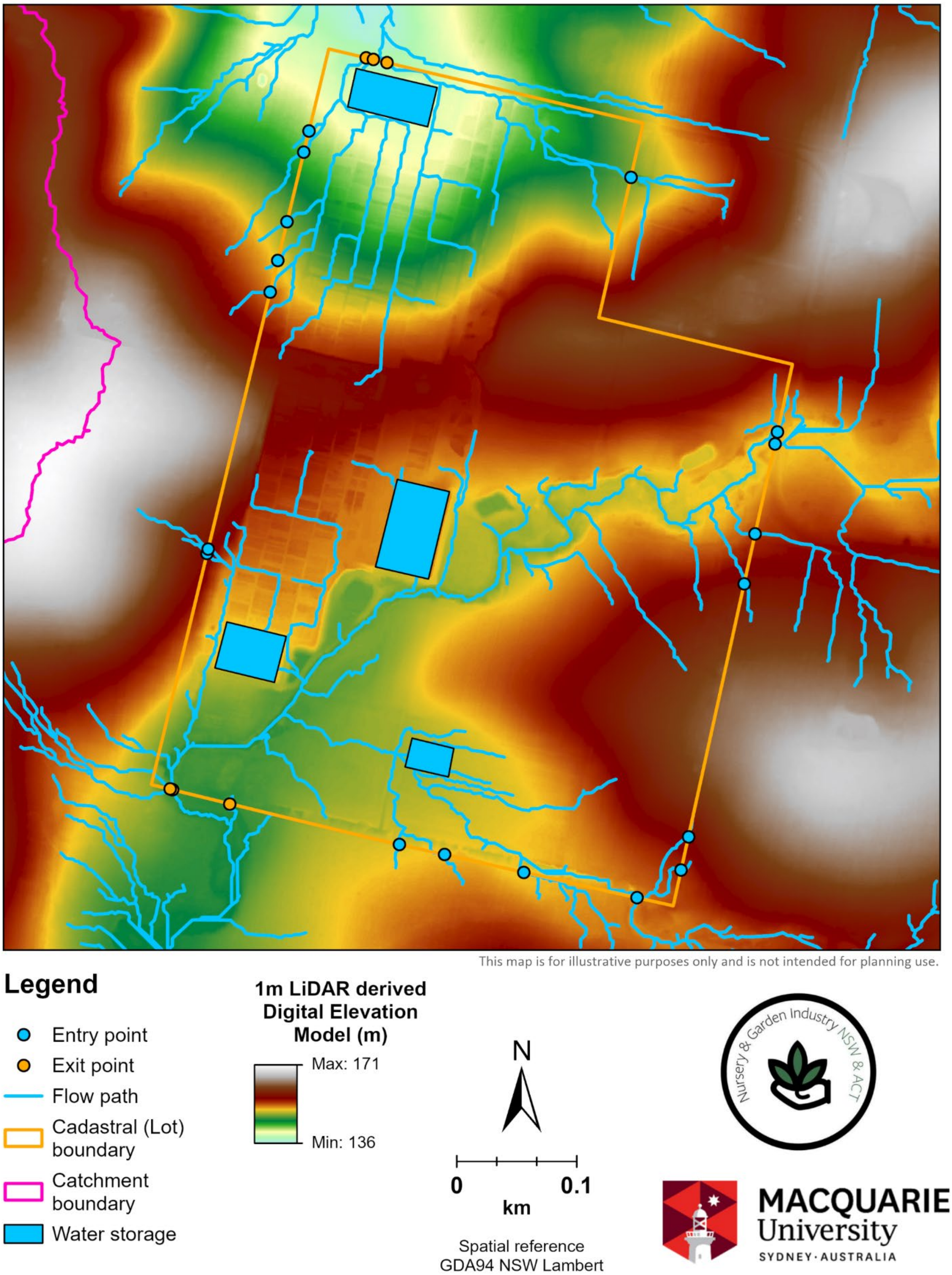


Figure 18. Example of detailed mapping of flow paths based on topography derived from a high-resolution 1 m DEM in the catchment around a production nursery.



Maxar; DCS Spatial Services, NSW, Government, 2024. Map prepared by Macquarie University for the Nursery and Garden Industry NSW and ACT Ltd. (NGINA) funded by the joint Australian Government and NSW Government Storm and Flood Industry Recovery Program - Sector Recovery and Resilience Grant. Although funding for this product has been provided by both Australian and NSW governments, the material contained herein does not necessarily represent the views of either government.

Figure 19. Example of detailed mapping of flow paths, water storages and flow entry and exit points based on topography derived from a high-resolution 1 m DEM within the lot of a production nursery.

6.2. Runoff and hydrology

KEY POINTS

- Mapping and modelling can identify runoff, erosion and potential inundation hotspots.
- Photo point monitoring is useful for visual inspection of water levels and water quality in water storages.
- Obtain storm and flood information if possible and establish monitoring sites and strategies.
- See fact sheets 1, 2, 3, 11 and 15.

Surface runoff and hydrology is influenced by flow paths, connectivity and position in the landscape. Other factors influence flow paths and connectivity, including topography and land use. For instance, nursery properties located at the bottom of a hillslope, surrounded by intensive agriculture or urban areas, may be highly connected to upstream areas and receive a lot of water from surrounding areas. These nurseries may be at higher risk of storm and flood impacts and water-borne contaminants. Assessment and modelling of potential flows and inundation patterns can provide insights into which areas are highly connected and may be at risk in and around production nurseries.

Runoff and hydrology should be considered in all three phases of the management cycle (Figure 20).

Phase 1: Before an event, assessing runoff and hydrological processes such as flow energy and potential inundation hotspots can help identify areas that may be at risk of flood damage and water-borne contaminants in catchments and on production nursery lots. Priorities include:

- ***Assessment of flow path connections, slope and stream power:*** Evaluate slope and flow path patterns in the catchment and nursery lot. Some of these may be directly linked to land use. Metrics such as stream power index (SPI) indicate where higher energy flows may occur, which will provide insights into likely infiltration, surface runoff, and erosion potential (Figure 21).
- ***Discharge and inundation modelling:*** GIS-based indices such topographic wetness index (TWI) can provide information about where water is likely to accumulate in the landscape (Figure 22), and hydraulic models may be used to simulate where inundation hotspots could occur under various rainfall scenarios (Figure 23).
- ***Establishment of photo point monitoring sites:*** Set up photo points at key locations near streams, storages, and wetlands to provide visual records of pre- and post- flood conditions (e.g. water level and water quality). Heavy rainfall events or flooding can increase nutrient inputs into water storages, which can result in increased turbidity, algal blooms and potential aquatic weed growth that can be seen and monitored with photographs (Figure 24).

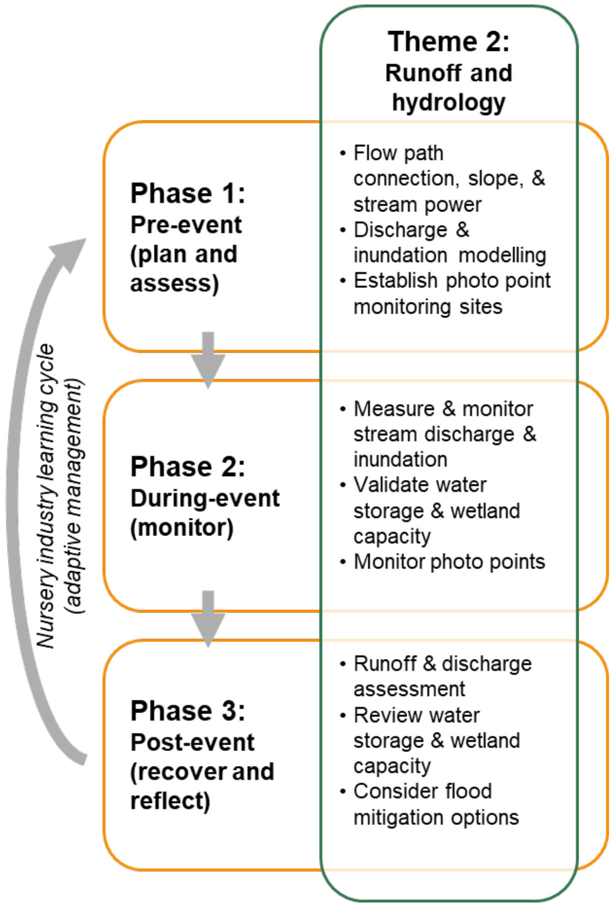
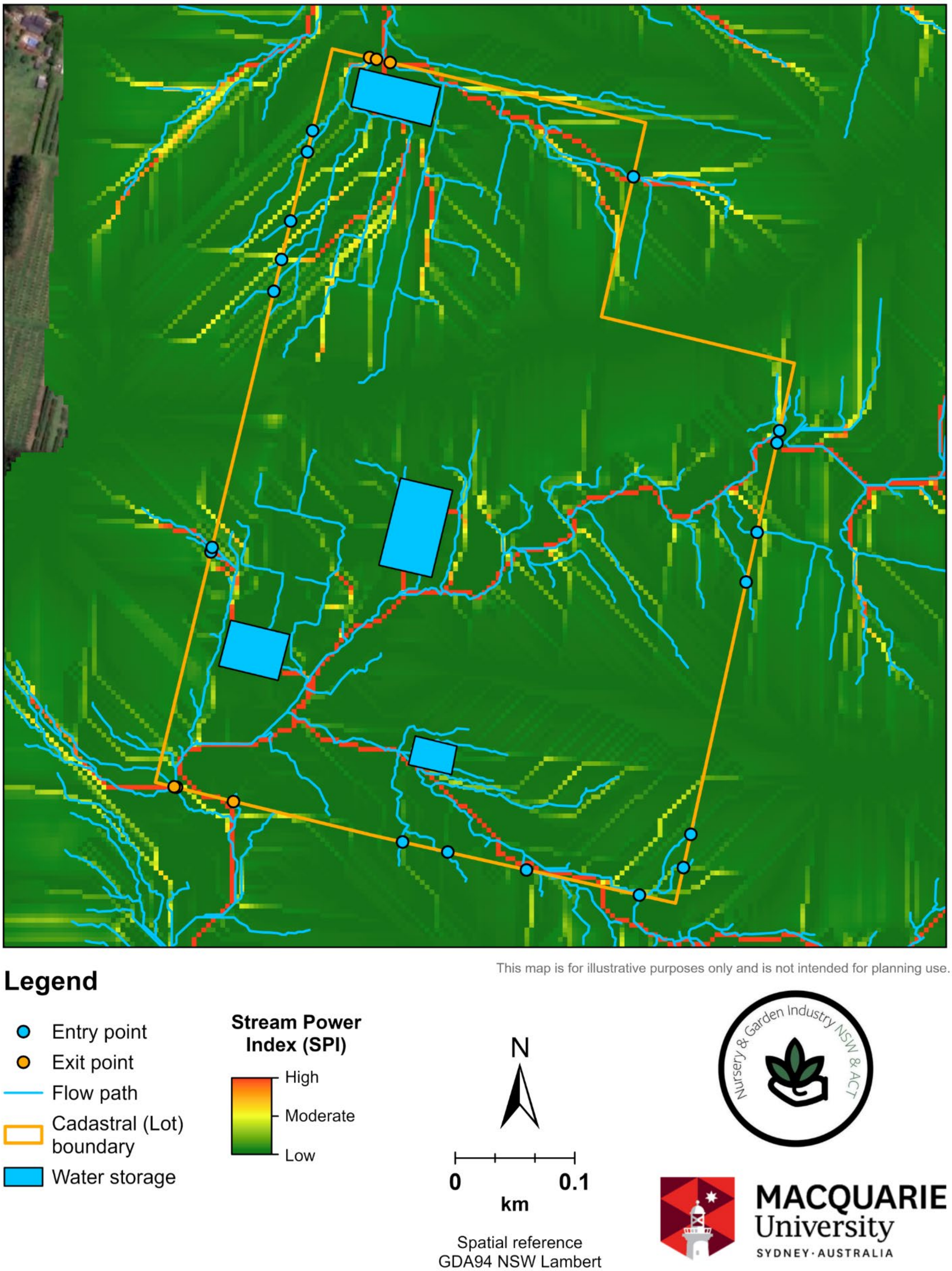
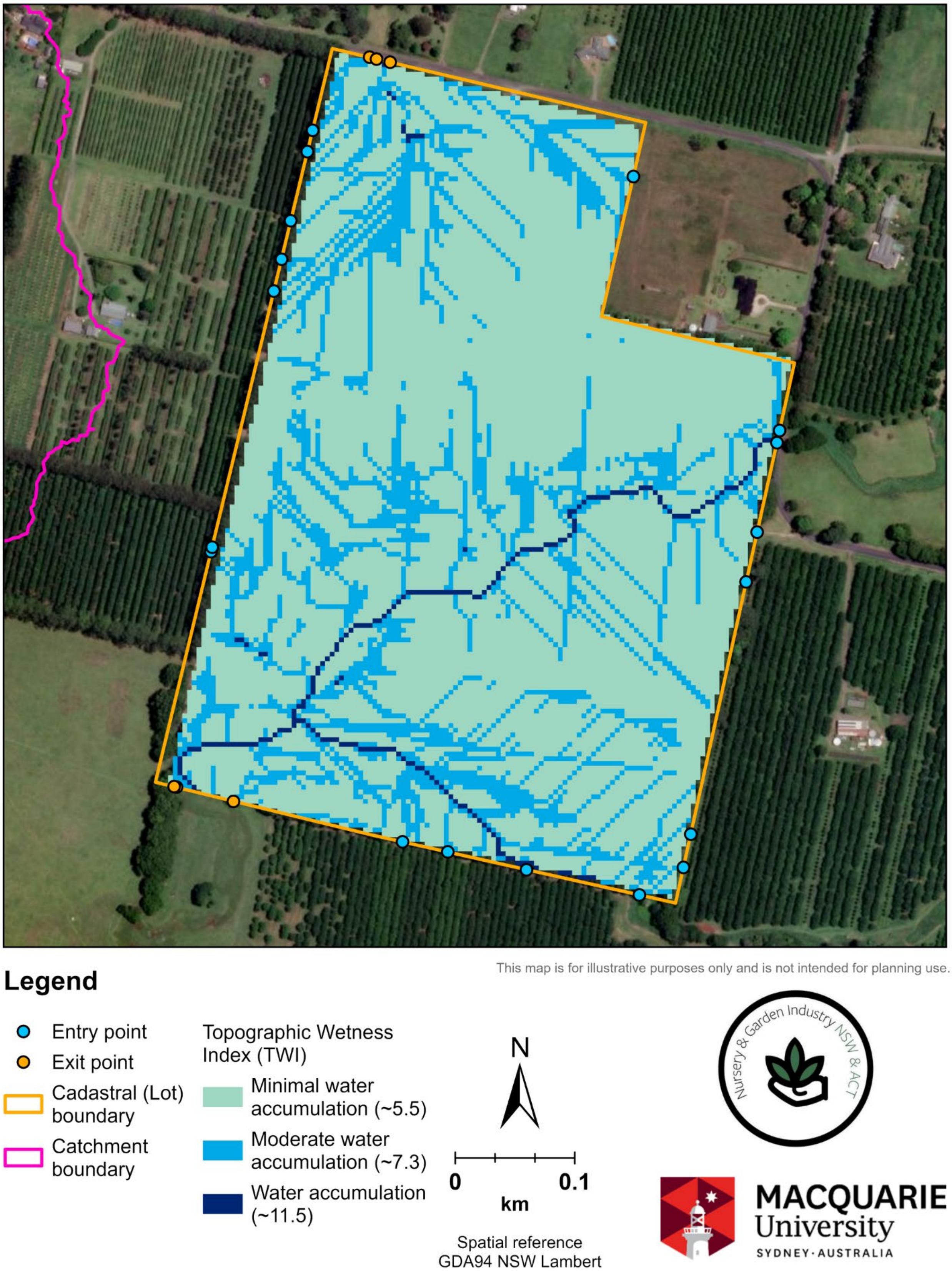


Figure 20. Priorities for runoff and hydrology across the three phases of the cycle.



Maxar; DCS Spatial Services, NSW, Government, 2024. Map prepared by Macquarie University for the Nursery and Garden Industry NSW and ACT Ltd. (NGINA) funded by the joint Australian Government and NSW Government Storm and Flood Industry Recovery Program - Sector Recovery and Resilience Grant. Although funding for this product has been provided by both Australian and NSW governments, the material contained herein does not necessarily represent the views of either government.

Figure 21. Example of detailed mapping of potential high slope and erosion-prone areas, defined by stream power index (SPI), within the lot of a production nursery.



Maxar; DCS Spatial Services, NSW, Government, 2024. Map prepared by Macquarie University for the Nursery and Garden Industry NSW and ACT Ltd. (NGINA) funded by the joint Australian Government and NSW Government Storm and Flood Industry Recovery Program - Sector Recovery and Resilience Grant. Although funding for this product has been provided by both Australian and NSW governments, the material contained herein does not necessarily represent the views of either government.

Figure 22. Example of detailed mapping of potential wet areas, defined by topographic wetness index (TWI), within the lot of a production nursery.

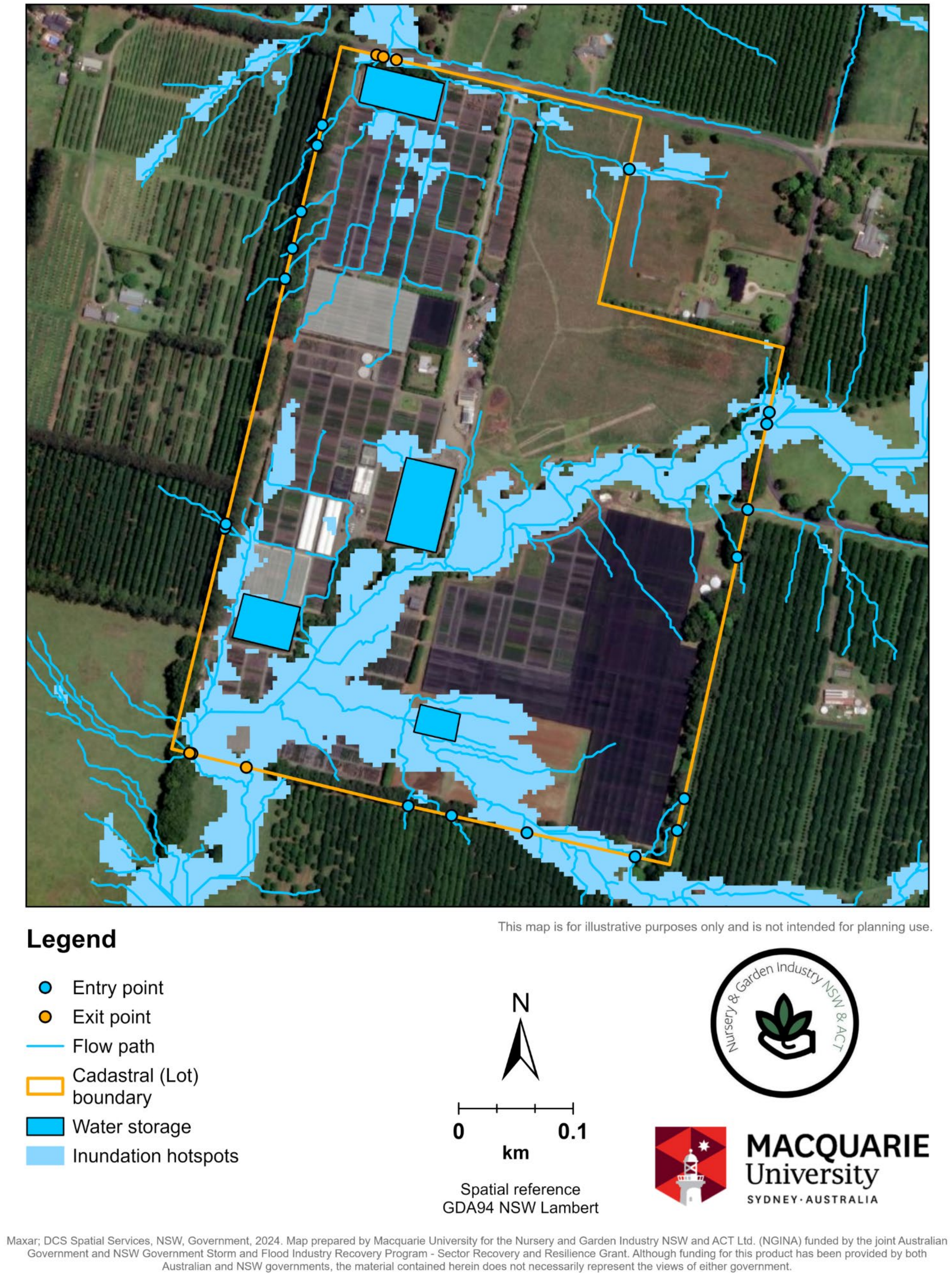


Figure 23. Example of detailed mapping of potential inundation hotspots, defined by overlapping HEC-RAS model results based on ten design rainfall scenarios, within the lot of a production nursery.

Figure 24. Example of photo point monitoring of a water storage showing changes in water level and water quality indicated by turbidity and growth of algae. A) before rainfall and runoff, B) during rainfall and runoff, C) hours after rainfall and runoff, and D) days after rainfall and runoff. Following a rainfall event water level will increase and water may become more turbid, contributing to growth of algae.

Phase 2: During an event, observing and measuring water and checking infrastructure capacity and effectiveness are essential. Priorities include:

- ***Water measurement and monitoring:*** Measuring and monitoring water levels in storages, overland runoff areas and, if possible, stream discharge in nearby creeks and rivers, will help to assess the volume and velocity of water flowing during an event. Assessing real-time data from government-maintained water gauges on major rivers can ensure awareness of potential riverine flooding risks and whether any actions are needed.
- ***Validation of water storage and wetland capacity:*** Observe water storage areas and wetlands (if present) to determine whether they overflow. As they near capacity, additional measures like controlled drainage or overflow relief may be necessary to prevent breaches.
- ***Photo point monitoring:*** Capture images at established photo sites to document real-time changes in water levels and water quality. These images can help direct management actions, for instance treating water or waiting several days after heavy rainfall before using it for irrigation to reduce contaminant dispersal.

Phase 3: After an event, assessing runoff behaviour and evaluating storage capacity can inform whether improvements are necessary for flood mitigation planning. Priorities include:

- ***Runoff and discharge assessment:*** Evaluate flow data and runoff observations to assess whether these matched expected patterns. This helps refine inundation estimates from models and identifies areas needing improved drainage, buffer zones, or additional water storage capacity that will help preparations for future storm and flood events.

- ***Review water storage and wetland capacity:*** Review whether water storage facilities and wetlands (if present) behaved as expected based on observed performance. Update the capacity or implement structural modifications to improve resilience to future events.
- ***Flood mitigation options:*** Based on data gathered throughout the event, identify additional mitigation strategies that can be implemented to reduce the risk of future events. For example, expand water storage capacity, add vegetation strips, or improve or construct wetlands to mitigate runoff and increase filtration (Figure 25), and reinforce stream banks to prevent erosion. Other options in wet areas may be to raise plant containers off the ground or to move valuable stock to higher ground to reduce inundation and water-borne contamination risks.

Figure 25. Example of A) unlined and B) lined water storages at production nurseries. Unlined storages lose some water to infiltration but have greater potential to support vegetation that will help to mitigate storm and flood impacts and provide wetland habitat with flow-on benefits to water quality. Lined storages lose less water to infiltration but support minimal vegetation and usually have limited wetland ecosystem benefits.

6.3. Water and soil contaminants

KEY POINTS

- Review and understand contaminant sources, transport pathways, and sinks.
- Measure and monitor water, soil, sediment and contaminants using a range of methods.
- Evaluate contaminants, compare to guidelines, and assess hotspots and critical control points.
- Implement best management practices.
- See fact sheets 1, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 15.

Identifying and understanding the types and amounts of contaminants that are likely to be present in water storages at production nurseries is important to adequately mitigate water contamination concerns. In addition, identifying potential sources of contaminants is crucial to inform management efforts. During storm and flood events, surface runoff can transport contaminants across the landscape and into and out of production nursery lots. For example, nurseries may receive runoff from adjacent agricultural fields with a combination of physical (e.g. silt), chemical (e.g. salt, nutrients) or biological (e.g. pathogens) contaminants.

Water and soil contaminants must be considered in all phases of the management cycle (Figure 26).

Phase 1: Before an event, understanding potential water storage contaminant sources and baseline water quality and soil or sediment conditions is essential for planning and mitigating risk. Priorities include:

- ***Review known sources and sinks of contaminants:*** Identify and document potential sources of contaminants likely to be in a nursery lot, or to enter a nursery lot during an event. Knowing the sources and sinks can help target high-risk areas for monitoring and remediation.
- ***Review baseline values for water, soil and sediment quality at nurseries:*** Collect baseline data for water, soil and sediment quality, focusing on key indicators like pH, salinity, turbidity, and heavy metals. Assess water quality using a handheld meter or collect water and soil samples for laboratory analysis. Collect samples from multiple locations around the nursery to get a representative view of initial conditions. These baseline values serve as a reference for assessing any changes in water, soil and sediment quality after flood events.

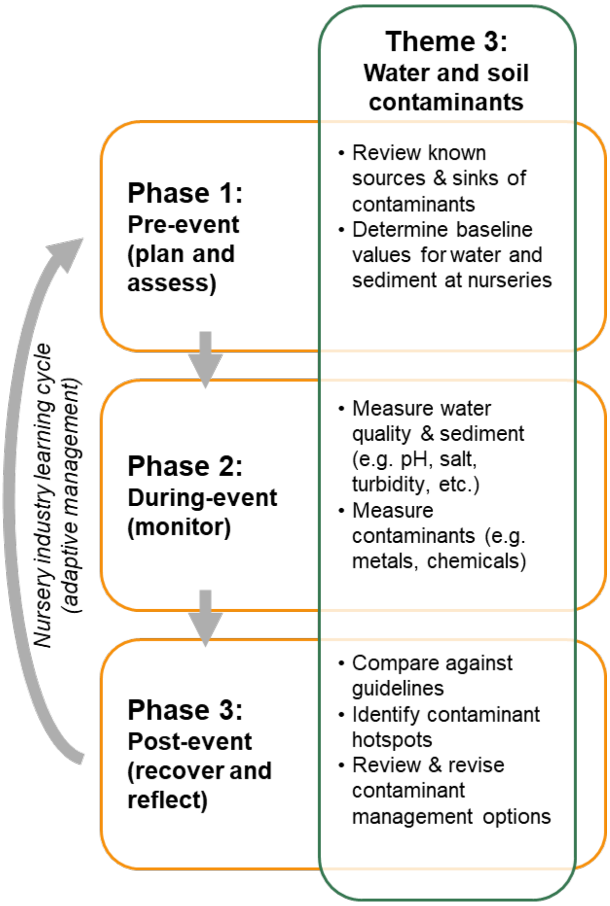


Figure 26. Priorities for water and soil contaminants across the three phases of the cycle.

Phase 2: During an event, measure and sample for water quality regularly, and/or maintain water sensors to allow for real-time monitoring of water, soil and sediment quality during flood events. This will allow for early detection of contaminants that may have been mobilised by floodwaters and that may pose a risk to plant production. Priorities include:

- ***Spot measurements of water, soil and sediment quality:*** Conduct regular spot checks of water, soil and sediment to detect changes in their quality from the baseline values as well as against water quality standards for NSW. This may be done using a handheld meter, or by taking water, soil and sediment samples and sending them to an accredited laboratory for testing. Sediment samples from the bottom of water storages can provide information about specific contaminants like heavy metals and nutrients that can be harmful to plants.

- ***Real-time water monitoring:*** Install and maintain water quality sensors in water storages to monitor water quality parameters, such as pH, electrical conductivity (EC), temperature and water depth. These sensors can collect data at a finer temporal resolution than manual sampling or testing, allowing nursery managers to identify changes in water quality in real time. For example, data collected from water quality sensors installed in water storages of the ten focus nurseries in this project provide information on water quality at an hourly time-interval for a one-year period (Figure 27). Results show that water quality parameters fluctuate over time in relation to external factors. For example, a coincident increase in pH and reduction in EC may be explained by addition of freshwater during rain events, while other factors such as evaporation, biological activity, low water levels and nutrient inputs can lead to concentration of salts and organic materials. Monitoring allows real-time decisions about water treatment.

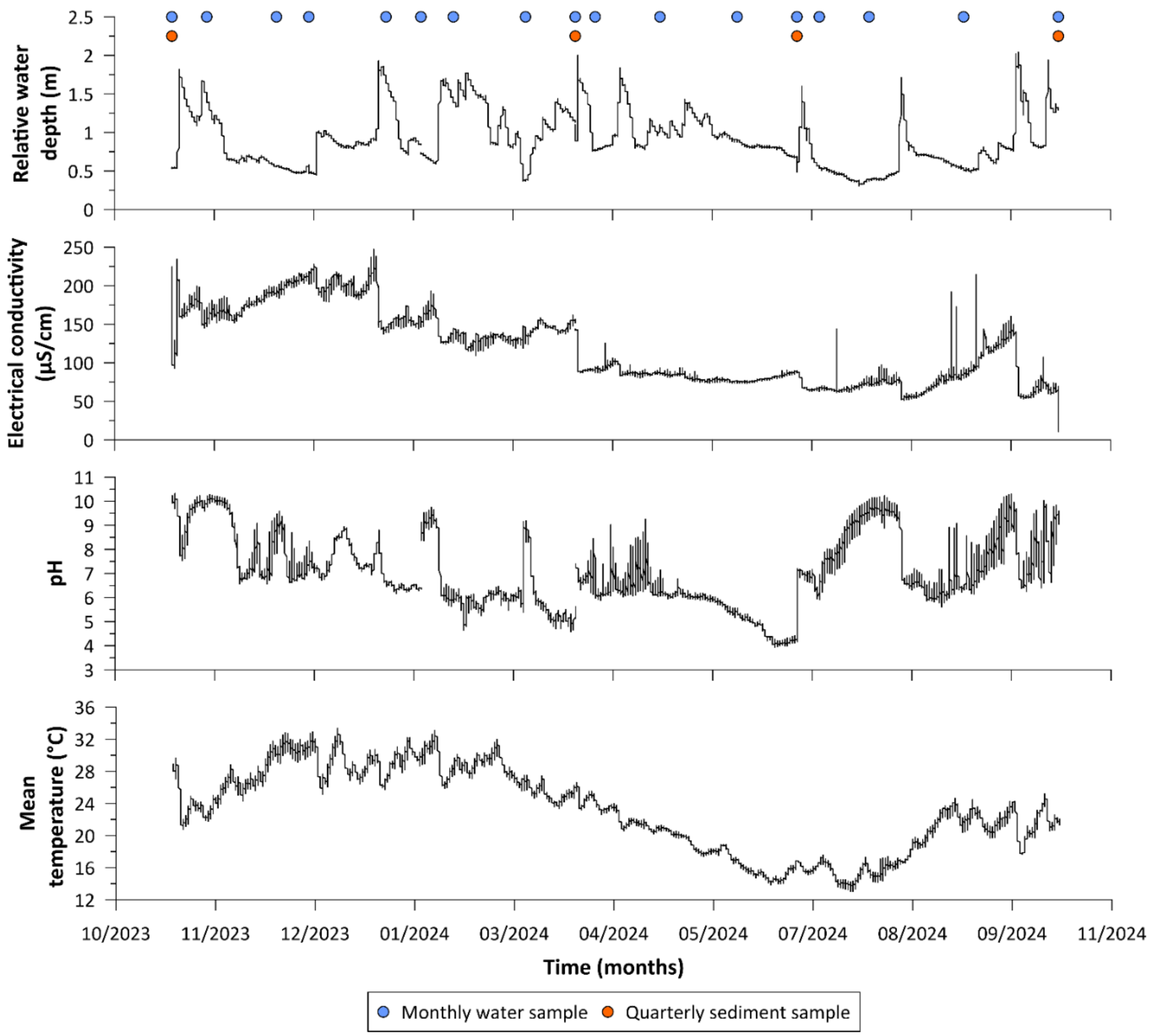


Figure 27. Example of hourly water quality data collected from sensors installed in a water storage for a one-year period. Blue and red dots indicate supplementary monthly water quality samples and quarterly sediment samples that were analysed in the laboratory.

Phase 3: After an event, evaluating contaminant levels, comparing to guidelines or standards, and assessing hotspots that require remediation are key to restoring water and soil quality and preventing future contamination. Fluctuations in parameters are expected, for instance, during storm events contaminants may be diluted and then afterwards become concentrated as water levels recede. This highlights the need for nursery managers to monitor and assess parameters over time to ensure a representative picture of water and soil and sediment quality is obtained. Priorities include:

- ***Regular water quality samples:*** Routinely collect water samples before, during and after events to be analysed in the laboratory. These provide robust data at intervals to assess deviations from baseline and how they compare to water quality guidelines. For example, monthly water samples were taken at focus nurseries for a one-year period and analysed in the DPI laboratory. Basic parameters (e.g. pH, EC, alkalinity, water hardness) vary within and between nurseries (Figure 28). Most measurements did not exceed guidelines, but some did for pH, water hardness and alkalinity. Nurseries should focus on addressing parameters likely to exceed guidelines, as well as those likely to most impact plant health requiring treatment.
- ***Investigate additional water quality parameters:*** Other parameters (e.g. nutrients and metals) provide useful information, however standards are not available for all parameters. Results from the focus nurseries indicate that all were above guidelines for phosphorous and iron, but below standards for total dissolved solids (TDS) (Figure 29). Both phosphorous and iron are essential nutrients, but excess levels can have adverse effects on plants. TDS is a measure of the combined content of all inorganic and organic substances dissolved in water, and high TDS indicates that water may be saline or contain excessive dissolved materials, which could affect plant health over time. While nitrate/nitrogen and sulfate do not have standards, they usually indicate nutrient inputs to water. These parameters can be monitored and compared to baseline levels to assess whether they have increased significantly or not.

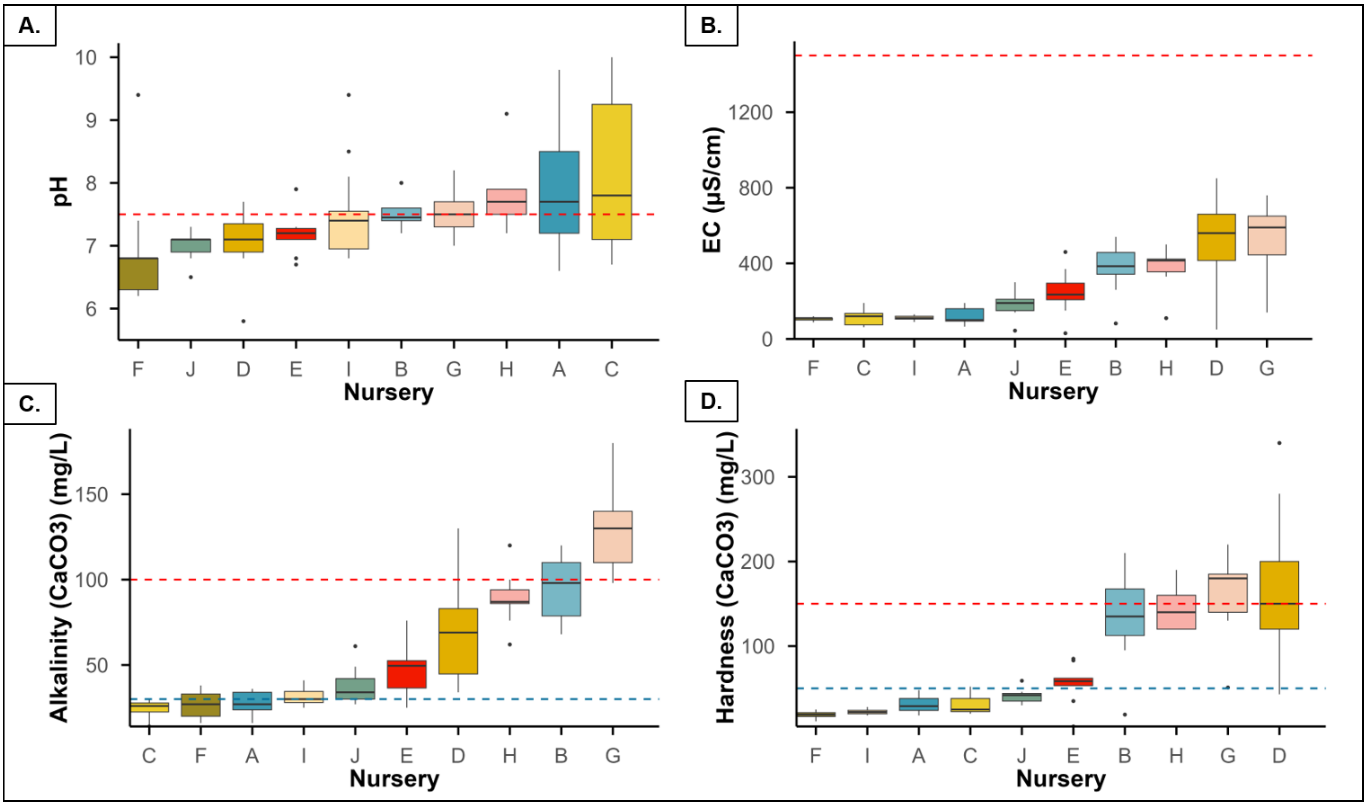


Figure 28. Basic monthly water quality parameters, including A) pH, B) EC, C) alkalinity, and D) water hardness for the focus nurseries. Boxplots show the median and standard deviation, and the black dots represent outliers. Water quality guidelines (ANZG, 2018) are shown by the red (upper limit) and blue (lower limit) lines.

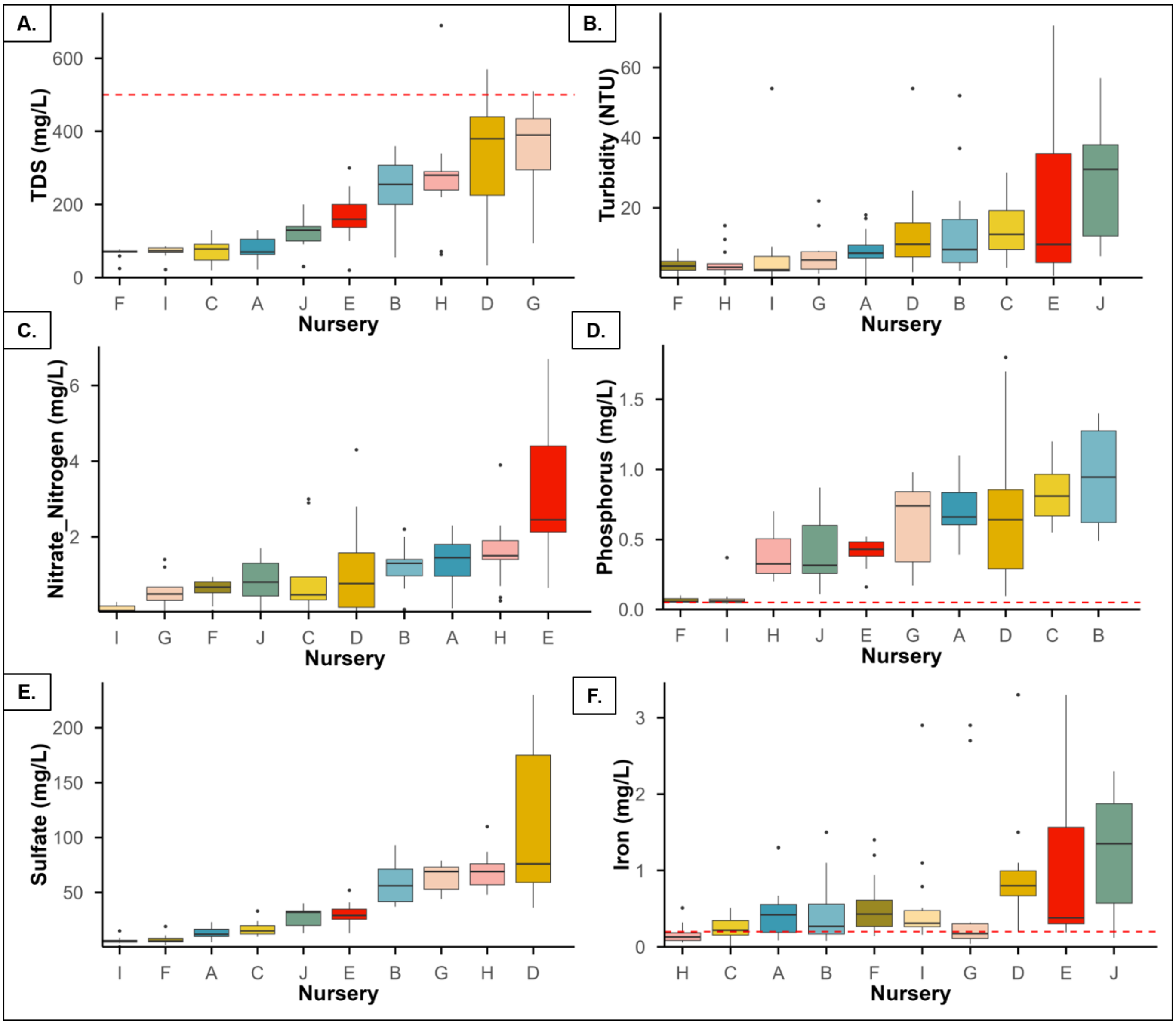


Figure 29. Selected additional monthly water quality parameters including A) total dissolved solids (TDS), B) turbidity, C) nitrate/nitrogen, D) phosphorous, E) sulfate, and F) iron for the focus nurseries. Boxplots show the median and standard deviation for each nursery, and the black dots represent outliers. Water quality guidelines (ANZG, 2018) are represented by the red (upper limit) and blue (lower limit) lines. Water quality guidelines are not available for all parameters.

- ***Consider water quality trends:*** Seasonal fluctuations and trends in water quality can inform the severity of specific periods of water contamination. Results from the focus nurseries indicated that there were seasonal trends for some water quality parameters, for example, during summer months the levels of nitrate/nitrogen, phosphate, sulfate and potassium were higher compared to winter months (Figure 30). This suggests that during the potting and growing seasons, fertiliser inputs may contribute to higher levels of these nutrients.
- ***Periodic sediment samples:*** Sediment collected for analysis in the laboratory can show the types and amounts of contaminants and their concentration. Results from the focus nurseries showed that none exceeded sediment quality standards, except for copper and zinc (Figure 31). Excess copper and zinc in sediment can negatively affect plant health by inhibiting root growth, reducing nutrient uptake, causing oxidative stress, and hindering plant growth and development. While these metals are essential micronutrients for plants, excessive amounts can become toxic and damage plant tissues, particularly when present in the root zone.

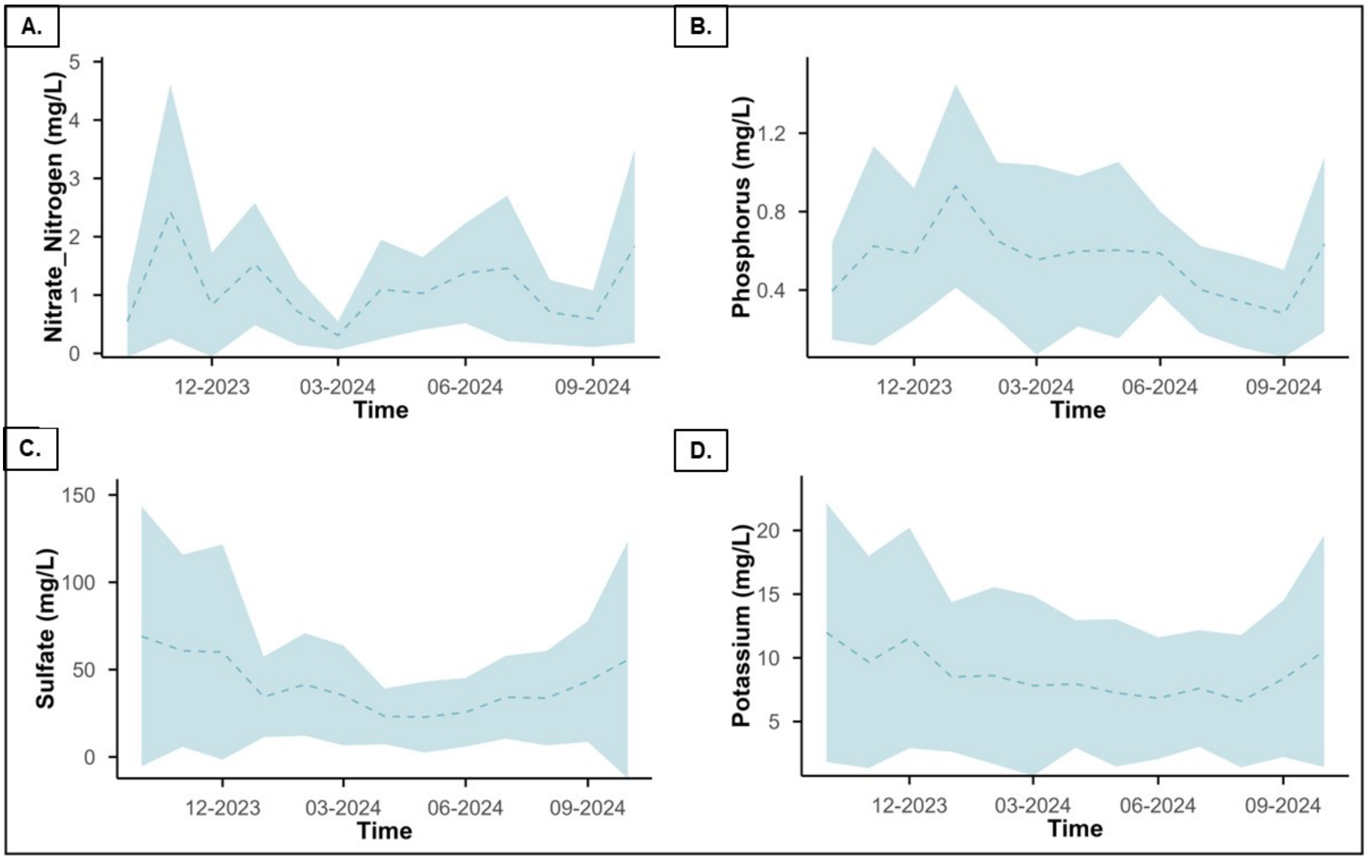


Figure 30. Selected water quality trends over time for the focus production nurseries, including A) nitrate/ nitrogen, B) phosphorous, C) sulfate, and D) potassium. The blue dashed line indicates the mean for all ten nurseries and ribbon indicates the variation within one standard deviation of the mean.

- ***Seasonal sediment quality trends:*** Trends based on quarterly sediment samples provide insights into fluctuations in soil and sediment contaminants over time (Figure 32). Results from the focus nurseries show trends in nitrogen which are likely linked to applications of fertiliser in summer and spring, however other parameters showed no clear seasonal trends.
- ***Assessment against water and sediment quality guidelines:*** Compare water, soil and sediment data to relevant water quality standards for NSW. This will identify any exceedances in contaminants, which can impact plant health. This assessment can also help to identify nutrient deficiencies that could impact plant growth.
- ***Identify contaminant hotspots:*** Identify and map hotspots of contaminants that may become critical control points based on information collected before, during and after storm and flood events. Critical control points are areas where targeted action can be focused to reduce contamination more broadly. By targeting critical control points, remediation efforts can be implemented to reduce the spread of contaminants to other parts of a production nursery.
- ***Review contaminant mitigation and remediation options:*** Management options should be considered to address water-borne contaminants and particularly those identified as critical control points. Best management practices can be developed to address major hazards and risk factors. For example, in the case of contamination in water storages, best management practices may include treating or filtering irrigation water, preventing standing water on the lot by adjusting irrigation systems and fixing drainage issues, raising containers off the ground, and placing gravel and liners below containers to promote infiltration and encourage lower-velocity surface runoff that will have less capacity to collect and transport contaminants into water storage areas.

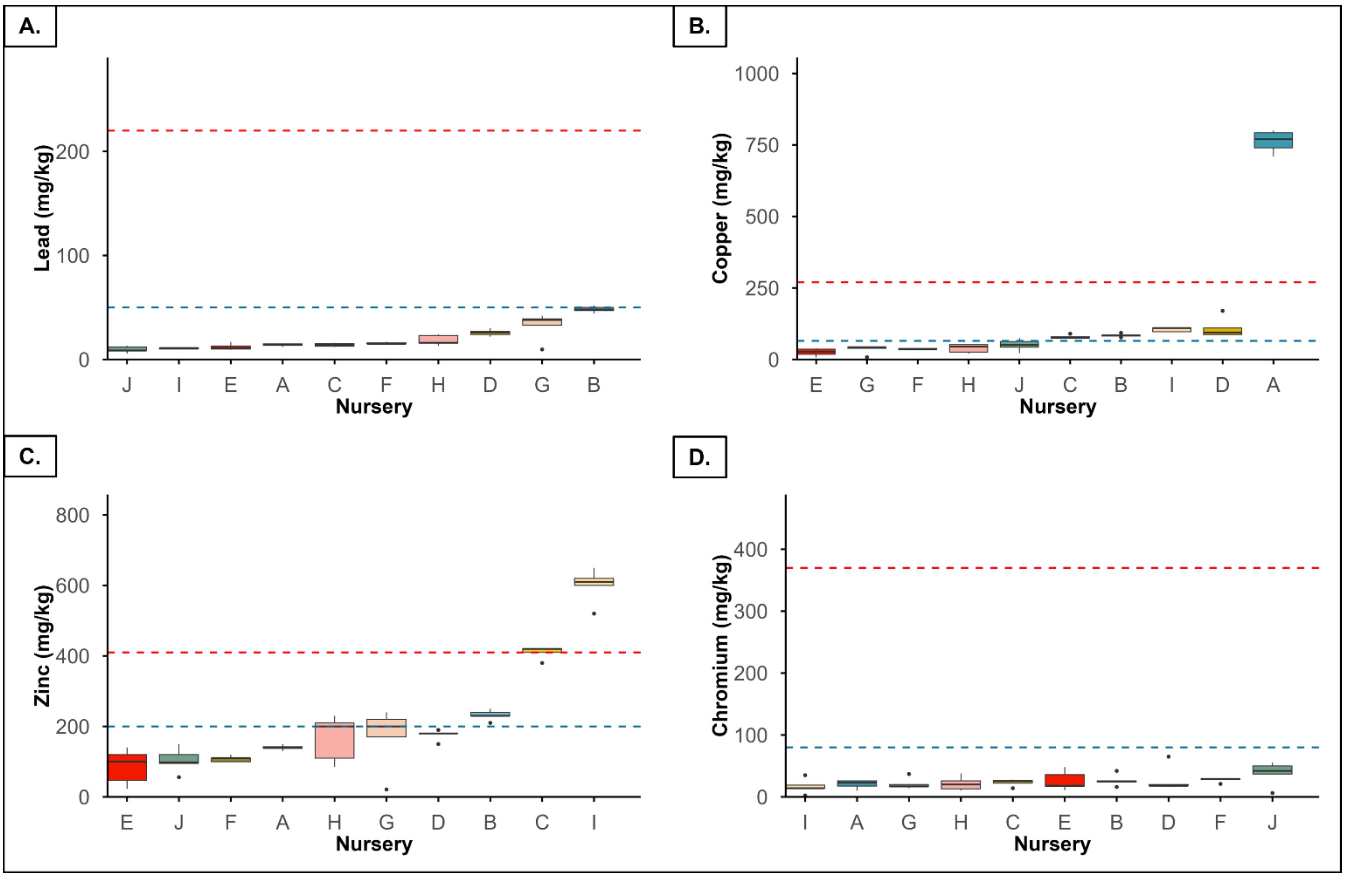


Figure 31. Selected quarterly sediment parameters including A) lead, B) copper, C) zinc, and D) chromium for the focus nurseries. Boxplots show the median and standard deviation for each nursery, and the black dots represent outliers. Sediment quality guidelines (ANZG, 2018) are represented by the red (upper limit) and blue (lower limit) lines. Guidelines are not available for all parameters.

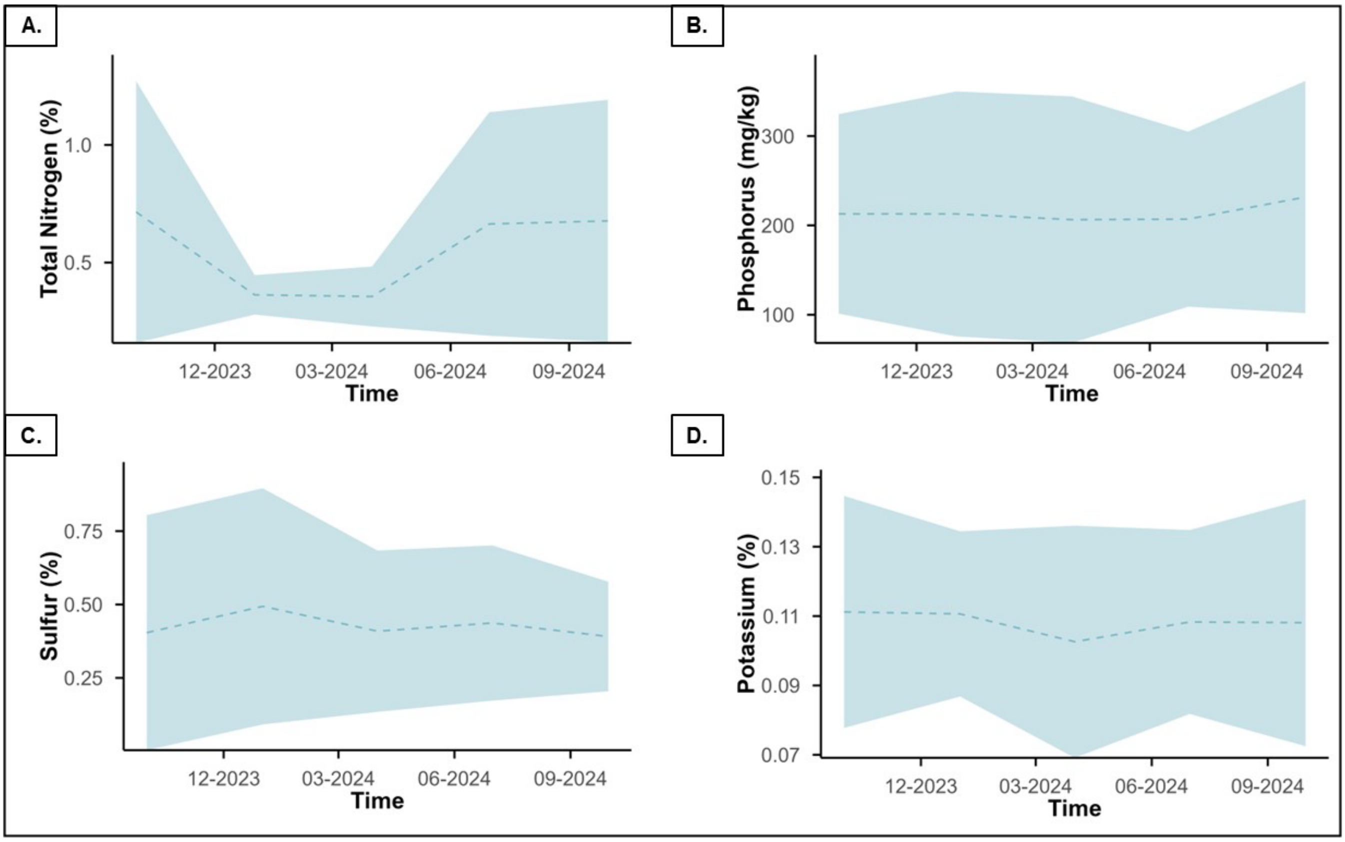


Figure 32. Selected sediment trends over time for the focus nurseries, including A) total nitrogen, B) phosphorous, C) sulfur, and D) potassium. Dashed line is the mean and the ribbon is one standard deviation.

6.4. Plant pathogens and weeds

KEY POINTS

- Plant pathogens and weeds can degrade water quality and affect crop health.
- Monitoring and testing for the presence of phytopathogens is important to reduce the risk of spread and disease.
- Weeds may need to be manually removed or treated to improve water quality.
- See fact sheets 1, 4, 12, 14 and 15.

Managing plant pathogens and weeds is crucial for maintaining crop health at production nurseries, especially given the potential for spread during storm and flood events. Phytopathogens, include fungi, bacteria and viruses that can cause disease related to blights, damping off, and downy mildews, which result in crop losses, and reduced plant quality, production, and marketability. Phytopathogens are difficult to control and often spread through irrigation water and can easily infect healthy plants. Aquatic weeds can grow excessively when nutrients and other contaminants sit in water storages during flood events, which can be extremely problematic causing eutrophication once they die and decompose. Weeds were not directly measured in this project.

Plant pathogens and weeds should be considered in all phases of the management cycle (Figure 33).

Phase 1: Before an event, understanding the types of weeds and pathogens present, along with their spatial distribution on the nursery property, allows for effective monitoring and management. Priorities include:

- ***Review known plant pathogens and weeds:*** Identify common plant pathogens (such as *Phytophthora*) that threaten production nursery plants. Identify critical control points of infestation and prioritise areas for monitoring and intervention. If weeds are present in water storages, identify the species of weeds and attempt manual removal or chemical treatment. Knowing the species can help assess whether increased nutrient inputs during floods will provide favourable conditions for growth and will allow proactive management.
- ***Assess the spatial distribution of weeds:*** Map and assess the distribution of weed populations near production nursery lots. Knowing which areas have invasive species and weeds can help to minimise exposure, particularly in flood-prone zones where seeds can easily be transported.

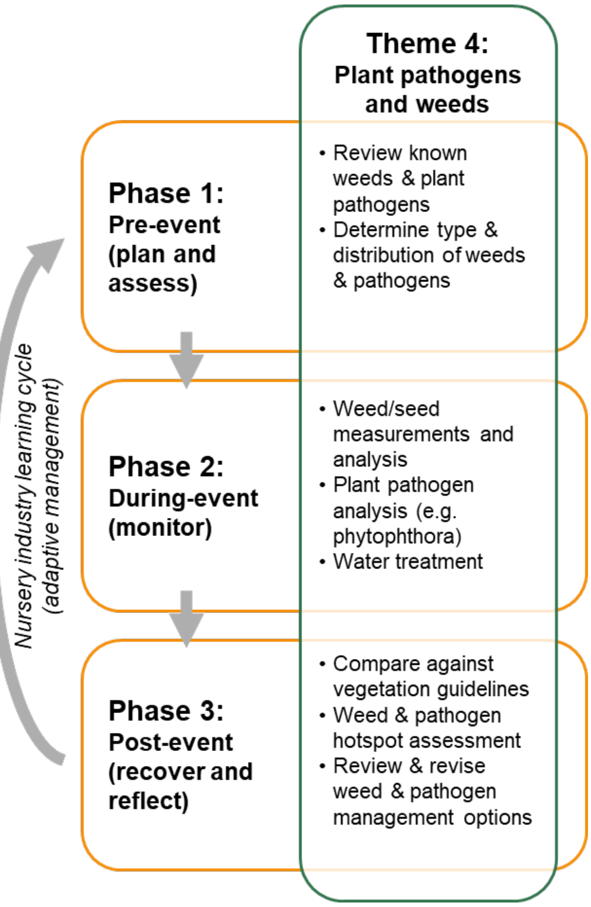


Figure 33. Priorities for plant pathogens and weeds across the three phases of the cycle.

Phase 2: During an event, monitoring for the presence of plant pathogens and weeds can help detect signs of potential contamination, allowing nursery operators to take early action. Priorities include:

- ***Plant pathogen analysis:*** Test for harmful pathogens (e.g. *Phytophthora*) focusing on areas where water pools or drains from soils, as these are prime locations for pathogen spread. In addition, test for the presence of pathogens in water storages and in treated water from the storages using appropriate methods. Monitoring for pathogens like *Phytophthora*, which thrives in wet conditions, will likely help reduce the incidence of plant infection.

- ***Partner with specialists:*** Expert advice and treatments may be warranted in cases of acute or chronic pathogen problems. Rapid pathogen tests are available for soils, but standardised methods are still being developed to assess pathogens such as *Phytophthora* in water. During this project, four focus production nurseries were tested for *Phytophthora* eight times in a one-year period. Bait stations were installed in open water storage dams at three depths below the surface (100 mm, 500 mm, and 1 m deep) and tested for the presence of phytopathogens. The results show that the incidence of *Phytophthora* was almost 100 % at all four nurseries (Figure 34A). That is, *Phytophthora* was present at every location in the dams (i.e. over time, in shallow and deep water, at the centre and edges). A range of *Phytophthora* species were identified in the four dams (Figure 34B). The species detected are mostly reported as polyphagous on woody hosts and have broad host ranges. The high incidence of multiple *Phytophthora* species suggests that nursery dams act as reservoirs for these pathogens, with important implications for plant disease management at production nurseries, as well as for the broader community (e.g. waterways, home gardens, parks) that may be subject to overflow from the nurseries. *Phytophthora thermophila* was dominant in all dams, but little is known about this species. On the other hand, *Phytophthora cinnamomi*, which is listed as Key Threatening Process under the NSW Biodiversity Conservation Act (2016) and Federal Environment Protection and Biodiversity Conservation Act (2019), was only found in one dam.
- ***Appropriate water treatment:*** All the production nurseries tested in this project treat their water to kill or neutralise pathogens before irrigation, but these findings confirm that water storages harbour significant communities of plant pathogens and that appropriate action is required to manage pathogens such as *Phytophthora cinnamomi* to ensure that it does not spread to other areas. Best management practices are required to effectively reduce or eliminate pathogens from water and sediment sources.

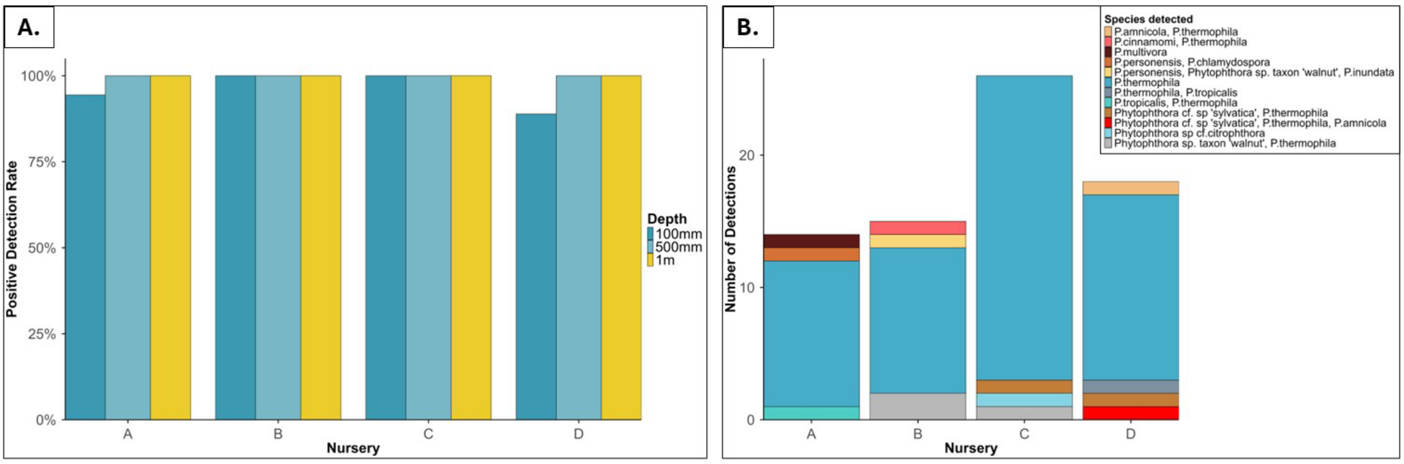


Figure 34. Summary of *Phytophthora* found in four water storages at focus production nurseries, including A) percentage positive rate across the water sampling times and depths for each nursery, and B) *Phytophthora* species detected for each nursery over the sampling period (Source: Plant Clinic, 2024).

- ***Weed analysis:*** Collect samples of weeds from areas vulnerable to seed dispersal, especially around water entry and exit points, and within water storages. Measure and analyse weed seeds to identify species that may have been transported by floodwaters, aiding in early detection and control. Avoid or minimise algae weed growth by monitoring and treating water storages (e.g. aeration) when eutrophication starts to occur during or after events (Figure 35).

Phase 3: After an event, assessment and consideration of pathogen and weed spread will allow nursery managers to take targeted actions for recovery and long-term resilience. Priorities include:

- ***Assessment against guidelines:*** Assess weed infestation and compare to vegetation management guidelines to ensure that weeds either remain within acceptable limits or are removed. Similarly, test for plant pathogens regularly and across multiple sites within a production nursery lot. If pathogen levels exceed known thresholds for infection, adjust management practices to address the hazard and to reduce risk.
- ***Identify plant pathogen and weed hotspots:*** Identify and map critical control points where pathogens and weeds have increased due to flooding (e.g. water storage reservoirs; Figure 35). These will be priority zones that require enhanced monitoring, treatment, or physical barriers to prevent further spread. For instance, if pathogens are found in plant containers, make sure to sterilise them before re-use to eliminate pathogen spread.
- ***Review plant pathogen and weed mitigation and remediation options:*** Consider pathogen and weed management practices, such as herbicide applications, physical removal, or pathogen-specific treatments like soil sterilisation or fungicide application. Modifying drainage and barriers to reduce areas prone to waterlogging can reduce pathogen growth and dispersal. It is important to use water disinfestation systems and monitor the efficacy of these systems.

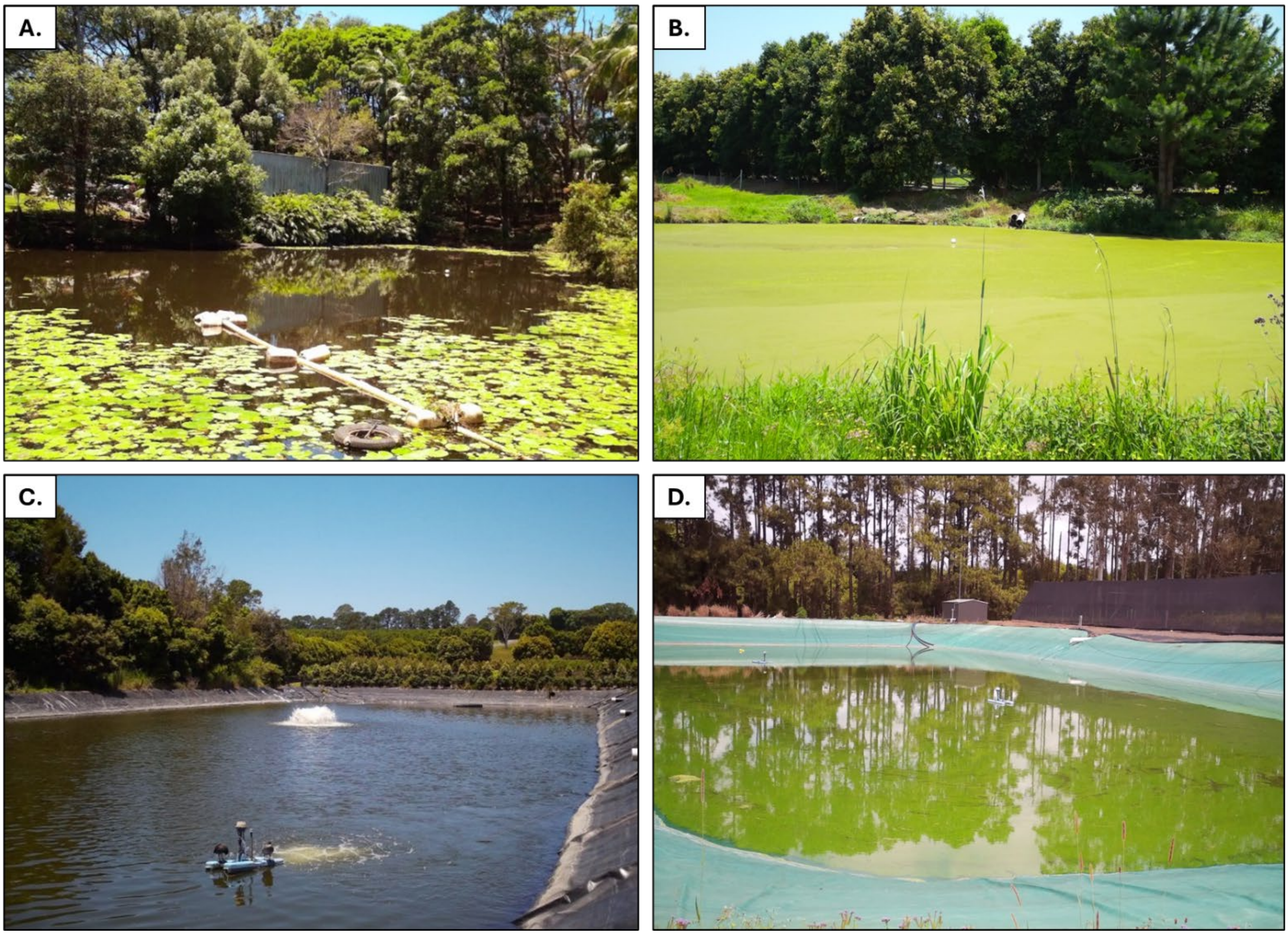


Figure 35. Presence and absence of weeds, aquatic plants and algae in four water storages at focus production nurseries, including A) an unlined dam with mixed native and weedy vegetation, aquatic plants and no algae following a storm event, B) an unlined dam with mixed vegetation and algae following an event, C) a lined dam with no algae after an event and with aeration treatment to reduce algae, and D) a lined dam with algae and no aeration treatment.

6.5. Aquatic biota

KEY POINTS

- Aquatic biota rely on good water quality but also help improve water through filtration and bio-uptake of nutrients and contaminants.
- Aquatic biota respond to toxic effects of contaminants and are indicators of water quality.
- Monitoring aquatic biota allows identification and prevention of water-borne contaminants risks.
- See fact sheets 1, 13 and 15.

Aquatic biota such as macroinvertebrates (bugs), aquatic plants, algae, and animals like frogs or fish, play a vital role in maintaining the ecological function and water quality of water storages, including those used in production nurseries. Their presence contributes to natural water purification, biological stability, and ecosystem resilience. Aquatic biota serve as a key indicator of water quality and ecosystem health and are useful to determine the effectiveness of contaminant containment and mitigation strategies. Aquatic biota were not directly measured in this project.

Aquatic biota, if present, should be considered in all phases of the management cycle (Figure 36).

Phase 1: Before an event, understanding baseline aquatic biota will support assessment and monitoring to detect changes in water quality, biodiversity, shifts in species composition, and potential toxic effects of specific contaminants. Priorities include:

- ***Review known aquatic biota:*** Establish baseline data on aquatic species present in water bodies to understand the current conditions.
- ***Review algae and aquatic plant contamination (ecotoxicology):*** Consider potential risks of nutrient enrichment and chemical exposure on aquatic ecosystems.

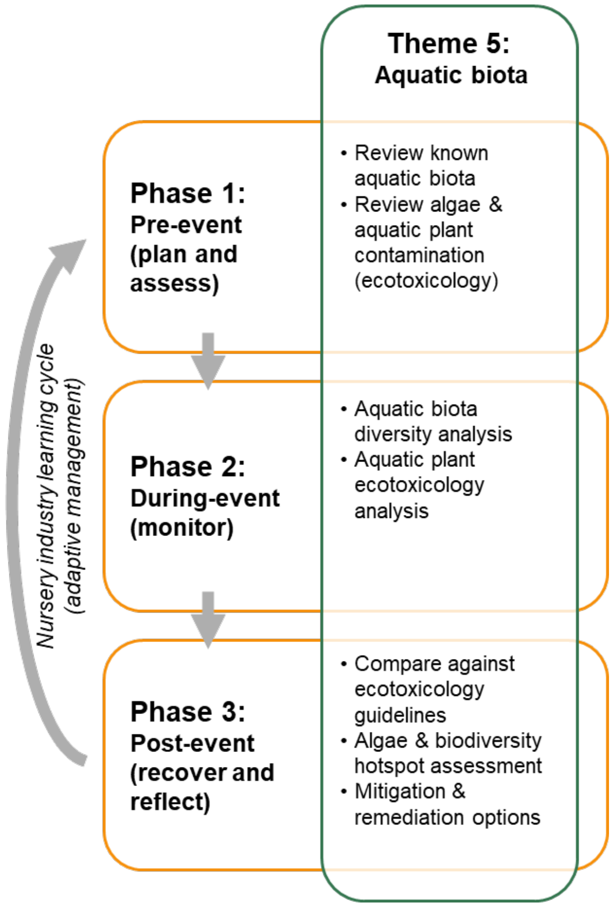


Figure 36. Priorities for aquatic biota across the three phases of the cycle.

Phase 2: During an event, observe and assess aquatic biota, especially if threatened species are present, or if pests are present (e.g. cane toads). Priorities include:

- ***Aquatic biota diversity analysis:*** Conduct surveys to detect changes in species diversity and population dynamics.
- ***Aquatic plant ecotoxicology analysis:*** Examine potential toxic effects of chemicals on aquatic plant communities.

Phase 3: After an event, improved understanding of aquatic biota can inform proactive strategies to prevent environmental degradation, respond to contamination events, and support the long-term sustainability of water sources and ecosystems. Priorities include:

- ***Comparison against ecotoxicology guidelines:*** Compare observed biotic responses with environmental quality standards to evaluate contamination impacts.
- ***Algae and biodiversity hotspot assessment:*** Identify areas of high ecological importance and monitor signs of ecosystem stress or degradation.

- ***Mitigation and remediation options:*** Develop and implement strategies such as bioremediation, habitat restoration, and improved waste management practices to restore impacted aquatic environments. Best management practices may include runoff management plans, vegetative buffer strips, and constructed wetlands to mitigate potential effects on aquatic biota.

Storm and flood events not only transport contaminants to production nurseries, but they also transfer contaminants from nurseries to the environment. Runoff from nurseries, which may contain nutrients, agricultural chemicals and pathogens, may enter waterways and drains downstream and disrupt the habitat and life-cycles of aquatic biota. Minimising contaminant runoff to the surrounding environment is crucial to prevent degradation of local aquatic ecosystems.

7. Risk assessment

A structured risk assessment of water quality hazards enables production nurseries to identify, evaluate, and manage risks associated with water sources and storages. This could potentially be further applied to water treatment systems and operational practices. This is especially important given the potential for pathogen transmission through irrigation water (e.g. *Phytophthora*, *Pythium*), chemical toxicity due to salinity or nutrient accumulation, and the need to meet regulatory or accreditation obligations (e.g. Nursery Industry Accreditation Scheme Australia (NIASA)/EcoHort standards).

A water quality risk assessment provides a robust framework for evidence-based decision-making. The process should begin with establishing the context, that is, defining production nursery operations, water sources (e.g. dam, bore, recycled, or mains water), and catchment position (proximity to source, transfer, or sink zones). The next step is to identify hazards, including biological (e.g. pathogens, weeds, pests), chemical (e.g. salinity, pH imbalance, heavy metals), physical (e.g. turbidity), and operational hazards (e.g. infrastructure failures or backflow). Following this, risks are analysed by assessing the likelihood and consequence of each hazard using data and expert judgement, against a qualitative risk matrix (Table 4). Risks are then evaluated to determine which are acceptable (or unavoidable) and which require further mitigation.

In concert with industry application of the adaptive framework presented in this document, supported by science and resources, targeted control measures can be implemented (e.g. installing filtration and disinfection systems, automating pH adjustment, upgrading infrastructure, and formalising standard operating procedures). Risk ratings can be updated as part of the adaptive cycle, in response to control measures, seasonal conditions or operational changes.

Table 4. Qualitative risk assessment matrix.

		Consequence				
		Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**
Likelihood	**Almost Certain**	Medium	Medium	High	Extreme	Extreme
	Likely	Low	Medium	High	High	Extreme
	Possible	Low	Medium	Medium	High	Extreme
	Unlikely	Low	Low	Medium	Medium	High
	Rare	Low	Low	Low	Medium	Medium

7.1. Influence of catchment position on risk

Production nurseries located at different positions within a catchment are exposed to varying levels and types of water-related hazards. These differences significantly influence their risk profile for water quality hazards (Table 5). Depending on the size and functionality of waterways and wetlands on or near nursery lots, they will have specific considerations such as mixing of external and self-generated contaminant loads, and control of runoff to surrounding areas (Figure 37).

Table 5. Summary of the implications of catchment position on water-related hazards and risk.

Catchment position	Water sources	Relative storm and flood hazard	Implications for risk assessment
Source zone (top of catchment)	Rainfall only	Low	Risk of pathogen and nutrient inputs is mostly self-generated. Limited flood risk, but poor water retention can lead to local runoff issues.
Transfer zone (middle of catchment)	Rainfall plus run-on from hillslopes	Moderate	Increased exposure to upstream runoff, including nutrients and pathogens. Higher variability in water quality inputs.
Sink zone (bottom of catchment)	Rainfall plus run-on from hillslopes plus flood waters from river	High	High flood risk and exposure to accumulated upstream contaminants. Requires more robust water treatment and flood preparedness strategies.

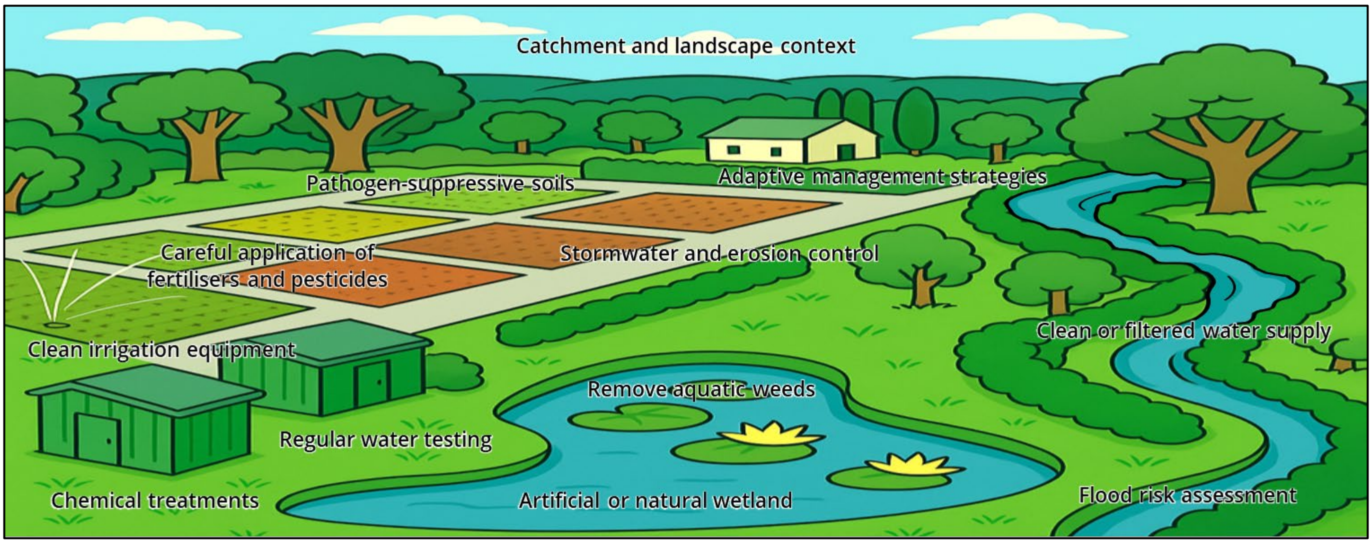


Figure 37. Examples of management considerations for water quality in a plant production nursery setting.

7.2. Water quality and contamination risk assessment

A scientifically supported understanding of water quality hazards and risk assessment is critical for the production nursery industry. The risk assessment below (Table 6) has been tailored for the nursery industry in NSW, specifically focusing on water quality hazards explored in this project aligned with the ISO 31000:2018 Risk Management Guidelines and incorporating principles from AS/NZS ISO 31000:2018, the Australian and New Zealand standard for risk management. AS/NZS ISO 31000:2018 provides a guide for organizations to manage risks effectively and emphasizes the integration of risk management across organizational activities and decision-making processes, but it is not industry-specific and can be applied to any organization within its context.

Table 6. Risk assessment of biological, chemical, physical and operational hazard types for NSW and ACT production nurseries.

Hazard Type	Hazard	Potential Cause	Potential Impact	Likelihood	Consequence	Risk Rating	Existing Controls	Further Actions
Biological	Pathogen contamination (e.g. *Pythium*, *Phytophthora*)	Contaminated dam or recycled water	Crop losses, plant death, disease spread	Likely	Major	High	Filtration systems, routine monitoring, chlorination	Improve pathogen-specific testing, adopt water disinfection methods
Chemical	Salinity (high EC levels)	Recycled water accumulation, groundwater	Reduced plant growth, soil degradation	Likely	Moderate	High	Monitoring EC, blending with freshwater	Develop salt-sensitive plant lists, invest in reverse osmosis
Chemical	Pesticide contamination	Backflow, incorrect disposal	Plant injury, regulatory non-compliance	Possible	Major	High	Backflow prevention, training and education	Install containment systems, chemical register audit
Chemical	High nutrient loads (e.g. nitrates, phosphates)	Runoff from fertilised areas; poor recycling practices	Algal blooms, clogging irrigation, altered plant nutrition	Possible	Moderate	Medium	Fertigation management, leachate capture	Regular nutrient testing and recycling system upgrades
Chemical	Heavy metal contamination (e.g. Zn, Cu)	Galvanised pipes; industrial runoff	Toxicity to plants, groundwater pollution	Unlikely	Major	Medium	Source water monitoring	Replace at-risk materials, conduct source tracing
Chemical	pH imbalance	Source water variability, chemical inputs	Nutrient uptake issues, plant stress	Possible	Minor	Low	Monthly testing, buffering agents	Automation of pH control systems
Chemical/ Physical	Low dissolved oxygen (DO)	Stagnant tanks, high organic matter	Root damage, pathogen risk	Rare	Moderate	Low	Aeration systems, tank cleaning	Schedule regular aeration checks
Physical	Turbidity/ sediment	Unlined dams, erosion	Blocked emitters, disease vectoring	Possible	Minor	Low	Buffering plants, filtration, settling tanks	Upgrade to multi-stage filtration
Operational	Runoff contamination	Poor drainage, storm events	External contamination of water sources	Possible	Moderate	Medium	Stormwater controls, site design	Adaptive framework, routine assessment and monitoring
Operational	Infrastructure failure	Pump, filter, pipe, or other malfunction	Water supply interruption, risk increase	Possible	Major	High	Preventative maintenance, system audits	Upgrade and integrate with adaptive framework

8. Existing guidelines and resources

8.1. Guidelines

NSW production nurseries should be aware of existing water quality guidelines to ensure compliance with environmental regulations, improve water use efficiency, and maintain plant health and productivity (Table 7). Guidelines also support accreditation, reduce environmental risks, and provide practical strategies for managing recycled water, runoff, and contaminants. They also help nurseries meet industry sustainability standards and adapt to climate change (Table 8).

Table 7. Summary of NSW-aligned guidelines and their components for water quality and use within the NSW and ACT production nursery industry.

Guideline	Components	Reference
Nursery Industry Water Management Best Practice Guidelines	Focus on water use efficiency, irrigation design, water recycling, nutrient and sediment control; updated to include monitoring protocols and sustainable management practices	Nursery and Garden Industry Australia (2010)
Managing Water in Plant Nurseries	Covers water sourcing, filtration, irrigation design, storage quality, drainage, and pathogen risk management	NSW Department of Primary Industries (2021)
Water Quality Australia, National Water Quality Management Strategy	Guidelines, benchmarks and targets for managing water quality across a range of risk profiles and uses	Australian and New Zealand Governments (2018)
NSW EPA/DPI Water Quality and Sampling Standards	Aligns with the ANZG (2018) Guidelines and prescribes methods for testing parameters like pH, EC, nutrients, and pathogens	NSW Environment Protection Authority (2022); Australian Government and New Zealand Governments (2018)
NIASA Accreditation	Audited Best Management Practice framework for irrigation, runoff, water testing, and effluent reuse	Nursery and Garden Industry Australia/Greenlife Industry Australia (N.D.)

Table 8. Summary of components within NSW-aligned guidelines for water quality relevant to the NSW and ACT production nursery industry.

Component	Purpose or outcome
Water efficiency	Benchmarking usage; documented management plans
Irrigation design	Uniform application rates, appropriate system selection, calibration
Water recycling	Collection, disinfection, reuse of runoff and wastewater
Sediment/runoff control	Drainage planning, sediment traps, litter management
Nutrient management	Minimising nutrient loss; maintaining stock water quality
Water quality monitoring	Regular testing of pH, EC, turbidity, nutrients using approved methods
Accreditation and compliance	NIASA/APPS audits; conformance to NSW EPA sampling standards

8.2. Resources

Existing online resources and toolkits are important for the NSW and ACT production nursery industry as they provide accessible information that links to concepts, knowledge and resources developed through this project and that can support best management practices (Table 9). These resources can help nursery managers to understand and start to address issues such as water quality, pathogen control, and the impacts of water availability due to climate variability. Engaging with these resources can foster informed decision-making, enhance compliance with regulations, and support continuous improvement. When viewed in line with the adaptive management framework from this project, such resources can help refine management strategies based on new data or emerging risks. This can help ensure that production nursery practices remain sustainable, resilient, and aligned with evolving scientific understanding and environmental standards.

Table 9. Summary of key resources available to support water quality and water-borne contamination best practices in the NSW production nursery industry. Note that not all web links will work in perpetuity.

Name – Agency	**URL**
Nursery Industry Water Management Best Practice Guidelines – Nursery and Garden Industry Australia	https://nurserycrops.ces.ncsu.edu/wp-content/uploads/2021/05/WATER-BMP-NGIA-Aug-2012-Final.pdf
Australian Plant Production Standard (APPS) – Water Management Toolbox	https://nurseryproductionfms.com.au/irrigation-water/ (an updated version of https://watertoolbox.ngi.org.au/) https://nurseryproductionfms.com.au/elearning/
Flood Knowledge Centre – Australian Bureau of Meteorology (BOM)	http://www.bom.gov.au/australia/flood/knowledge-centre/ http://www.bom.gov.au/australia/flood/knowledge-centre/understanding.shtml http://www.bom.gov.au/australia/flood/knowledge-centre/preparing.shtml
NSW Department of Planning and Industry (DPI)	https://www.dpi.nsw.gov.au/agriculture/water https://www.dpi.nsw.gov.au/agriculture/water/quality https://www.dpi.nsw.gov.au/agriculture/lup https://www.dpi.nsw.gov.au/agriculture/chemicals
NSW Environment Protection Authority (EPA)	https://www.epa.nsw.gov.au/your-environment/water https://www.epa.nsw.gov.au/your-environment/water/polices-guidelines-and-programs
Water NSW	https://www.waternsw.com.au/water-services/water-quality/monitoring-and-reporting
Water Quality Toolkit – Penn State University	https://extension.psu.edu/a-water-quality-toolkit-for-greenhouse-and-nursery-production
Water Quality Australia Guidelines – Australian and New Zealand Governments (ANZG)	https://www.waterquality.gov.au/ https://www.waterquality.gov.au/anz-guidelines https://www.waterquality.gov.au/anz-guidelines/guideline-values/default/primary-industries https://www.waterquality.gov.au/anz-guidelines/guideline-values/default/sediment-quality-toxicants
Framework, fact sheets and review – Macquarie University and NGINA	Framework: https://doi.org/10.25949/AS0X-VX91 Fact sheets: https://doi.org/10.25949/JH43-4N56 Literature review: https://doi.org/10.1016/j.scitotenv.2024.178084

8.3. Best management practices

Production nurseries should develop and implement site-specific best management practices linked to existing guidelines to help manage storm and flood impacts and to reduce the spread of water-borne contaminants. Best management practices may focus on preventive planning, effective response, and recovery strategies and are structured to protect nursery plants and water quality.

Best management practices are specific plans or activities designed to help improve irrigation and nutrient management practices to decrease contamination of surface or groundwater. The purpose of implementing best management practices is to address water quality or water and nutrient management issues identified at critical control points, increase plant production efficiency, decrease costs of treatment, and protect the downstream environment. While best management practices provide broad guidelines, they can be modified and adapted for the site-specific needs of individual production nurseries.

Outlined here are broad best management practices that may be adopted to reduce contamination risk while maximising production yield and reducing economic loss. Importantly, these best management practices can be modified by nursery growers to suit their own requirements.

<u>Design and layout of nursery infrastructure</u>

- Position valuable stock on higher ground when possible, and avoid placing sensitive plants in low-lying, flood-prone zones.
- Raise containers off the ground or use gravel or lining below the containers to reduce contamination with the soil on the ground. Grow vegetative buffer strips where runoff is high to promote infiltration and reduce runoff.
- Construct artificial wetlands, when possible, to filter runoff water from the nursery properties. This will reduce contaminated water entering streams downstream.

<u>Regular monitoring and record-keeping</u>

- Establish a regular monitoring program to track water, soil and sediment quality, before, during and after storm and flood events, to maintain baseline data for contaminants.
- Keep detailed records of all water, soil and sediment test results, chemicals used for treatment, and observations of storm and flood impacts to refine future response strategies.

<u>Training and education</u>

- Train staff on flood response procedures, including how to handle and contain contaminants.
- Educate workers on the importance of containment, waste management, and other practices that reduce contamination risks.

<u>Maximise irrigation efficiency and minimise leaching</u>

- Regularly check irrigation equipment to ensure irrigation efficiency is achieved and help nursery operators recognise when systems are not operating optimally. This will reduce areas being overwatered or underwatered.
- Monitor the leaching fraction from containers, which is the amount of water leached from the container divided by the amount of irrigation applied.
- Consider cyclic irrigation, which involves irrigating multiple times throughout the day with scheduled time intervals between watering. Cyclic irrigation increases efficiency and plant water use, while reducing the total leachate fraction from containers. Reducing runoff volume

from containers reduces fertiliser loss and thus economic loss, while reducing the risk of environmental pollution.

- Arrange containerised plants based on water requirements and plant canopy size and structure to reduce low water-use plants from receiving excess water. However, when grouping by water use is not possible, containers can be grouped by volume which ensures that plants with similar water needs are grouped.

Water storage reservoirs

- Ensure drainage network is sufficient to capture runoff. Direct drainage trenches to on-site storage reservoirs where the water can be treated before it is discharged to the environment or reused for irrigation.
- Minimise contact of runoff with the ground to reduce contamination, and so runoff trenches should be lined with an impermeable material.
- In the case that production nurseries do not capture or reuse water, alternative methods can be used to filter water before it is released to the environment, such as vegetated buffer zones, grass strips, and constructed wetlands. Production areas can be sloped to prevent water accumulation and to allow runoff to flow to vegetative buffers or wetlands for filtering. These methods capture sediment, reducing the contaminant load entering the environment.

9. Recommendations

Based on the findings from this project summarised in this framework document, specific water quality issues and contamination concerns relevant to the NSW production nursery industry have been identified and assessed in the context of landscape and other environmental processes. Below is a set of recommendations grouped into technical, operational, strategic, and regulatory categories to support implementation of aspects of the framework across all scales of nursery production.

Technical monitoring and treatment

1. Implement routine water quality monitoring.
    - Parameters: EC (salinity), pH, turbidity, dissolved oxygen (DO), nutrients (nitrates, phosphates), pathogens (e.g. *Phytophthora*, *Pythium*), and heavy metals.
    - Frequency: At least monthly for key parameters; more often for recycled water.
2. Install and maintain treatment systems.
    - Use multi-stage filtration, UV disinfection, or chlorination for pathogen control.
    - Consider reverse osmosis or blending strategies to manage salinity in recycled water.
3. Use sediment traps or settling tanks.
    - Reduce suspended solids and turbidity from dam or surface water inputs.
4. Automate pH adjustment.
    - Integrate real-time pH control systems in fertigation setups, especially for sensitive crops.

Infrastructure and design

5. Upgrade and maintain irrigation infrastructure.
    - Ensure no backflow into clean water supplies from fertigation or chemical mixing tanks.
    - Replace galvanised or corroding pipes that may leach zinc or copper.
6. Design water storage and distribution to avoid stagnation.
    - Use closed tanks where possible.
    - Install aerators or circulation pumps in storage tanks to maintain DO levels.

7. Design drainage and runoff capture systems.
    - Prevent nutrient-rich runoff from entering surface water or contaminating water supplies.
8. Classify nursery catchment position (source, transfer, sink).
    - Adjust infrastructure and treatment needs based on exposure to upstream inputs or floodwaters.

Operational management

9. Develop a Water Quality Risk Management Plan.
    - Include a site-specific risk register, sampling schedule, and emergency response plan.
10. Train staff on water hygiene, chemical use, and monitoring.
    - Ensure everyone understands the links between water quality and plant health.
11. Track and log all water tests and corrective actions.
    - Keep records for quality assurance, certification, and audit purposes.
12. Participate in industry certification programs.
    - Examples: Nursery Industry Accreditation Scheme Australia (NIASA), EcoHort.

Strategic and climate-resilient planning

13. Conduct flood risk assessments using local catchment data.
    - Use BOM or council flood maps to assess exposure at different rainfall intensities.
14. Invest in water recycling and reuse systems.
    - Design closed-loop systems that treat and reuse irrigation water safely.
15. Prepare for climate variability.
    - Plan for both drought (water scarcity) and intense rainfall (flooding, contamination).
16. Engage in water source diversification.
    - Avoid over-reliance on a single source; mix surface, groundwater, and rainwater where feasible.

Regulatory compliance and best practice

17. Ensure compliance with environmental and water use regulations.
    - Including state EPA guidelines and local water authority conditions.
18. Align practices with AS/NZS ISO 31000:2018 Risk Management Guidelines.
    - Use this for structured assessment, risk ranking, and review.
19. Undertake regular third-party audits.
    - Validate water quality systems and management plans against industry benchmarks.
20. Collaborate with local water management bodies.
    - Access technical support, early warnings, and funding for improvements.

Development of a water quality compliance matrix

Considering the recommended water quality and contamination concern management options together with regulatory frameworks and best practices applicable to the NSW and ACT production nursery industry, including AS/NZS ISO 31000:2018, NIASA, EcoHort, and state environmental regulations, a water quality compliance matrix would serve to draw key elements together (Table 10). This draft matrix needs further input and refinement by members of the production nursery industry before it can be considered for application to the industry. What is presented is intended as a starting point to catalyse and facilitate discussions and future projects within the industry to address and inform best management practices and accreditation and compliance schemes.

Table 10. Summary of a potential water quality compliance matrix for the production nursery industry.

Recommendation Area	Specific Action	Compliance Requirement	Relevant Standard or Program	Evidence of Implementation
Monitoring	Monthly testing of EC, pH, DO, pathogens	Demonstrates due diligence and early hazard detection	ISO 31000, NIASA, ANZG	Water quality logbook, test reports
Treatment	Disinfection system for recycled water	Prevention of pathogen spread	NIASA, EcoHort	Installation records, standard operating procedures
Infrastructure	Install backflow preventers	Prevents contamination of clean supply	Plumbing Codes, NIASA	Maintenance checklist, system diagram
Drainage	Capture and treat runoff from production areas	Minimises environmental pollution	EPA stormwater guidelines	Site drainage plan, inspection records
Planning	Catchment-based flood risk analysis	Preparedness for extreme events	Local council flood planning	Flood risk map, mitigation plan
Operational	Develop a water quality risk management plan	Comprehensive risk identification and response	ISO 31000	Documented plan, reviewed annually
Training	Educate staff on hygiene and water testing	Builds capacity and reduces human error	NIASA, WHS	Training logs, standard operating procedure sign-off
Documentation	Maintain records of tests, treatments, incidents	Audit readiness and continuous improvement	EcoHort, ISO 31000	Digital and physical water management log
Certification	Participate in NIASA and EcoHort schemes	Demonstrates best practice	NIASA, EcoHort	Accreditation certificate, audit results

10.Conclusion

Production nurseries play a crucial role in the horticultural supply chain, relying on adequate water quality and quantity for irrigation and plant production. Flood events resulting in surface runoff pose a significant risk to water quality by introducing contaminants such as sediment, salt, heavy metals, phytopathogens, nutrients, weeds and others. This project, conducted by Macquarie University in collaboration with NGINA, assessed these risks and developed an adaptive framework to support industry awareness and strategies to manage water contamination and recover efficiently after storm and flood events. The decision-support framework was constructed for production nurseries based on information, observations and scientific data collected during this project, and uses a three-phase approach to the adaptive management cycle based on five key themes of the project. The framework is therefore a strategic tool underpinned by scientific evidence that is designed to help production nurseries assess water contamination concerns for water storages pre- and post-storm and flood events. It will encourage implementation of effective mitigation measures and recovery action plans to ensure continued operations of production nurseries following major events. It can help production nurseries prioritise critical recovery actions to reduce contamination and economic loss, and to prepare for future events with minimal disruption to nursery operations. This approach will help build resilience so that nurseries can withstand and recover from future storm and flood events more efficiently.

Through a multi-disciplinary approach, the project identified key catchment- and lot-scale factors for consideration, identified and measured key contaminants in water storage reservoirs, analysed water quality data over the course of one year at ten focus production nurseries, estimated potential inundation hotspots, and will support the review and development of best management practices to enhance water quality and production nursery resilience. The research emphasises the importance of understanding and addressing the factors contributing to water quality issues before, during and after flood events to mitigate impacts on plant production. Development of informed best management practices can serve to improve nursery infrastructure design, optimise irrigation and nutrient management, and ensure effective water treatment and emergency response strategies. By adopting suitable measures, production nurseries should be able to minimize economic losses, sustain plant health, and ensure fewer and less severe interruptions to trade following extreme weather events.

The findings from this project contribute to a broader understanding of water contamination risks and their management, not only for NSW and ACT production nurseries but also for other water-intensive agricultural industries that rely on water capture, storage and recycling. Continued collaboration among researchers, industry partners, community stakeholders, and policymakers will be essential to refining and implementing these strategies. Strengthening resilience against extreme weather events will ultimately safeguard the production nursery industry and help to maintain environmental and economic stability in the horticultural supply chain.

11. References

Australian and New Zealand Governments (ANZG), 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Available online: https://www.waterquality.gov.au/anz-guidelines (last accessed 23 June 2025).

Bureau of Meteorology (BOM), 2016. Design rainfall data system 2016 [data]. © Commonwealth of Australia (Bureau of Meteorology) 2016. Available online: http://www.bom.gov.au/water/designRainfalls/index.shtml (last accessed 16 June 2025).

Bureau of Meteorology (BOM), 2022. AHGF Catchment v3.3 (ID: 33), Australian Hydrological Geospatial Fabric catchment layer [data]. © Commonwealth of Australia (Bureau of Meteorology) 2022. Available online: http://www.bom.gov.au/water/geofabric/download.shtml (last accessed 23 June 2025).

Bureau of Meteorology (BOM), N.D. Water Data Online [data]. Available online: http://www.bom.gov.au/waterdata/ (last accessed 16 June 2025).

Department of Customer Service (DCS) NSW, 2021. NSW Cadastre web service [data]. © Department Customer Service, Spatial Services. Available online: https://datasets.seed.nsw.gov.au/dataset/nsw-cadastre-web-service/resource/dc16cfc1-25f2-4631-a715-15ec7096baf9 (last accessed 16 June 2025).

Department of Customer Service (DCS) NSW, N.Da. New South Wales 1 metre Resolution Digital Elevation Model – 2x2 km tiles [data]. © Department Customer Service, Spatial Services. Available online: https://elevation.fsdf.org.au/ (last accessed 23 June 2025).

Department of Customer Service (DCS) NSW, N.Db. Eastern New South Wales (Zone 56) 5 metre Resolution Digital Elevation Model – 110x110 km tiles [data]. © Department Customer Service, Spatial Services. Available online: https://portal.spatial.nsw.gov.au/client (last accessed 23 June 2025).

Department of Planning and Environment (DPE) NSW, 2017. NSW Landuse 2017 v1.5 [data]. © Department of Planning and Environment. Available online: https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017-v1p5-f0ed-clone-a95d (last accessed 16 June 2025).

Department of Primary Industries (DPI) NSW, 2021. Managing water in plant nurseries, 3rd Edition. AgGuide Water Series. Tocal College, NSW Department of Primary Industries. 249 pp. ISBN 9781760584566.

Environment Protection Authority (EPA) NSW, 2022. Approved methods for the sampling and analysis of water pollutants in NSW. https://www.epa.nsw.gov.au/Licensing-and-Regulation/Licensing/Environment-protection-licences/Licensing-under-POEO-Act-1997/licensing-to-regulate-water-pollution/Approved-methods-for-sampling-and-analysing-water-pollutants (last accessed 23 June 2025).

ESRI, 2020. World Imagery Wayback Basemap [data]. Available online: https://livingatlas.arcgis.com/wayback/ (last accessed 18 June 2025).

Gallant, J.C, Austin, J., 2016. Topographic Wetness Index derived from 1" SRTM DEM-H. v2. CSIRO [data]. Available online: https://doi.org/10.4225/08/57590B59A4A08 (last accessed 16 June 2025).

Gallant, J.C., Wilson, J.P., 2000. Primary topographic attributes. Chapter 3 in: Wilson, J.P. and Gallant, J.C. Terrain Analysis: Principles and Applications, John Wiley and Sons, New York. ISBN 9780471321880

Gomes, M., Ralph, T.J., Humphries, M., Graves, B.P., Kobayashi, T., Gore, D., 2025. Waterborne contaminants in high intensity agriculture and plant production: A review of on-site and downstream impacts. Science of the Total Environment, 958. Article #178084. https://doi.org/10.1016/j.scitotenv.2024.178084

Hydrologic Engineering Center (HEC), 2016. HEC-RAS (Hydrologic Engineering Center's River Analysis System) v5.0.1. Available online: https://www.hec.usace.army.mil/software/hec-ras/ (last accessed 16 June 2025).

Hydrologic Engineering Center (HEC), 2022. HEC-RAS 2D User's Manual v6.6. U.S. Army Corps of Engineers. Available online: https://www.hec.usace.army.mil/confluence/rasdocs/r2dum/6.6 (last accessed 16 June 2025).

Moore, I.D., Burch, G.J., Mackenzie, D.H., 1988. Topographic effects on the distribution of surface soil water and the location of ephemeral gullies. Transactions of the American Society of Agricultural and Biological Engineers, 31, 1098-1107. https://doi.org/10.13031/2013.30829

Moore, I.D., Grayson, R.B., Ladson, A.R., 1991. Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrological Processes, 5, 3-30. https://doi.org/10.1002/hyp.3360050103

Nursery and Garden Industry Australia (NGIA), 2010. Nursery Industry Water Management Best Practice Guidelines. Available online: https://nurserycrops.ces.ncsu.edu/wp-content/uploads/2021/05/WATER-BMP-NGIA-Aug-2012-Final.pdf (last accessed 16 June 2025).

Nursery and Garden Industry Australia (NGIA)/Greenlife Industry Australia, N.D. NIASA Accreditation Program – Nursery Industry Accreditation Scheme Australia. Available online: https://www.greenlifeindustry.com.au/ (last accessed 17 February 2023).

Plant Clinic, 2024. PlantClinic Report. Macquarie University, Phytophthora Nursery Dam Project NGINA. Phytophthora and Pythium service. Reference 25.036, UID1249731057.

Ralph, T.J., Gomes, M., Graves, B.P., Lybeck, C.T., 2025. Water quality fact sheets for production nurseries. Macquarie University. https://doi.org/10.25949/JH43-4N56